Electronic identifier: 12609

Date of electronic submission: 27/07/2014

The University of Manchester makes unrestricted examined electronic theses and
dissertations freely available for download and reading online via Manchester eScholar at
http://www.manchester.ac.uk/escholar.

I hereby declare that this print version of my thesis/dissertation is a TRUE and ACCURATE
REPRESENTATION of the electronic version submitted to the University of Manchester's
institutional repository, Manchester eScholar.

Author's signature ..............................................

Date signed .........................................................
Imaging of Soil Moisture in the Root Zone using Capacitively Coupled Electrodes

A thesis submitted to The University of Manchester for the degree of

Doctor of Philosophy

in the Faculty of Engineering and Physical Sciences

2014

PAUL ANTHONY NEWILL

SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING
3.6.3: Summary of Analytical Solutions for the Insulated Electrode System ..........139
3.8: Analytical Solution Conclusions .................................................................140
3.9: Finite Element Modelling of Insulated Electrodes ........................................141
3.10: Increasing Insulating Layer Thickness to Reduce Simulation Constraints ..........145
  3.10.1: Simulation Time for Increasing Layer Thickness ....................................146
  3.10.2: Change in Accuracy for Increasing Layer Thickness .............................147
3.11: COMSOL FEM Simulation for Varying Bulk Materials ................................149
3.12: Comparison of 3x3 and 4x4 cm² Test Cell in COMSOL.................................152
3.13: FEM Simulations for Adjacent-Plate Electrodes .........................................155
3.14: SMP Graphical User Interface ........................................................................159
3.15: Using FEM to determine the region of influence and conductivity of soil from rhizotron test data ......................................................................................162
3.16: Conclusions to FEM Simulations .................................................................178
4: Measurement and Test Procedure Overview .....................................................182
4.1: Test Equipment Used and Characterisation ....................................................183
4.2: Rhizotron Measurement System ......................................................................192
4.3: Multiple Parallel-Plate Measurements .............................................................204
4.4: Parallel-Plate Test Procedure ...........................................................................205
4.5: Rhizotron Measurement System Test Procedure .............................................210
5: Results and Discussion .......................................................................................212
  5.1: Characterisation of the Insulating Electrode Method in the Parallel-Plate Test Vessel ..............................................................................................................213
    5.1.1: Measurement of Electrical Conductivity for Water Based Electrolytes with Bench Conductivity Meters .................................................................214
    5.1.2: Measurement of Electrical Conductivity for Water Based Electrolytes through the Insulated Electrode Method .........................................................219
  5.2: Measuring Change in Electrical Impedance for Varying Soil Moisture, Compaction and Temperature ...................................................................................225
    5.2.1: Change in Electrical Impedance due to Variation of Moisture Content .......226
    5.2.2: Change in Electrical Impedance due to Variation of Soil Compaction .......239
    5.2.3: Change in Electrical Impedance due to Variation of Soil Temperature ......248
  5.3 Tests of Maize Growth within Rhizotron Vessels .............................................266
    5.3.1: Destructive and Qualitative Analysis .........................................................269
    5.3.2: Quantitative Analysis of Post-Test Gravimetric Moisture Content ..........277
<table>
<thead>
<tr>
<th>Table 2.1: Soil Mineral Characteristics (Davies, 1972)</th>
<th>39</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.2: Typical Densities and Porosities of soils (Rowell, 1994)</td>
<td>44</td>
</tr>
<tr>
<td>Table 2.3: Permeability Rate Classifications of Soil (Scherer, 1996)</td>
<td>52</td>
</tr>
<tr>
<td>Table 3.1: Calculated resistance and capacitance values for distilled, tap and saline solution based on the proposed dimensions of the parallel-plate test cell.</td>
<td>119</td>
</tr>
<tr>
<td>Table 3.2: Calculated resistance and capacitance values for three soil types based on the dimensions of the parallel-plate test cell. Values taken from Smith (1993)</td>
<td>120</td>
</tr>
<tr>
<td>Table 3.3: Calculated resistance and capacitance values for all simulation parameters for the analytical solution</td>
<td>120</td>
</tr>
<tr>
<td>Table 3.4: The influence of $C_B$ and $C_W$ on $C_{TOTAL}$</td>
<td>121</td>
</tr>
<tr>
<td>Table 3.5: Calculated resistance and capacitance values for distilled, tap and saline solution</td>
<td>131</td>
</tr>
<tr>
<td>Table 3.6: Calculated resistance and capacitance values for three soil moisture contents based on values taken from Smith (1993)</td>
<td>136</td>
</tr>
<tr>
<td>Table 3.7: COMSOL Materials used, and associated electrical parameters. Values for a 75$\mu$m insulating layer and bulk material of tap water</td>
<td>143</td>
</tr>
<tr>
<td>Table 3.8: Scaled electrical conductivity and permittivity for 75, 500 and 5000 $\mu$m thickness insulating layer</td>
<td>145</td>
</tr>
<tr>
<td>Table 3.9: Solution time, mesh elements and elements per second for a COMSOL simulation of tap water with three different thicknesses of insulating layer</td>
<td>147</td>
</tr>
<tr>
<td>Table 3.10: Calculated conductivity and resistance and capacitance values for all simulation parameters for the analytical solution</td>
<td>149</td>
</tr>
<tr>
<td>Table 3.11: Percentage difference and standard deviation % between MATLAB and COMSOL simulations for all six bulk materials</td>
<td>152</td>
</tr>
<tr>
<td>Table 3.12: Average percentage difference between parallel- and adjacent-plate real impedance within the plateau region for all six bulk materials. FEM simulation data</td>
<td>159</td>
</tr>
<tr>
<td>Table 3.13: Values of electrical conductivity used during FEM simulations to determine region of influence for adjacent-plate measurements</td>
<td>164</td>
</tr>
</tbody>
</table>
Table 3.14: Simulated values of electrical impedance for all three positions of the cube, and the error percentage difference against the reference impedance of 2.14 kΩ ................................................................. 177

Table 4.1: Particle Size Distribution for 18-Acre soil. Performed by Agvise Laboratories (Agvise 2013) ........................................................................ 187

Table 4.2: Four pressure levels used to compact the soil .................................. 191

Table 5.1: Sodium Chloride test quantities and measured values of electrical conductivity acquired with the SevenMulti Conductivity Meter .......................................................... 216

Table 5.2: Scaled electrical conductivity and % difference between test iterations 1 and 2, for the bench conductivity meter method ................................................................. 217

Table 5.3: Selected plateau frequency for each level of salinity, based on visual observation of the spectroscopic impedance for test iterations 1 and 2. ........................................ 222

Table 5.4: Proposed and measured sodium chloride test quantities, electrical impedance measured with the insulated electrode method and converted values of electrical conductivity ........................................................................ 222

Table 5.5: Scaled electrical conductivity and % difference between test 1 and 2 for the insulated electrode method ........................................................................ 223

Table 5.6: Plateau region estimates based on spectroscopic real impedance plots found in Figures 5.4 to 5.6 ................................................................. 230

Table 5.7: Estimated plateau frequencies for 5-30% soil moisture content ...... 232

Table 5.8: Values of electrical impedance and percentage change from previous sample impedance for each test iteration, at all levels of soil moisture content ........................................................................ 234

Table 5.9: Empirically determined values of Capacitance, and calculated relative permittivity values for test 01 ........................................................................ 237

Table 5.10: Measured values of electrical impedance (Ω) for each compaction level, at each level of soil moisture content and for all 3 test iterations ............... 243

Table 5.11: Percentage change in measured impedance from compaction level 1 for each soil moisture content – test 1 ................................................................. 244

Table 5.12: Percentage change in measured impedance from compaction level 1 for each soil moisture level- test 2 ................................................................. 244

Table 5.13: Percentage change in measured impedance from compaction level 1 for each soil moisture level- test 3 ................................................................. 244

Table 5.14: Percentage change in measured impedance from level 1 to 4
compaction for tests 1-3

Table 5.15: Measured real impedance for each level of compaction for 5% gravimetric soil moisture content from test 1, based on the plateau frequency of 5 kHz. Empirical simulation values were obtained through SMP GUI

Table 5.16: Measured values of electrical impedance (kΩ) for each temperature at each level of soil moisture content, and for all 3 test iterations

Table 5.17: Percentage change in measured impedance from value at 5°C, for each soil moisture content – test 1

Table 5.18: Measured real impedance for each temperature for 15% gravimetric soil moisture content from test 3, based on the plateau frequency of 5 kHz. Empirical simulation values were obtained through SMP GUI

Table 5.19: Measured electrical impedance of 5% gravimetric soil moisture between 5-40°C, and theoretical values calculated on measured value at 25°C. Data taken from Test 3

Table 5.20: Percentage difference between measured impedance and 2%/°C linear scaling temperature correction, for all soil moisture contents. Highlighted region denotes an example diurnal temperature range

Table 5.21: Comparison of plant height and total mass for growth test 2

Table 5.22: Post-test gravimetric soil moisture content for rhizotron growth test 1. Highlighted column denotes control vessel

Table 5.23: Post-test gravimetric soil moisture content for rhizotron growth test 2. Highlighted column denotes control vessel

Table 5.24: Measured and theoretical values of impedance (Ω) and error margins for temperature variations in T1-FNS4, first 15 days of test data

Table 5.25: Measured, theoretical and error margins for temperature variations in T1-FNS5, Impedance extracted at 6 days throughout test duration

Table 5.26: Measured electrical impedance at five excitation frequencies, in an arbitrary electrode pair for all three test cells; Electrode pair; 19-25. Measurement data from day 07 after test start

Table 5.27: Start and end impedance for multiple measurement locations. Table position relative to actual measurement position. Test 1. Test data for FNS3-5. Highlighted cells denote control vessel
Table 5.28: Start and end impedance for multiple measurement locations. Table position relative to actual measurement position. Test 2. Test data for FNS3-5. Highlighted cells denote control vessel ............................................................ 313

List of Figures

Table: Figure 2.1: Soil Texture Triangle (White, 1979) ......................................................... 38
Figure 2.2: Soil structure conditions; a: Good b: Moderate c: Poor (Vaderstad, 2005) ................................................................. 42
Figure 2.3: Air Capacity in Soil Pores (White, 1979) ................................................................. 45
Figure 2.4: Soil Saturation, Field Capacity, Wilting Point and Hygroscopic Coefficient Levels (Brady, 1974) ................................................................. 47
Figure 2.5: Classes of Soil Water (Davies, 1972) ................................................................. 47
Figure 2.6: Soil Water Surface Retention Pressures (Brady, 1974) ........................................ 50
Figure 2.7: Available Water for Different Soil Textures (Brady, 1974) ..................................... 51
Figure 2.8: Soil Water Surface Retention Pressures (Repeat of Figure 2.6) ........................ 56
Figure 2.9: Electric current and potential lines for a four-electrode measurement of the soil resistivity (Knodel, 2007) ................................................................. 71
Figure 2.10: Electrical model for the double layer capacitance ........................................ 79
Figure 2.11: Dielectric constant ε (increasing) and conductivity σ (increasing) as a function of frequency – Known as β-dispersion (Schwan, 1994) ...................... 85
Figure 2.12: Equivalent circuit for a C⁴D system ................................................................. 100
Figure 2.13: Equivalent circuit for C⁴D with a series inductor placed in series. RL is the resistance associated with the inductor L ................................................................. 101
Figure 3.1: Electrical Model for C⁴D as Proposed by Wang (2012) ...................................... 109
Figure 3.2: Insulated electrode measurement system block diagram and equivalent electrical circuit ................................................................. 110
Figure 3.3: Simplified equivalent electrical circuit with both electrodes combined .................. 111
Figure 3.4: Separated elements of equivalent electrical model. a: insulating layer, b: bulk material .............................................................................. 112
Figure 3.5: Comparison of analytical solution and measured real impedance for tap water measured in a parallel-plate configuration. Simulation parameter R_W
= 2 \times 10^{12} \Omega.

Figure 3.6: Comparison of analytical solution and measured real impedance for tap water measured in a parallel-plate configuration. Simulation parameter $R_W = 1.5 \times 10^6 \Omega$.

Figure 3.7: Comparison of simulated real impedance for two insulating layers of varying thickness. Bulk material of saline solution.

Figure 3.8: Spectroscopic complex impedance of the insulating layer.

Figure 3.9: Spectroscopic complex impedance of the insulating layer.

Figure 3.10: Simulated spectroscopic complex impedance of tap water as bulk material.

Figure 3.11: Simulated spectroscopic current flow through the resistive and reactive elements for tap water.

Figure 3.12: Simplified electrical model for insulating layer of both electrodes combined and bulk material.

Figure 3.13: Simulated spectroscopic complex impedance of the full analytical solution for tap water. Point A represents the Plateau region created by the insulating layer. Point B represents the plateau region created by the bulk material.

Figure 3.14: Simulated spectroscopic current flow of the full analytical solution for tap water. Point A represents the Plateau region created by the insulating layer. Point B represents the plateau region created by the bulk material.

Figure 3.15: Simulated real, imaginary and absolute complex impedance for tap water.

Figure 3.16: Simulated real, imaginary and absolute complex impedance for distilled water.

Figure 3.17: Simulated real, imaginary and absolute complex impedance for a saline solution.

Figure 3.18: Comparison of simulated real impedance of the complex solution for the full analytical model. Bulk materials of distilled, tap and saline solution.

Figure 3.19: Simulated real, imaginary and absolute complex impedance for dry soil.

Figure 3.20: Simulated real, imaginary and absolute complex impedance for moderately wet soil.
Figure 3.21: Simulated real, imaginary and absolute complex impedance for saturated soil. 

Figure 3.22: Comparison of simulated real impedance of the complex solution for the full analytical model. Bulk materials of dry, moderate and saturated soils.

Figure 3.23: Comparison of simulated real impedance of the complex solution for the full analytical model for all bulk materials.

Figure 3.24: a: COMSOL FEM model for parallel-plate test cell. b: COMSOL Mesh structure. Cell dimensions; 3x3cm electrode, 4.6cm electrode spacing and 75μm insulating layer.

Figure 3.25: Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of tap water. Note the two plots overlap.

Figure 3.26: COMSOL FEM models and mesh structures for the parallel-plate test vessel using three values of electrode thickness; a-b: 75 μm, c-d: 500 μm, e-f: 5000 μm.

Figure 3.27: COMSOL simulated real impedance for three insulating wall thicknesses. Note that the 75μm curve is not visible as it overlaps almost exactly with the 500um curve.

Figure 3.28: Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of Saline Solution.

Figure 3.29: Comparison of MATLAB and COMSOL simulated real impedance. Bulk material is dry soil.

Figure 3.30: COMSOL based FEM model for the 4x4 test cell.

Figure 3.31: Comparison of real impedance for a 3x3 and 4x4 cm² test cell with tap water as the bulk material. Simulated with COMSOL.

Figure 3.32: Comparison of 3x3 and 4x4 COMSOL simulated real impedance with measured real impedance of tap water. Measurements performed with HP 4192A impedance analyser between 10Hz to 13 MHz. Measurement plateau region estimated to be 100 kHz to 1 MHz.

Figure 3.33: COMSOL FEM for an adjacent-plate measurement, dimensions based on the rhizotron measurement system.

Figure 3.34: Comparison of COMSOL simulated real impedance for parallel- and adjacent-plate for a bulk material of tap water.

Figure 3.35: Comparison of COMSOL simulated real impedance for parallel- and
adjacent-plate for a bulk material of distilled water. 

Figure 3.36: SMP GUI created to allow empirical modeling and rapid analysis of effects of changing simulation parameter values. 

Figure 3.37: SMP GUI with simulation data empirically fitted to measurement to determine electrical properties. 

Figure 3.38: Example COMSOL results showing current flow and potential distribution for adjacent electrodes and a uniform conductivity distribution. 

Figure 3.39: Model used to explore sensitivity as a boundary between different conductivities is moved along the X-axis. Contrasting layer set to 12cm from centre point of electrodes. 

Figure 3.40: Effect on conductance due to High and Low impedance materials being introduced along the x-axis. Marker demonstrates distance where contrasting layer has no measurable effect. 

Figure 3.41: Model used to explore sensitivity as a boundary between different conductivities is moved along the Y-axis. Contrasting layer set to 16cm from centre point of electrodes. 

Figure 3.42: Effect on conductance due to High and Low impedance materials being introduced along the y-axis. 

Figure 3.43: Demonstrating the electric field in the y-axis. Boundary set at 5 cm from edge of electrodes and demonstrates the region of influence. 

Figure 3.44: Model used to explore sensitivity as a boundary between different conductivities is moved along the Z-axis. 

Figure 3.45: Effect on conductance due to High and Low impedance materials being introduced along the z-axis. 

Figure 3.46: Example vessel constructed to demonstrate region of influence of adjacent-plate electrode measurements. 

Figure 3.47: New test vessel with a volume representing the region of influence around the electrodes. 

Figure 3.48: Effect on conductance as conductivity of medium increases. 

Figure 3.49: Plot of Simulated electrical impedance for ten values of conductivity, and a plot of measured impedance over a 42 day period. Values of simulated impedance can be used to backwards estimate values of electrical conductivity, two examples shown. 

Figure 3.50: Model used to explore sensitivity to localised regions of
conductivity contrast, cube of localised conductivity in Position 1

Figure 3.51: Effect on Impedance due to localised conductivity regions measuring 3x3x2.7 cm

Figure 4.1: Complete rhizotron measurement system

Figure 4.2: Rhizotron system block diagram

Figure 4.3: Saved rhizotron measurement data format

Figure 4.4: Measurement protocol for rhizotron system

Figure 5.1: Measured spectroscopic impedance for an electrolyte of increasing salinity, test iteration 1

Figure 5.2: Measured spectroscopic impedance for an electrolyte of increasing salinity, test iteration 2

Figure 5.3: Electrical conductivity of the electrolyte with increasing salinity. Measured values based on two measurement methods; Bench conductivity meter and insulated electrode method

Figure 5.4: Measured real impedance for test 1; 5-30% soil moisture

Figure 5.5: Measured real impedance for test 2; 5-30% soil moisture

Figure 5.6: Measured real impedance for test 3; 5-30% soil moisture

Figure 5.7: Estimated plateau frequencies for 20-30% soil moisture content based on measured values for 5-15%, test 01

Figure 5.8: Measured real impedance for increasing soil moisture content based on estimated plateau frequencies. Test 1-3

Figure 5.9: Empirical data fitting to determine parameter values soil wetted to 5% moisture content. Where; $C_W = 70\text{pF}$, $R_W = 45\text{M} \Omega$, $C_B = 1.5\text{pF}$, $R_B = 1.4$ MΩ. Test 01; 5% Moisture Content

Figure 5.10: Empirical data fitting to determine parameter values soil wetted to 15% moisture content. Where; $C_W = 70\text{pF}$, $R_W = 15\text{M} \Omega$, $C_B = 3.5\text{pF}$, $R_B = 4.6$ kΩ. Test 01; 15% Moisture Content

Figure 5.11: Impedance for increasing compaction pressure of 5% gravimetric soil moisture content

Figure 5.12: Impedance for increasing compaction pressure of 5% gravimetric soil moisture content. Zoom on plateau region

Figure 5.13: Measured impedance for increasing soil moisture compared to variation from compaction for test 1

Figure 5.14: Measured real impedance for decreasing temperature between 5-
40°C in soil wetted to 20% moisture content; Test 3. .......................................................... 251
Figure 5.15: Measured real impedance for decreasing temperature between 5-
40°C in soil wetted to 20% moisture content; Test 3. Zoom on plateau region. ...
Figure 5.16: Change in measured impedance due to change in soil temperature and correlated change in temperature within the soil. 20% moisture content; test 3. ........................................................................................................................................ 252
Figure 5.17: Empirical fitting of data for soil temperature testing. 15% soil moisture content at 5°C, test iteration 3 ................................................................................................................................. 256
Figure 5.18: Measured real impedance for varying temperature. Data taken from Test 3 ................................................................................................................................................................................................. 258
Figure 5.19: Measured and theoretical real impedance for increasing temperature of soil at 5% gravimetric moisture content ................................................................................................................. 260
Figure 5.20: Measured and theoretical real impedance for increasing temperature of soil at 10% gravimetric moisture content ................................................................................................................. 261
Figure 5.21: Measured and theoretical real impedance for increasing temperature of soil at 15% gravimetric moisture content ................................................................................................................. 261
Figure 5.22: Measured and theoretical real impedance for increasing temperature of soil at 20% gravimetric moisture content ................................................................................................................. 262
Figure 5.23: Measured and theoretical real impedance for increasing temperature of soil at 25% gravimetric moisture content ................................................................................................................. 262
Figure 5.24: Measured and theoretical real impedance for increasing temperature of soil at 30% gravimetric moisture content ................................................................................................................. 263
Figure 5.25: Real impedance change for increasing temperature compared to soil moisture content ........................................................................................................................................................................... 265
Figure 5.26: Rhizotron vessels plant growth test 1; Post-test visual observations ............................................................................................................................................................................................................. 271
Figure 5.27: Rhizotron vessels plant growth test 2; Post-test visual observations ............................................................................................................................................................................................................. 273
Figure 5.28: Destructively sampled root bundles for growth test 2. A) T2-FNS4, B) T2-FNS5 ........................................................................................................................................................................................................................................... 275
Figure 5.29: Post-test photographs of soil cores from growth test 2. A) T2-FNS3, B) T2-FNS4, C) T2-FNS5. Highlighted region of T2-FNS4 denotes possible area of localised compaction based on visual observation ........................................................................................................... 276
Figure 5.30: Available Water for Different Soil Textures (Brady, 1974) ........................................................................................................................................................................................................................................... 280
Figure 5.31: Measurement number, and assigned electrode pairings based on measurement protocol for rhizotron testing. View from soil side of rhizotron. 

Figure 5.32: Conditional Formatting of measured real impedance in all three rhizotrons, for first measurement after test start. Blue = low impedance, Red = high impedance. View from soil side of rhizotron.

Figure 5.33: Conditional formatted data for non- and corrected real impedance in vessel T1-FNS4.

Figure 5.34: Measured impedance for first 15 days (350 test iterations) in vessel T1-FNS4. Non-filtered data shows the temperature effects on impedance.

Figure 5.35: Measured impedance for full test duration in vessel T1-FNS5. Non-filtered data shows the temperature effects on impedance.

Figure 5.36: Real impedance at measurement #62, electrodes 38-39 in vessel T1-FNS4. Non-filtered.

Figure 5.37: Real impedance at measurement #62, electrodes 38-39 in vessel T1-FNS4. Filtered.

Figure 5.38: Measured real impedance between electrodes 19-25 in growth test 1, taken on Day 07, for all 3 Rhizotrons.

Figure 5.39: Measured Real Impedance between electrodes 45-46, for Rhizotron T1-FNS4 at all five excitation frequencies.

Figure 5.40: Measured Real Impedance between Electrodes 45-46, for Rhizotron T1-FNS5 at all five excitation frequencies.

Figure 5.41: Measured Real Impedance between Electrodes 45-46, for Rhizotron T1-FNS3 at all five excitation frequencies.

Figure 5.42: Movie representation of plant growth tests over complete growth test 1. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on maximum and minimum values for all three test vessels.

Figure 5.43: Movie representation of plant growth tests over complete growth test 2. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on maximum and minimum values for all three test vessels.

Figure 5.44: Movie representation of plant growth tests over complete growth test 1. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on values of impedance for the estimated wilting
Figure 5.45: Movie representation of plant growth tests over complete growth test 2. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on values of impedance for the estimated wilting point.

Figure 5.46: Movie representation of plant growth tests over complete growth test 1. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set to show variation of control vessel.

Figure 5.47: Movie representation of plant growth tests over complete growth test 2. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set to show variation of control vessel.

Figure 5.48: Measured Impedance in Test 1 for FNS3, 4 and 5 for the duration of the test for selected measurement pairings.

Figure 5.49: Measured Impedance in Test 2 for FNS3, 4 and 5 for the duration of the test for selected measurement pairings.

Figure 5.50: Photograph of plant growth in Rhizotron T2-FNS5 at: A) Day 05, B) Day 27.
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>2 Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3 Dimensional</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AWC</td>
<td>Available Water Content</td>
</tr>
<tr>
<td>C4D</td>
<td>Capacitively Coupled Contactless Conductivity Detection</td>
</tr>
<tr>
<td>CSV</td>
<td>Comma Separated Variable</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EC</td>
<td>Electrical Conductivity</td>
</tr>
<tr>
<td>ECT</td>
<td>Electrical Capacitance Tomography</td>
</tr>
<tr>
<td>EM</td>
<td>Electro-Magnetic</td>
</tr>
<tr>
<td>EIM</td>
<td>Earth Impedance Method</td>
</tr>
<tr>
<td>EIS</td>
<td>Electrical Impedance Spectroscopy</td>
</tr>
<tr>
<td>EIT</td>
<td>Electrical Impedance Tomography</td>
</tr>
<tr>
<td>ERT</td>
<td>Electrical Resistance Tomography</td>
</tr>
<tr>
<td>FC</td>
<td>Field Capacity</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground Penetrating Radar</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HC</td>
<td>Hygroscopic Coefficient</td>
</tr>
<tr>
<td>HP</td>
<td>Hewlett Packard</td>
</tr>
<tr>
<td>HPIB</td>
<td>Hewlett Packard Interface Bus</td>
</tr>
<tr>
<td>GPIB</td>
<td>General Purpose Interface Bus</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MRI</td>
<td>Magnetic Resonance Imaging</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PSD</td>
<td>Particle Size Distribution</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>PSR</td>
<td>Pore Space Ratio</td>
</tr>
<tr>
<td>RC</td>
<td>Resistor-Capacitor</td>
</tr>
<tr>
<td>RMD</td>
<td>Root Mass Density</td>
</tr>
<tr>
<td>SISP</td>
<td>Sensing, Imaging &amp; Signal Processing</td>
</tr>
<tr>
<td>SMP</td>
<td>Simulation Model Parameters</td>
</tr>
<tr>
<td>SP</td>
<td>Spontaneous/Self Potential</td>
</tr>
<tr>
<td>SWC</td>
<td>Soil Water Content</td>
</tr>
<tr>
<td>TabUMS</td>
<td>Tab Universal Measurement System</td>
</tr>
<tr>
<td>TDR</td>
<td>Time Domain Reflectometry</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solids</td>
</tr>
<tr>
<td>UoM</td>
<td>University of Manchester</td>
</tr>
<tr>
<td>UTC</td>
<td>Universal Time Convention</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>UV</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>VES</td>
<td>Vertical Electrode Sounding</td>
</tr>
<tr>
<td>VSA</td>
<td>Visual Soil Assessment</td>
</tr>
<tr>
<td>WP</td>
<td>Wilting Point</td>
</tr>
</tbody>
</table>
Nomenclature

\[ C_a \] Air capacity
\[ C_B \] Bulk capacitance
\[ C_P \] Polarisation capacitance
\[ C_{W(n)} \] Capacitance of insulating layer
\[ Cu/CuSO_4 \] Copper/ copper sulphate
\[ EC_a \] Apparent electrical conductivity
\[ \varepsilon \] Air filled porosity
\[ \varepsilon_r \] Relative permittivity
\[ k \] Geometric factor
\[ \theta \] Volumetric water content of soil
\[ \theta_{FC} \] Volumetric field capacity
\[ \theta_{WP} \] Volumetric wilting point
\[ L \] Inductance associated with electrophoresis
\[ NaCl \] Sodium Chloride
\[ \rho \] Resistivity
\[ \rho_a \] Apparent resistivity
\[ R_b \] Bulk resistance
\[ RL \] Resistance associated with electrophoresis inductance
\[ R_p \] Polarisation resistance
\[ R_s \] Resistance of bulk material in electrophoresis
\[ R_W \] Insulating layer resistance
\[ \sigma \] Conductivity
\[ SiO_2 \] Silica Dioxide
\[ T1-FNS3 \] Refers to rhizotron growth test 1, vessel FNS3
\[ V_i \] Input voltage
\[ V_o \] Output voltage
\[ V_r \] Voltage change from a single electrode
$Z_B$ Total impedance of bulk

$Z_P$ Polarisation impedance

$Z_W$ Total impedance of insulating layer
Abstract

This research explores the use of insulated electrodes to determine electrical impedance distributions within soil cores. It is used to infer the effect of roots on soil moisture which, in turn, can provide knowledge relating to crop breeding programmes. These programmes are becoming increasingly important in order to address challenges posed by global population growth and climate change.

Direct contact electrical impedance measurements in soil are frequently used but these are vulnerable to electrochemical effects and corrosion. Insulated electrodes are used in the present work to overcome these difficulties and a modified electrode model has been proposed. Measurements require the acquisition of spectroscopic complex impedance and extraction of the real impedance to infer soil moisture content.

Calculated and simulated impedance, from the analytical solution and an FEM model respectively, were compared to measurements performed within a parallel-plate test cell containing saline solutions. The effects of moisture, compaction and temperature on soil impedance measurements have been explored. Finally, two growth trials using maize plants and control vessels were performed to create 2D images of impedance distributions, from which moisture placement was inferred.

Results show that for saline electrolytes, the insulated electrode method was capable of estimating the impedance of tap water to within 10% of calibrated laboratory equipment. For soil based measurements, the variation of moisture content from 5\%-30\% resulted in a 1000-fold decrease in impedance. The change was most significant in drier soils. For compaction based testing, at 5\% moisture content soil impedance decreased by approximately 40\%, compared to only 20\% in the wettest samples. Temperature testing revealed an impedance change of approximately 2%/°C, in agreement with earlier reports.

Plant growth trials revealed increases in electrical impedance due to soil drying from an initial value of 1-2kΩ when the soil was wetted to field capacity, to as much as 60kΩ when dry. Only small changes were evident in the control vessels. It was also found that areas exposed to potential evaporation, such as at the surface closest to the plant stem, suffered significant losses in moisture content, reaching as high as 15-20kΩ.
This research utilises a measurement technique which has not previously been used to measure soil impedance to infer moisture content. The research also found that the scaling of a thin layer within an FEM model can significantly reduce computational demands, while retaining accuracy, and allow more complex FEM simulations to be performed on a less powerful computer.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.
Copyright Statement

i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and s/he has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trade marks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://www.campus.manchester.ac.uk/medialibrary/policies/intellectualproperty.pdf), in any relevant Thesis restriction declarations deposited in the University Library, the University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on presentation of Theses.
Acknowledgments

I would like to express my gratitude to my supervisor, Professor Trevor York, and his persistent requirement for weekly meetings attempting to keep me on a straight and narrow path. I am also grateful to him for allowing me to throw potatoes around a laboratory, in the name of science, for what seemed like months on end. I am truly thankful for your wealth of experience and knowledge, and the desire to push me academically further than I thought possible.

I would also like to thank Dr. Bruce Grieve, Director of the e-Agri Sensors Centre for leading the e-Agri group and allowing me to study with them, and for being my co-supervisor throughout my research. I owe a large debt of gratitude to both Dr. Frank Podd and Dr. Simon Hammersley for always being willing to assist whenever possible, whether through physically helping with experiments or answering my masses of questions. Finally, from the e-Agri group, I would like to thank all other members of staff and fellow students for the continued support and friendships.

I am also grateful for all the staff in the mechanical engineering workshop, for the continual creation of small intricate vessels in which my early soil measurements were performed.

I would like to thank both the Engineering and Physical Sciences Research Council for funding the research project, and Syngenta for funding the University Innovation Centre and providing additional sponsorship allowing me to afford to live a relatively normal life with a family while studying. From Syngenta, I would also like to thank Claudio Screpanti and his team for the assistance and knowledge provided for plant testing programmes.

This brings me onto my final acknowledgement, my family. I am forever indebted to my wonderful wife Laura who, 10 years ago, encouraged me to give up my dead-end job and return to full time education to realise my potential. I don’t, however, think she expected it would take this long for me to leave! I am grateful for her allowing me to frequently work late into the night and at least attempting to be interested by the strange combination of soil and electronics. I am also grateful for my two wonderful children, Layla and William, who daily make me smile and have never yet failed to cheer up a gloomy PhD student who may have occasionally suffered from mid-thesis blues.
1: Introduction

1.1: Background and Motivation

According to Innovations for Poverty Action, it is estimated that 70% of the world’s population rely on agriculture for all or part of their income (IPA, 2011). Farmers are at the mercy of nature, with a ‘poor season’ potentially destroying all, or partial, income for that year. This dependence on nature, coupled with rising global population (PRB, 2013) and the possibility of climate change causing a shift in possible land farming usages (Zhang, 2011), places strain on farmers, farming techniques and the quantity of food which can be supplied. A compound effect of these factors is caused by increased fresh water consumption for personal usage from within the rising population while it is also reported that agriculture requires 92% of annual global freshwater supplies (Science Now, 2012).

Through enhanced irrigation techniques and more efficient crops with an increased yield, the growing demand may be able to be satisfied and provide a greater return for the farmer.

It has previously been proven that crop performance can be enhanced through rapid phenotyping of strong genetic traits shown during early crop development (Hickey, 2012 and Walter, 2007). Typically, these crop based studies are performed above the soil surface, as below surface measurements are inherently difficult to perform. However, there is a desire to explore opportunities for sub-surface measurements, in and around the rhizosphere, the region closest to plant roots, to infer properties relating to the health of a plant. One possibility is to infer plant health and growth characteristics from moisture distribution around the plant root system. Very little information is currently available, however, relating soil water movement to root growth. The ability to measure soil moisture content and its movement through soil will lead to the ability to infer water uptake of plants since the majority of water in the soil is lost through evapotranspiration; evaporation from the soil surface, and transpiration as water is used by the plant.

In order to provide this knowledge of soil moisture content and its movement, it must first be understood how water moves in and around the soil, and what factors affect the spatial and temporal variation of soil moisture. In order to achieve this, the basic principles of soil must be considered. Once an understanding of soil is achieved it is necessary to consider
the current methodologies that are available for measuring soil properties, and in particular, its moisture content. Soil is inherently complex and measurements are challenging. The potential variability that exists within a small soil sample presents difficulties in acquiring repeatable data. As such, crop monitoring programs are often manually performed in control fields and are both invasive and destructive, typically requiring the crop to be removed from the soil to perform measurements on both soil and roots. Destructive sampling does not lend itself to temporal measurements, which are crucial for soil water analysis relative to root growth.

The following section provides a brief overview of some basic properties of soil. A more thorough review of soil and its characteristic properties is provided in chapter 2.

1.2: Soil – The Basics

Soil is created from particles of broken rock generally caused by weathering and erosion. There is no single definitive description of soil as it can vary widely, with each ‘type’ of soil having merits according to the particular application (White, 1979 and Brady, 1974). Soil is defined by four basic components, with the ratios of these components providing what is known as the texture of the soil. The components are sand, silt, clay and organic matter, both living and dead. The soil can be classified by performing a particle size distribution (PSD) to determine the ratio of sand, silt and clay particles, and the quantity of organic matter. The structure of the soil is defined by the way in which the soil texture components are physically arranged, and can therefore be easily changed. The structure and porosity of the soil are also closely linked. The way the soil is worked has a substantial effect on structure and porosity, and a negligible effect on texture. It is the variance in soil texture and structure that leads to difficulties in measuring with soils due to the inherent heterogeneity of soil samples and subsequent challenge of achieving repeatability between tests.

One of the basic functions of soil is to provide a supportive structure to plant root systems, and also provide nutrients and water in order for the plant to grow and become established. The soil type influences its water retention capability. Clay based soils can hold a larger quantity of water than sandy soils as the smaller clay particles create smaller voids
in which a stronger capillary attraction is present. Therefore, the clay based soils are able to hold more water at a pressure much greater than gravity can exert. For sandy soils the force of gravity is often stronger than the capillary attraction due to the larger pore spaces between particles, and as such more water is naturally drained downward through the soil. As water builds up in the soil it tends toward saturation, at which point the soil can hold no more water, and any excess begins to converge on the surface. At saturation point the force of gravity will be stronger than the force with which the soil can hold the water, and water will begin to drain down through the soil. The point at which gravity becomes weaker than the force with which soil can hold water is termed the field capacity (FC). As further water is removed from the soil, predominantly through evapotranspiration, it approaches the wilting point (WP). The WP is defined as the point at which plants can no longer extract water from the soil as it is held too tightly between particles. Between the FC and WP is termed the available water capacity (AWC), which is the total water available to the plant root system.

1.3: What is desired from Soil Measurements?

The quantitative study of the earth, and its physical properties and attributes is known as geophysics. Through geophysics, the subsurface of the earth can be investigated non-destructively, a process which is inherently difficult due to multiple components beneath the surface and the inability to achieve visual verification except through destructive methods (Weymouth, 1992). Many geophysical mapping systems have been previously implemented which have aimed to provide images of subsurface soil morphology, often with the desire to monitor soil moisture content. Perhaps the most common studies are performed either with ground penetrating radar (GPR), electrical resistivity measurements (Greve, 2010, Chang Seop, 1997 and Binley, 2001), or from surface probes (Herman, 2001 and Szarka, 1987). However, GPR is typically limited by soil moisture content (Binley, 2001), and in very wet soils measurement range is severely restricted. Other technologies such as neutron probes (Greacen, 1981) are inhibited by cost and legislation and are not so commonly performed.
Measurements in typical geophysics applications using surface-penetrating electrical currents are taken between pairs of electrodes placed at the soil surface. Individual impedance measurements of soil will provide only a bulk measurement of apparent resistivity between electrodes. A more complete measurement of the soil is achieved through physical movement of the electrodes above the ground to change the region of soil under test. Using Vertical Electrical Sounding (VES) the separation between current injection electrodes is changed to determine horizontal boundaries beneath the soil surface. Loke (2001), Barker (1981) and Dahlin (1996) describe 2D resistivity surveys in environmental applications. Using profiling, electrodes with a fixed separation are moved along the surface of the ground to create a map of the soil resistivity at a fixed depth. Vertical transitions between soil types, rocks and air pockets can be imaged. In terms of electrical properties, the biggest factor affecting the electrical impedance of soil is its moisture content. As water increases within the soil more ionic pathways are created and electrical resistance decreases. However, electrical impedance of soil is also a function of many other parameters such as soil structure, texture, compaction, temperature, organic matter and salinity. In order to estimate the water content from measurements of electrical impedance, it is also necessary to be able to quantify the effects such factors have on the electrical impedance so they can be negated.

Despite the efforts of geophysicists, relatively little sub-surface imaging has been performed at the individual plant scale, and particularly with the aim of inferring relationships between soil properties and plant systems. A few examples, (Amin, 1993, Hedberg, 1993, Anderson, 1992, Luo, 2008), have monitored soil water movement and macropore configuration of undisturbed soil cores. These use either X-Ray or magnetic resonance imaging (MRI), which offer very high resolution, but are limited by size, equipment cost and agility to adapt to different conditions. X-ray techniques can typically only be performed on shallow depth soil cores due to absorption. Using electrical resistance tomography (ERT) Binley (1996) inferred the preferential flow of water through an undisturbed soil column. The work performed by Werban (2008) is largely unrivalled. They looked at plants and their root systems on an individual scale by the use of two linear arrays of electrodes, to determine the electrical resistance properties of the soil in relation to root water-uptake with a buried plane of electrodes. While it was invasive in nature, they achieved promising results of water distribution down to the centimetric scale. Contact based electrical impedance measurements of soil present some challenges, however. Typically, they require a solid galvanic contact between electrodes and soil to
enable current flow. In addition, electrode polarisation occurs due to a change between electron and ionic conduction at the soil-electrode interface. Finally, contact with the saline soil can lead to corrosion of the electrodes. Therefore, the present work has similarities to that of Werban et al in terms of scale, use of arrays of electrodes and electrical impedance measurements, but has explored the use of insulated electrodes which has the potential to reduce the influence of the indicated limitations. In this research, measurements are conducted in small vessels called rhizotrons which are typically used to enable observation of the root zones of plants during growth, and as such are both non-destructive and non-invasive. More on the rhizotron vessel, and associated research is provided in the literature review.

1.4: Research Aims

The long term aim of this research is to enhance rapid phenotyping with the goal of improving factors such as yield, early warning detection of disease and drought resilience for crops based on information acquired through electrical impedance measurements of soil. The measurements will be related to soil moisture content, from which root water uptake can be inferred. For example, it is proposed that information relating root water uptake to plant performance above the surface could be used to improve drought tolerance through monitoring individual genetic crop traits, and selecting those which show advantageous qualities.

The short term aim of the research reported here was to explore the relationship between electrical impedance measurements using insulated electrodes to soil moisture content. The scientific aim is to use acquired images showing water movement to inform phenotyping for crop breeding programmes.

This research focuses primarily on overcoming the shortfalls of current methods of measuring soil moisture using electrical impedance measurements. Electrical impedance measurements were chosen as they are relatively simple and can therefore be implemented for a low cost. An important aspect of the work is the use of insulated electrodes in a technique referred to as Capacitively Coupled Contactless Conductivity Detection (C4D), typically used to determine the conductivity of an electrolyte solution in a
capillary pipe during electrophoresis, through non-contact measurements. Gas (1980) described the principles of C4D and how the technique is applied to electrophoresis. The benefits of C4D electrical impedance measurements are the resistance to corrosion of electrodes from saline soil and reduced electrode polarisation at the soil-electrode interface through the removal of the requirement for galvanic contact. C4D is applied to measurements in soil for the first time and the present work includes consideration of a new electrical model.

1.5: Scope of Thesis

This research project discusses an electrical measurement system to study soil moisture, to infer relationships between root water uptake and crop performance. The thesis utilises modifications made to a methodology in order to perform insulated electrical impedance measurements of soil, both in a parallel and adjacent electrode formation. The initial research motivation of “smart agriculture” is encompassed by the e-Agri research initiative (University of Manchester, 2013) within the University of Manchester. Within this group it was Dr. Frank Podd who first established the possibility of insulated electrodes being used to perform capacitively coupled measurements particularly relating to soil, and the key aspect of a thin electrode coating. Dr. Frank Podd also developed the software and electronics hardware required to provide the switching patterns enabling the interrogation of all adjacent electrode configurations of the rhizotron array of electrodes.

The main areas for discussion in this thesis, however, relate to the use of this methodology to determine the electrical properties of soil through capacitively coupled measurements, and the relationships that exist between these electrical properties and soil moisture, temperature and compaction for a single soil type. To confirm the plausibility of this, a chapter is dedicated to the derivation of an analytical solution and subsequent simulations of the contactless electrical measurement system based on water and soil. The focus of the work is then shifted to the experimental data achieved from using the methodology.

It should be noted that while the research is predominantly experimental based, it does not include greenhouse or field trials, which are both outside the scope of this project. It was decided to first determine whether the technology was capable of measuring soil moisture
in favourable conditions before greenhouse and field trials were considered, which are both suggestions for future work.

1.6: Challenges Experienced

Throughout the research programme several significant challenges have been experienced. The area which presented the major challenge was working directly with soil. Water based measurements, while not completely homogeneous, offer some form of repeatability and generally behave as one expects. Soil based measurements, however, suffer from such heterogeneity that samples taken from even the same batch of soil have very different physical and electrical properties. For example, each time a soil sample is removed and replaced back into a test cell its structure changes. In drier soils in particular, this change of structure will alter the ionic current pathways through the soil, which will change its electrical impedance value. Since it is not possible to replace soil in exactly the same formation within the test vessel, repeat measurements are typically required to create a range of values, making absolute values of electrical impedance difficult to achieve. This variability has therefore led to the requirement of refined measurement techniques to reduce heterogeneity, such as meticulous observance of soil moisture levels and physical placement of soil within vessels, weighing samples where possible to check the mass of the soil is within a satisfactory range between samples. For temperature testing, thermometers were used to correlate temperature with electrical impedance. For non-temperature based testing, the ambient temperature was still controlled within an environmental chamber, kept at ambient temperature to ensure minimal temperature change throughout the test. Water samples used to wet soil were stored in the laboratory for 24 hours prior to testing to allow them to naturalise to ambient temperature, again to reduce any temperature effects. For compaction based testing a method was implemented to ensure that soil samples were compressed to the same pressure, therefore allowing repeatable analysis of how compaction affects electrical impedance. For all soil moisture tests performed in the parallel-plate formation cell deionised water from a laboratory supply was used, to ensure a consistent supply of water, rather than using the laboratory tap water supply, which could vary significantly between samples. Since soil suffers from such heterogeneity it was
decided to only test with one soil type in this research to provide a basis. Future work would involve the use of multiple soil types to deliver an improved data set.

The second most significant challenge experienced was the inability to perform visual verification of test data. While there is a visual difference, particularly in the colour difference between wet and dry soil, any mid-moisture stages are impossible to quantify with the naked eye and observance of a wet soil is only possible when a dry soil is also available to perform a relative visual observation. Despite their visual observation advantages from having a clear side, tests performed in rhizotron vessels suffer from lack of visual verification, as the clear Perspex viewing area does not lend itself to photographs for analysis, due to the reflections caused. This is, one of the driving motivations for the use of electrodes along the back plane of the rhizotron. A typical rhizotron only allows limited visual verification of the soil and plant roots, whereas the array of electrodes presented in this research can interrogate into the soil to provide another dimension of analysis.

Working with plants has also presented a significant challenge, as temporal testing becomes difficult. Too much interference with the plant or soil structure throughout or between testing may cause stress to the plant, leading to the requirement of restarting tests. Also, for the plant growth testing, four seeds were planted at the top surface of the rhizotrons to ensure seed propagation. Once seedlings had emerged the redundant ones were removed to leave one plant. There is therefore an element of uncertainty as tests would need to be restarted if no seeds propagated. Plant growth tests are also long, with both tests here taking 6 weeks to complete. Errors in test procedure could be very costly in time if repeats had to be performed.

The final significant challenge encountered was presented by the use of an insulating dielectric which created a capacitively coupled measurement. This is discussed in more detail later, however, a summary is provided here. It was determined that the dielectric coating must be as thin as possible to reduce its reactance. A high reactance would limit the ability to determine bulk material properties. Making the dielectric coating as thin as possible jeopardises its mechanical strength, which is not ideal for soil based measurements which can feature porous and sharp constituent components. Perforation of the dielectric coating will result in direct electrical contact at the soil-electrode interface and remove all the benefits of a capacitively coupled measurement. However, one benefit of the multi-electrode system is that failure of a very few electrodes does not completely compromise the test, as data can be copied from adjacent measurements and spatial
resolution is marginally affected. This is possible due to the smooth transitions of soil lithology, where set, defined layers are not present and therefore adjacent measurements are typically very close in value to each other. It should also be noted that while the integrity was a possible cause for concern, throughout all tests performed there was no damage caused to the insulating covering for both parallel and adjacent measurements. Care was taken when inserting soil and removing samples post-test, with rhizotrons typically washed with water rather than soil scratched away from the surface. Therefore, when care is taken there is no reason to believe the insulating coating is weak.

1.7: Thesis Organisation

Chapter 2 presents background information regarding soil properties and soil based electrical measurements. It includes discussion of the current state of the art in terms of technologies used to measure soil electrical properties and concludes with the specific technology used in this research.

Chapter 3 presents simulated results for the chosen methodology. Since the methodology was one that was modified from another technology and applied to this research, simulations were required to determine the applicability and validity of the methodology in terms of determining soil moisture content. Simulations are performed to determine the feasibility of capacitively coupled measurements in a parallel-plate configuration, followed by further simulations to determine the limits of operation for various bulk materials, from multiple types of water, to soil wetted to different moisture contents. Both a numerical and finite element method (FEM) simulation were performed, using MATLAB and COMSOL respectively. A numerical model provides a simulated value of spectroscopic impedance for relatively low computational power. However, a simple analytical solution only exists for parallel-plate measurements. For adjacent-plate measurements, as found in the rhizotron, no such simple relationship exists. Therefore a physics based FEM model was first compared to the numerical analysis, and then used to determine whether the adjacent-method is also capable of determining moisture content with capacitively coupled measurements.
Following the simulations, the research progressed to performing laboratory based measurements. Chapter 4 provides a detailed section on the specification of all hardware and software used, as well as specific test procedures for all measurements performed. Where applicable, custom software and hardware was best described without jeopardising any intellectual property that does not belong to the author. The aim of this section was to afford the reader the potential to replicate any tests if required. The reading of this section is therefore not required, yet will provide an overview of specific information relating to equipment used and specific procedures if desired.

Chapter 5 is the results and discussions chapter in which a detailed analysis of all test results is provided. First, test results are compared to simulation data for consistency and to provide confidence in the hardware. This is followed by a discussion of the repeatability of measurements, for both water and soil based measurements. The results of soil moisture, compaction and temperature variation testing are then discussed. The results section climaxes with a discussion on plant growth tests in rhizotron test vessels, in which the candidate technology was used to observe soil moisture movement over the duration of a long-term trial in which maize plants were grown. Maize plants were used as the medium with which soil could be removed from the soil and to confirm whether root placement in the vessels affected its operation. Concluding this chapter is a section detailing the possible future work which could be performed following this research.
2: Background Information and Literature Review

This chapter is separated into two main sections. First, it discusses the background information relative to soil based measurements, predominantly focusing on the composition of soil, the relative water movement and how changes to soil composition can severely affect measurement repeatability. The second section is a review of appropriate literature relating to soil based measurement devices and techniques. It is conducted in order to determine the chosen methodology for soil based measurements, with an aim to measure soil moisture content and movement. From the literature review the chosen modality and measurement vessel style are proposed.

2.1: Soil

The aim of this section is to provide a basic knowledge of soil properties which are required to understand the research and work discussed in this research. It will highlight standard terminology used within soil testing and some of the techniques used to determine soil properties.

Those who rely on agriculture for their livelihood will continue to desire to improve aspects such as yield and drought tolerance in order to improve or guarantee a return for their products. Manual generic techniques such as crop rotation cycles are often used as different crops will extract different nutrients from the soil. By default, these crop rotations are generic, and not dynamic to the requirements of the localised soil or individual crops. Modern day farming utilises improved farming techniques through pesticides and fertilisers, improved farming machinery and enhanced crop irrigation programs. Those who embrace technology aim to provide information as to the best locations to seed, which parts of the field have healthier soil, when to both seed and harvest and aim to monitor crop health during the growing season. There are a plethora of soil-measurement instruments available which aim to provide the farmer with some of the information required. These instruments are discussed within this chapter, section 2.2. In order to improve agricultural practices one must first understand soil.
2.1.1: Soil Characteristics

Soil, water and rock are the three core materials covering the earth (Soil Science Society of America, 2013). Soil is created from particles of broken rock caused by weathering and erosion. There is no definitive expression for soil as it can vary widely, with each ‘type’ of soil having benefits and drawbacks depending on its application. Throughout this report, the focus will be on soil from an agriculture perspective, looking at what characteristics will hinder and benefit crop production, alongside factors which will determine electrical properties. One focus of this research is soil moisture content, both how it can be monitored and optimised to increase crop yield.

There are many different ways in which one can ‘measure’ soil. Traditionally, farmers use visual techniques to characterise soil. While visual techniques can provide useful data they are also a destructive measurement, requiring either a cut-away of the soil to enable soil layer observation or removal of small sections by hand to determine qualitative properties. Visual measurement and characterisation also lends itself to misinterpretation as they are subjective, therefore training is required to correctly understand how the soil should be interpreted.

If one was to use measurement equipment to determine soil properties and conditions, in-situ quantitative measurements can be achieved, which can also be non-destructive to soil or crops. Monitoring soil through already developed sensors often requires relatively little training when compared to that of visually inspecting soil, however cost of hardware and implementation in the field scale can be a major concern. Since measurements are quantitative rather than qualitative, they are easier to correlate to previous findings, to form trend patterns within the soil and visually represent data.

Therefore, any measurement techniques should be reliable for use in a harsh and often sub-surface environment, accurate enough to benefit those using them and relatively cheap compared to other methods available, in order to appeal to those within agriculture.
What is Soil?

Soil composition must be understood, whether for measurements of soil moisture or the desire to grow plants and crops. Soil has four basic components (United States Department of Agriculture, 1999), with the ratios of these components defining what is known as the texture of the soil. The components are sand, silt, clay and organic matter, both living and dead. The soil can be classified by performing a particle size distribution. A PSD is performed by using a series of stacked sieves with a decreasing mesh size, and a mechanical shaker. The soil sample is placed in the top sieve and vibrated until it has passed through the sieves. Since there will be a range of particle sizes, the sieves will catch a quantity of soil for those particles larger than that mesh size. Once completed, each sieve sample is weighed and can be used to determine the ratio of sand, silt and clay particles. However, the sieve method isn’t capable of determining the PSD of the smallest particles, and so the Hydrometer method is used, in which the sample is placed in water, and particle sizes are determined according to Stokes law (Clifton, 1999).

The texture of a soil is fixed, and its classification cannot be altered unless the ratio of any of the four components is changed. However, the structure of the soil is defined by the way in which the soil texture components are physically arranged, and is therefore easily changed. The structure and porosity, water and air between soil particles, of the soil are also closely linked together. The way the soil is worked has a substantial effect on structure and porosity, and a smaller effect on texture. While the texture of a soil is the same whether loose or compacted, its porosity and structure will be different.

Soil Texture Classification

The soil texture triangle, Figure 2.1, shows the method in which soil is classified based on its PSD and the appropriate naming conventions used for each class. There are eleven major textural classes, based upon the British Standards system of particle size grading, established by the Soil Survey of England and Wales, 1974 (White, 1979). The texture of the soil is its most important property as the soil structure quality can be increased through
effective farming methods, however, the texture cannot be changed so easily. Soil texture types are defined by the proportions of the constituent minerals. A *loam* has equal amounts of sand, silt, and clay, i.e. a flat PSD. Each type of soil has very different qualities, and can vastly affect the growing conditions for crops. Soil texture can affect drainage, water storage, working properties and crop suitability.

The difference in size between the smallest clay particles to coarse sand and gravel can vary as much as 10 000 fold. Due to the variations in size of soil components, a very large difference in surface area can be found between clay soils and sandy soils. Table 2.1 shows the mineral sizes of clay, silt, and sand, and the difference in surface area at the same volume, due to different sized particles. Surface areas are expressed with reference to the surface area of 2 mm diameter coarse sand.

![Soil Texture Triangle](image)

**Figure 2.1: Soil Texture Triangle (White, 1979).**

Soils with larger pores, such as a sandy loam, will hold less water than a clay soil and drain quicker. This is due to the large air gaps between the pores, and either gravitational pull or
crop roots, being able to remove water easier from the soil as water is held at less pressure within bigger pores. Although clay soils hold more water, the pores are much smaller and the suction required to remove this water is greater. As stone content increases within a soil sample it can hold less water, making crops more susceptible to drought. It is difficult to generalise the typical soil found within even a relatively small area of a farmer’s field as variations are so large. Even within a small area there can be multiple soil textures and structures. It is because of this that frequent measurements over small areas of soil are required to accurately estimate soil properties within a field. A single soil sample in a field is inadequate.

<table>
<thead>
<tr>
<th>Soil Mineral</th>
<th>Mineral Size (diameter)</th>
<th>Surface Area Ratio of Same Volume of Different Size Fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>≤2 µm</td>
<td>More than 1000</td>
</tr>
<tr>
<td>Silt</td>
<td>2 - 20 µm</td>
<td>100 – 1000</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.02 – 0.1 mm</td>
<td>20 – 100</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.1 – 0.2 mm</td>
<td>10 – 20</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.2 – 0.5 mm</td>
<td>4 – 10</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>0.5 – 2.0 mm</td>
<td>1 – 4</td>
</tr>
<tr>
<td>Gravel/ stones</td>
<td>2.0 – 20.0 mm</td>
<td>0.1 - 1</td>
</tr>
</tbody>
</table>

Table 2.1: Soil Mineral Characteristics (Davies, 1972).

The quality of soil texture and structure is dependent on the use it is intended for and the required characteristics. For example, sandy, coarse-textured soil drain easily and quickly after rainfall, are easily worked and its temperature tracks that of ambient more quickly than a clay soil. However, sandy soil also has a lower moisture-holding capacity than a clay soil and crops within a sandy soil must therefore be watered more frequently. Sandy soil must be fertilized more often as it has a lower nutrient-holding capacity than a clay soil. When vegetative cover is lacking, a sandy soil is susceptible to wind and water erosion. A clay based soil is largely the opposite of sandy, it holds a large quantity of water and provides good, strong anchorage for plant roots. Therefore, soil choice depends on the application.
Properties of Sand, Silt and Clay

Sand is the coarsest of the three main soil components, as was seen in Table 2.1. It is predominantly made up from silica (Silicon dioxide, or SiO$_2$). It is usually found in the form of quartz, which because of chemical inertness and considerable hardness is the most common material resistant to weathering. Despite the hardness of sand, it can be broken down by exploiting deficiencies in the particle lattice to produce silt. The main way in which this is achieved is through abrasion during transport, particularly within water. Silt is chemically distinct from clay, and is generally isodiametric.

Clay is generally formed due to chemical weathering of sand/ silt, from carbonic acid. While sand, silts and clay are generally distinguished by particle size, clay is also estimated from the soils plasticity. Clay is formed from thin plate-shaped particles, held together by electrostatic forces, so present cohesion (Agri Info., 2011).

Organic Matter

Soil organic matter is the accumulation of partially decayed and partially synthesized plant and animal residues, and is predominantly from excrement and carcasses. Organic matter is continually broken down and forms plant nutrients. It occurs as a result of the work of soil microorganisms; bacteria, fungi, various mites and other microarthropods (Mohammadi, 2011), and therefore must also be constantly renewed by the addition of plant residues. Organic matter is often broken down manually to increase its exposure to oxygen and subsequently accelerate the decaying process. While this provides nutrients quicker, it also reduces long term soil quality. Organic matter only represents about 3 to 5% by weight of the topsoil. However, its benefits far outweigh its low percentage representation. The effect of organic matter on the physical condition of soils increases the amount of water which the soil can hold, and therefore the amount of water available to the plant. According to the Vaderstad Visual Soil Assessment “Soil organic matter plays a pivotal role in regulating most biological, physical and chemical processes in soil, which collectively determine soil health. It promotes infiltration and water retention, it helps
develop and stabilise soil structure and cushion the impact of wheel traffic and cultivators and it also reduces the potential for wind and water erosion.

Organic matter is also an important source of, and major reservoir for, plant nutrients. Its decline reduces the fertility and nutrient-supplying potential of the soil” (Vaderstad, 2005).

Organic matter also provides a useful visual indicator by observation of soil colour. When compared to the uncultivated area, soil with poor organic matter content will be grey and pale, whereas soil high in organic matter will be darker, and richer in colour.

**Soil Structure**

The structure of the soil can also be considered as the architecture and should not to be confused with soil texture. Farmers have much more influence on soil structure than texture, however, it is generally only between crop seasons that farmers can utilise the chance to enhance soil structure due to fear of damaging growing crops. Good crop growth is dependent on good soil structure with some crop varieties used to improve soil structure between crop cycles.

The structure of the soil is the arrangement and packing of particles resulting in clods of soil called aggregates, or peds. The structure of soil is altered through external sources, such as cultivation, and farm machinery, and due to natural causes from gravity, heat and root and water penetration through the soil. Figure 2.2 shows three varying degrees of soil structure. A good soil structure has many finer aggregates, and very little clodding. A poor soil structure has very few fine aggregates, and significant clodding. This clodding occurs due to external disturbance, perhaps from farmers’ machinery due to tilling for example. Poor soil maintenance can cause a concretion or cementation of the top most layer of the soil, thus removing any direct paths for rain water and irrigation down to the subsoil and therefore causing surface erosion and drought conditions for the crops. Cementation of the top surface has a higher chance of occurring in soils with a lower organic matter content, and poor structure.
Again, Vaderstad (2005) states that good soil structure “…regulates soil aeration and gaseous exchange rates, the movement and storage of water, soil temperature, root penetration and development, nutrient cycling and resistance to structural degradation and erosion. It also promotes seed germination and emergence, crop yields and grain quality.

Good structure also increases the window of opportunity to cultivate at the right time and minimises tillage costs in terms of tractor hours, horsepower requirements and the number of passes required to prepare the seedbed.”

The formation of aggregates is less important than the spaces between them, which is the defining factor of soil porosity. Porosity affects the way, and rate, in which air, water and the roots penetrate through the soil.

Alongside external sources, natural changes in soil structure occur, and can be classified in two areas; physical and biological. Physical processes include the drying and wetting of soil which causes cracks to occur and changes the structure. Freezing and thawing can also create air voids within the soil as water expands during freezing. Biological processes include the change of structure from root growth, due to their removal of water from the soil required for the plant to grow. Small animals, such as worms, beetles, ants etc. create burrows within the soil improving porosity, and also provide organic matter through
excrement or when they die. Micro-organisms break down and decay dead crops and animals to create humus, an important material for binding particles together (Mohamaddi, 2011).

Freshly cultivated soil is particularly high in soil pore space. Over time, however, consolidation occurs which is the natural settling of the soil due to gravitational forces. While consolidation is the term for natural causes of soil reduction, compaction is used when external forces are applied, such as farm machinery for example. Both consolidation and compaction can reduce the quality of soil structure significantly. As the top surface of soil is damaged, a compact skin, cementation, can be created across the top soil layer which restricts soil drainage, and the penetration of roots. The ability of a soil to resist damage due to these factors depends on both the structural stability of the soil, and the water content. Sandy soils are weak as a result of low clay minerals, which bind soil particles together. Soils which are too wet suffer from compaction, and soils too dry suffer from increased clodding. Therefore there is a small window in which the soil is at the correct moisture level to cultivate, known as the cultivation window. Since soil structure is dependent on soil texture, the cultivation window differs between soil types.

Tillage from farmers often requires the use of large, heavy machines to ‘optimise’ the soil for crop growth. However, while attempting to optimise the soil, tillage also has drawbacks with compaction caused by heavy machinery as previously mentioned. No-till agriculture is a method of farming where the soil is not disturbed through tillage. One of the main benefits of such a method is that the soil is left to aerate due to less compaction, and subsequently more water can be held within the soil. Less tillage of the soil also reduces fuel and machinery costs, alongside labour and water usage for irrigation.

In order to characterise soil structure at varying moisture contents, Albert Atterberg defined four states for soils, which were later refined by Arthur Casagrande; solid, semi-solid, plastic and liquid (Polidori, 2007). A solid soil is one that has no water and therefore no pliability. Semi-solid soils have a small amount of water, and have limited pliability, but are brittle. A soil which is said to be in the plastic state is one which shows plastic like qualities, in that it will retain its form when subjected to external force, for example, from a tractor wheel. Soil in the liquid state no longer has the structure of a soil, but instead a liquid due to the excess of water present.
Porosity

Pores within the soil are essential for the movement of air, water and nutrients around the soil. They allow for improved root growth as air gaps make it easier for the crop roots to penetrate through the soil. Table 2.2 shows the typical densities and porosities of soils. Since the porosity of a soil depends on the water content, the soil moisture content must also be stated when measuring porosity. Soil pores greater than 60 µm can be seen with the naked eye, and are termed *macropores* while soil pores less than 60 µm are termed *micropores*. The larger macropores are very important in relation to water and air movement through the soil compared to the smaller pores (Vaderstad 2005).

<table>
<thead>
<tr>
<th></th>
<th>Particle density (g cm⁻³)</th>
<th>Dry Bulk Density (g cm⁻³)</th>
<th>Porosity (cm³ cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultivated mineral soils, plough horizons;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium-heavy texture</td>
<td>2.60</td>
<td>0.8-1.4</td>
<td>0.69-0.46</td>
</tr>
<tr>
<td>Light texture</td>
<td>2.60</td>
<td>1.4-1.7</td>
<td>0.46-0.35</td>
</tr>
<tr>
<td>Sub-soils and parent materials</td>
<td>2.65</td>
<td>1.5-1.8</td>
<td>0.43-0.32</td>
</tr>
<tr>
<td>Grassland and woodland</td>
<td>2.40</td>
<td>0.8-1.2</td>
<td>0.67-0.50</td>
</tr>
<tr>
<td>Peats</td>
<td>1.40</td>
<td>0.1-0.3</td>
<td>0.93-0.97</td>
</tr>
</tbody>
</table>

Table 2.2: Typical Densities and Porosities of soils (Rowell, 1994).

Porosity, or the pore space ratio (PSR) is measured as the ratio of total soil volume to volume of the pores (Rowell, 1994);

\[
Pore \ Space \ Ratio = \frac{\text{volume of pores}}{\text{total soil volume}} \quad \text{Equation 2.1}
\]
Pores within the soil that are not filled with water are filled with air. Air-filled porosity, $\epsilon_a$, is defined in Equation 2.2 (Rowell, 1994);

$$\epsilon = \frac{\text{volume of soil air}}{\text{volume of dry soil}} \tag{Equation 2.2}$$

It follows that air filled porosity is the pore space ratio minus the volumetric water content, $\theta$, Equation 2.3;

$$\epsilon = PSR - \theta \tag{Equation 2.3}$$

Figure 2.3 shows the fraction of the volume of soil for air and water for varying soil types. It can be seen that for clay soils the air capacity is low due to the smaller clay particles filling any of the larger pore spaces, but that air capacity increases as the soil tends towards a majority of sand, with larger particles and larger air gaps between them.

Figure 2.3: Air Capacity in Soil Pores (White, 1979).
2.1.2: Soil Water

This section discusses the way in which water is held within soil, classifications of soil moisture contents relative to availability for plants and methods to determine soil moisture content.

Soil Water and Structural Water

Soil Water Content (SWC) is defined as that which can be removed through the heating of soil for at least 24 hours, at a temperature of 110°C (Department of Transport, 1999). It can be defined in two ways, first by mass as the gravimetric water content, Equation 2.4;

\[
\text{Soil Water Content (\%)} = \frac{\text{weight of water}}{\text{weight of oven dry soil}} \times 100 \quad \text{Equation 2.4}
\]

Or as a fraction by volume;

\[
\theta = \frac{\text{volume of water}}{\text{volume of dry soil}} \quad \text{Equation 2.5}
\]

Structural Water is the remainder of water within the soil after oven drying at 110°C has occurred, and is held within the soil minerals. This water must be heated to approximately 700°C in order to be removed and for this reason structural water is typically excluded from the definition of soil water as during typical soil moisture experiments it will not change.

There are typically four classifications as to the soil condition based on the water content; saturated soil, field capacity, wilting coefficient (also known as wilting point or permanent
wilting point) and hygroscopic coefficient (HC), Figure 2.4. The pore size, water availability and state of the soil for each of the four classifications are shown in Figure 2.5.

![Soil Saturation, Field Capacity, Wilting Point and Hygroscopic Coefficient Levels](figure2.4)

*Figure 2.4: Soil Saturation, Field Capacity, Wilting Point and Hygroscopic Coefficient Levels (Brady, 1974).*

![Classes of Soil Water](figure2.5)

*Figure 2.5: Classes of Soil Water (Davies, 1972).*
Saturation

As water enters the soil, primarily from rainfall or irrigation, air within the soil begins to be displaced. Smaller soil pores begin to fill with water first, followed by the larger pores, which initially retain air. Once all soil pores are filled with water the soil is saturated and said to be at its maximum retentive capacity. At saturation the matric potential, the potential energy of the water which is attracted to soil solids and always of a negative value, is very close to zero. It may be supposed that this level of water is ideal for crop growth, however, it is not since crop roots may perish due to lack of air within the soil. The air-filled pore space must be approximately 10% by volume for most roots to survive (Kirkham, 2004). After wetting of the soil to saturation, gravity continues to draw water down through the soil, with larger pores being drained of water first as their matric potential is lower, and therefore water is released easier (Brady, 1974). The soil water will eventually drain until it reaches Field Capacity.

Field Capacity

Field Capacity, $\theta_{FC}$, is the remaining water content in soil after it has been saturated and allowed to drain freely until the downward movement of water is terminated. This occurs when the matric potential equals or exceeds that of gravitational force, i.e. the water is held within the soil pores more tightly than gravity can pull it downwards. Within a typical irrigation situation, the FC is usually achieved 2-3 days after saturation. At FC, water is held in the soil by surface wetting of the particles. Since they are in contact these result in capillary forces. Water occupies less than total pore space, unless the soil is saturated. The level of suction at which gravitational drainage stops is generally between 50 and 100 mbars, dependant on soil type. At high negative matric pressures, air will fill the pores, but water will still surround the particles. As water is further removed from the soil it tends towards the wilting point.
Wilting Point

The wilting point, $\theta_{wp}$, is the minimal moisture the plant requires to prevent wilting. Soil water is primarily lost in two ways, plant growth and evapotranspiration. Plants at the WP begin to lose turgor, the pressure against the cell wall from within the plant and provides the plant with the ability to stand, and at this point cannot recover even when water is again delivered to the roots. At the WP, the pressure at which the soil is holding the water within its smaller pores is greater than that of which a plant can exert. An approximate level of pressure at which WP generally occurs is 15 bars, but this will fluctuate dependent on soil type. WP is dependent on several factors, such as the soil profile, soil layer water profiles, transpiration rate of a plant, and temperature.

Hygroscopic Coefficient

Beyond the WP a small amount of water still remains within the soil. However, the soil is held within only the very smallest pores. As the soil dries further, even the smallest pores are eventually dried of water, until only water held as a small vapour around soil particles remains. The pressure at which the hygroscopic coefficient occurs is approximately 31 bar, twice that of the WP, despite having only 20% less water content, according to Figure 2.6. Soils high in clay content will have a higher HC than sand and silt soils, as clay soils have an increased ability to hold more water due to their small particle size and therefore larger surface area. However, this water is of no use to the plants as it is held at too much matric pressure, and the roots cannot remove it from the soil. Hygroscopic water is also known as bound water.
Soil and Water Interaction/ Matric Potential

Water is held within the soil in two ways; as a thin layer around the soil particles, and within pore spaces. Soil above the WP has water stored in both the thin layer around the soil, and the soil pores. Soil below the WP can store only water vapour, as the thin layer around the soil particle. Figure 2.6 details the water held to soil particles, and the pressure at which they are held. For many British soil types the field capacity is close to 50 mbars, when all pores greater than 60 µm diameter are drained of water. At this point, the air capacity $C_a$ may vary from 0.1 to 0.3 as a fraction of soil volume, within topsoil, dependant of soil texture and structure.

![Figure 2.6: Soil Water Surface Retention Pressures (Brady, 1974).](image)

Available Water Content

The water content available to the crop is that between field capacity and wilting point. The AWC is higher for clay soils, and lower for sandy soils. It can be seen that as soil texture increases in heaviness, Figure 2.7, the WP and FC both increase. A soil increases in heaviness as it tends towards a clay soil, due to a higher density caused by a smaller particle sizes. However, as the soil type exceeds silt loam soils the FC levels out. From Figure 2.7 it can be seen that sandy soils have much less soil water available to crops, and both FC and WP are much lower also.
Figure 2.7: Available Water for Different Soil Textures (Brady, 1974).

Water Loss from Soil

When crops are present, transpiration is the biggest loss of water within the soil (USGS, 2013). A small amount of water may continue to fall downwards, towards the water table known as gravimetric water, but the majority is used through transpiration. Evaporation also occurs, which is the process of vaporisation of the top most soil moisture. Evaporation occurs due to the heat of the sun, and can form a hardened barrier in the very top of the soil. The combination of transpiration and evaporation is known as evapotranspiration.

Permeability

Permeability is a measure of the soils ability to pass air and water through it. Soils with a permeability below 0.2in/hr and above 6 in/hr are said to be poor with regards to irrigation either due to water moving too fast and not allowing the roots to utilise it, or too slow and
causing the soil to flood. Table 2.3 shows the classification of soils in relation to quality as a result of permeability. The rate of movement for drainage is dependent on the continuity of large pores throughout the soil, through which the water travels, and the permeability of the slowest layer. At a short time after rainfall begins, a cap can be formed across the surface of the soil caused by small soil particles filling the surface pores. This cap effectively seals the subsoil and can cause the rain water to run off the surface, increasing erosion. This is particularly a problem in clay soils, which swell with the presence of water.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Infiltration Rate (inches/hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very slow</td>
<td>Less than 0.06</td>
</tr>
<tr>
<td>Slow</td>
<td>0.06 to 0.2</td>
</tr>
<tr>
<td>Moderately slow</td>
<td>0.2 to 0.6</td>
</tr>
<tr>
<td>Moderate</td>
<td>0.6 to 2.0</td>
</tr>
<tr>
<td>Moderately rapid</td>
<td>2.0 to 6.0</td>
</tr>
<tr>
<td>Rapid</td>
<td>6.0 to 20.0</td>
</tr>
<tr>
<td>Very rapid</td>
<td>Greater than 20.0</td>
</tr>
</tbody>
</table>

Table 2.3: Permeability Rate Classifications of Soil (Scherer, 1996).

2.2: Measurements in Soil

The main purpose of the chapter prior to this point was to inform the reader of issues regarding soil, and provide a platform from which scientific measurements could begin to be considered. As previously mentioned, visual soil assessment (VSA) can be used as an inexpensive method of monitoring soil conditions. Soil demonstrates many visual indicators as to its properties, for example, soils high in organic matter are darker and richer in colour than those poor in organic matter which are grey. Soil texture and structure can also often be monitored visually. At field scale, farmers will frequently use touch to monitor a soil alongside visual techniques with the texture able to be estimated through rubbing a soil sample between fingers. In an attempt to make visual analysis quantitative, the VSA utilises
a scoring scheme to rate soils on particular visual properties (Vaderstad, 2005). Results are weighted also, so the more important factors achieve a higher weighted score. Despite these attempts to improve data from visual assessment, the technique is still subjective and often destructive.

Gravimetric measurements are among the most common techniques for determining quantitative soil moisture percentage as an indicator of water availability for crops. However, there are significant disadvantages with this method; it is time consuming, must be performed in the laboratory and again destructive. An alternative method which is in-situ and non-destructive, with inferior results, may be advantageous over gravimetric measurements as it will both save time and offer the ability to perform repeat and temporal measurements.

The quantitative study of the earth, and its physical properties and attributes is known as geophysics. Through geophysics, the subsurface of the earth can be investigated non-destructively, a process which is inherently difficult due to multiple components beneath the surface and the inability to achieve visual verification except through destructive methods (Weymouth, 1992). Several modalities have previously been developed to determine the properties of near-surface materials with an aim to infer characteristics such as water content, soil composition, the placement of underground water stores, or the estimation of the depth of the water table. Those modalities which focus on characterisation of near-surface soil are primarily discussed in this literature review. The thin region of soil closest to the roots is known as the rhizosphere. This soil is directly under the influence of the roots and represents the soil-root interface, and maintaining its integrity is essential when measuring plants. Soil outside the rhizosphere is known as the bulk soil and is the volume of soil in which potential roots will grow. In its simplest terms, measurements on plants in soil will be a function of bulk soil, root-soil interface and plant cell structure.

In order to perform measurements on the individual plant scale, techniques and methodologies are drawn from those applied in geophysics, but applied at a smaller scale. Since geophysical studies and measurements are often performed at ‘field scale’ they provide coarse resolution data. This coarse resolution is adequate for determining factors such as underground water flow, average soil moisture content throughout a field, waste management, detection of natural hazards, detection of the water table etc. It is not, however, adequate for determining characteristics of individual plants or the rhizosphere.
The improvement of measurements for a finer resolution is achieved often by scaling down geophysics methods ideally to centimetre, or lower, resolution. Using previously developed techniques one can utilise those theories and principles developed on a large scale and determine how they apply on a small scale. For example, spacing between a surface array of electrodes in electrical resistance tomography could be reduced to achieve a shallower measurement depth in which the plant root system may become measurable. However, as electrodes decrease in size so does the volume of soil that is interrogated.

The research performed in the following sections considers the methods currently available for determining soil properties in situ, and their advantages and disadvantages. It also outlines any new methodologies or techniques which may be adapted to determining soil moisture content. The goal of the literature review is to determine both the measurement technique and vessel geometry to be used in order to achieve the aims of the research programme, which are to improve rapid phenotyping of crops through observation of strong genetic traits. These traits will be observed through measurement systems which are aimed at inferring moisture content movement within the soil, particularly relating to root water uptake.

This literature review is separated into five sections. The first two sections discuss those modalities used to determine properties of the sub-surface soil, both electrical and non-electrical. From the modalities discussed, it was decided to implement electrical resistivity measurements for this research programme. This was based on the ability to provide relatively cheap and quantitative measurements of the soil electrical resistance, with an aim to establish soil moisture content. The second section, therefore, provides a more detailed overview of work performed by other groups relating to electrical resistivity measurements in soil. This section is followed by consideration of measurements on a small scale relating to both non-invasive and invasive measurements on plants and root systems within soil. From this discussion it was concluded that a rhizotron test vessel would be ideal as it allows for visual observation of roots and soil characteristics. To combine both electrical resistance measurements and rhizotron test vessels, it was proposed that a rectangular array of electrodes was implemented along the back internal surface of the rhizotron in order to provide high spatial and temporal resolution of the soil and root system while still offering visual observation of root growth. The final section of the literature review addresses issues relating to the use of electrical resistivity measurements within soil, predominantly the effects of electrode polarisation and corrosion. Therefore a
technique called C4D is implemented, in which a thin insulating layer is placed across the surface of electrodes to reduce polarisation effects, and remove the possibility of corrosion. The use of C4D in soil based measurements has not been reported before.

2.2.1: Non-Electrical Techniques

This section outlines multiple techniques and methodologies which are currently available for measuring soil properties, particularly the moisture content, through non electrical-based measurements. The aim is to establish the validity of each technique based on attempting to measure the soil moisture content around the rhizosphere. This will ultimately lead to a favoured technology which is applicable to this research. For the majority of the measurements discussed, the aim of the modality is to determine the moisture content of the soil, however, some techniques which aim to detect other soil properties are also briefly discussed.

Tensiometers

Tensiometers directly measure the physical suction (matric potential) required by the plant to access water from the soil for its current moisture content (Lourenço, 2007). A plant will have a certain ability to extract water from the soil, relative to its size and health. If a soil is heavily laden with water, the pressure required by the plant to remove water from the soil will be low. As the soil dries it will require higher pressure to remove the water as it will be held in smaller gaps between soil particles, and therefore have a higher capillary force. Tensiometers operate by allowing the soil solution to come into equilibrium with a reference pressure indicator through a permeable surface placed in contact with the soil. This is achieved through a ceramic cup at the bottom of the tensiometer, which must be in direct contact with the soil. As the soil gets drier or wetter, the change in pressure directly reflects the pressure required to extract water from the soil. There is a direct correlation between soil moisture tension, and soil moisture content for a given soil type. This
relationship is known as the soil-moisture release curve. Once a soil-moisture release curve has been characterised for a particular soil it can be used to estimate soil water content.

The operating specification of tensiometers is typically quoted in units of Pascals. A standard tensiometer has a quoted range of -0.09 to 0.1 MPa with ±0.5 kPa accuracy (Delta-T, 2013). The positive value of pressure potential is called tension. Thus, if a pressure potential value of -15 kPa is measured in a soil, the tension of that soil is 15 kPa. In order to compare to the soil water surface retention pressures as provided by Brady (1974), Figure 2.8, the values of atmospheric pressure are converted to MPa. At the wilting point, Brady suggests a pressure of 15 atm, which is equivalent to approximately -1.5 MPa, compared to the tensiometer specification of -0.09 MPa. At field capacity Brady claims a pressure of 1/3 atm, which when converted approximates to a value of 0.33 MPa. These values indicate that a generic tensiometer is within range for measuring field capacity, but for dry soils a standard tensiometer is unable to determine the moisture content as wilting point approaches. While tensiometers are considered an accurate method of determining soil moisture retention, van der Ploeg (2009) discusses the use of a polymer tensiometer, which can measure a much higher matric potential, closer to the wilting point at -1.6 MPa, than a standard tensiometer. The enhanced range of matric potentials improves the range of soil moistures which can be determined through tensiometers.

Despite their accuracy, tensiometers have multiple disadvantages. While they are non-destructive, they are invasive, requiring a long shaft to be inserted into the soil in the region of interest. Inserting a tensiometer into the soil will require either a pilot hole to be drilled, disrupting the soil around the region of interest, or simply be pushed into the soil.
which will cause localised compaction, and potentially damage the porous tip. Since air expands and contracts relative to temperature it can lead to inaccurate vacuum readings if air were present inside the tensiometer. However, when no air is present in the tensiometer, the measurement has the advantage of being completely independent of soil temperature. Tensiometers are also a slow method of measuring soil moisture content as the equilibrium can take between 5-30 minutes before an accurate reading should be taken.

The final disadvantage of tensiometers, and the most relevant to this work, is the limited spatial resolution available. Each tensiometer only has a small sphere of influence, at approximately 1-5cm around the ceramic tip. Therefore, they typically provide a value of moisture content for only a small area which is then assumed to be true for a larger area. Due to their invasive nature and small sphere of influence, tensiometers are not a viable technique for this work.

**Neutron Probe**

Neutron probes utilise fast neutrons emitted from a radioactive source into the ground, from which the soil moisture content is determined by the change of speed in reflected neutrons (Greacen, 1981). Typically, neutron probes are buried in the ground inside aluminium access tubes from which radioactive alpha particles, travelling at speeds of approximately 6,000 miles per second, are emitted due to a pellet of americium-241 and beryllium in the tip. The emitted particles decay over time as they ‘bounce’ off particles with a low atomic weight, such as hydrogen atoms. This reflection slows the fast neutrons which can only be detected when they have slowed to approximately 1.7 miles per second. Continuous use of the probe will result in a state of equilibrium in the form of a cloud of neutrons around the probe, the size of which depends on the soil moisture content. For a dry soil, which will not slow as many neutrons, the cloud will extend further than that experienced for a wetter soil.

Since the fast neutrons are decayed when they interact with hydrogen atoms this technique for measuring soil moisture content is largely unaffected by other soil
parameters such as salinity and temperature. However, there are some soil parameters which can affect the slowing of neutrons, besides soil water. Certain elements in the soil such as boron, cadmium, iron and chlorine also have a high absorption capacity for slow neutrons. A site soil survey can reduce these effects, by revealing the chemical composition of the soil, and factoring it into the results. The neutron probe also has a large sphere of influence when compared to other methodologies such as the tensiometer.

One major disadvantage of neutron probes is the exposure to radiation. It is considered hazardous to health, and users must be accredited to use equipment. Also, the probe must be inserted to a sufficient depth to ensure the radiation emitted stays below the soil surface, as neutrons escaping through the surface will not be reflected back to the source, and will therefore provide an inaccurate reading. This typically results in measurements in the top 100 mm of soil to be voided. Neutron probe measurements also require a soil calibration for each test site, increasing both test time and cost. Neutron probes are also removed between testing, and therefore cannot perform temporal measurements unless replaced in the soil at exactly the same location. The hardware costs for the probes alone are approximately £2-3k per unit (Evans, 1996) plus any additional hardware required for post-test data analysis.

While neutron probes have advantages, particularly to immunity of salinity and temperature variations with regards to soil moisture content, the underlying legal requirements for use mitigate against its general popularity. Due to unavoidable neutron losses in shallow soils, laboratory based tests are not suited to this technique.

Seismic Refraction and Reflection

The final technique discussed in this section is that of seismic refraction, by which seismic waves are created at the surface and penetrate down into the ground, typically by hammer-plate, weight drop, buffalo gun or explosives (Shahrukh, 2012). The seismic waves propagate down into the ground until they are reflected or refracted by boundaries in subsurface layers. The reflected and refracted waves are detected by arrays of passive electrodes called geophones, similar in principle to accelerometers, and detect movement.
These geophones are spaced in an array like structure across the ground surface. Geophones convert ground movement into a voltage through an internal spring mounted mass inside a coil. As the mass moves, an electrical signal is generated proportional to the movement of the ground from the reflected or refracted wave. Recent designs in sensors have used an active micro electro mechanical system (MEMS) to measure the ground movement (Milligan, 2011), however they are not passive, and suffer from higher noise levels, so are only suitable for applications with large forces of reflected and refracted waves.

While seismic refraction offers the ability to determine the underground lithology, it does not provide information relative to soil moisture content. Also, the technique of creating seismic waves does not suit small localised scale measurements, but is instead one which is suited to large scale measurements, such as those found in typical geophysics applications.

The focus of the literature review now shifts to electrical based measurements. For electrical based measurements, an electrical signal is typically introduced into the soil and a detector is used to determine the change in signal caused by the soil. The goal is then to relate the change in signal to soil properties.

### 2.2.2: Electrical Techniques

This section provides an overview of the most common electrical based methods used to determine soil properties. For some of the discussed modalities, the soil moisture is not measurable, however, they are provided as background information to provide sustenance for the argument to use the chosen methodology, which is highlighted at the end of this section.
**Spontaneous/ Self-Potential (SP)**

The earth has naturally occurring electric currents beneath the surface which can occur from two or more electrolytic solutions of differing concentrations, which causes a flow of ions between them. Potential fields of a few millivolts can be measured with the aim to explore mineral structure often for oil and water applications. There are two common applications for SP; borehole and surface measurements. Borehole measurements typically detect permeable beads and estimate the formation of water salinity and clay content. Surface applications map the relative changes in the SP value typically with the goal of identifying the path of ground water flow in the subsurface (Gallas, 2011).

Since this method relies on self-potentials which arise from beneath the ground’s surface, it will be of no use to laboratory based measurements, in which only small vessels are used, and therefore little, if any, self-potentials will exist.

**Ground Penetrating Radar (GPR)**

Ground penetrating radar is a non-destructive geophysical technique in which a high resolution waveform, 10 – 1000 MHz, is injected and penetrate into the ground (Guo, 2013). The general aim is to determine the soil properties through analysis of the reflected signals, which occur when the wave reaches a boundary with a contrasting electrical property. The specific aim is to detect voids and buried obstructions through spatial monitoring of observed reflections at the boundaries. Lower frequency signals penetrate further into the ground and are better suited for geophysical surveys. Higher frequency waves, while giving an improved resolution, penetrate a shallower distance into the ground and are typically used for applications such as non-destructive testing on concrete.

Dependent on the frequency used, Guo states that the minimum detectable root size ranged from 0.25 to 4cm, with 1500 to 2000 MHz offering the highest spatial resolution. Davis and Annan (1989) used GPR to determine placement of objects, changes in underground media, location of cracks and voids, overburden properties, buried walls, pipes and tunnels.
Despite the advantages mentioned, one of the main disadvantages with GPR is that the depth range is limited by electrical conductivity. High conductivity attenuates the signal by dissipating the energy into heat, and thus reduces penetration depth. The technique is therefore suited to dry, arid conditions for deep measurements. In ice, an electrical insulator, this could be as far as a few hundred metres compared to approximately 10-15 metres in typical soils. Another disadvantage of GPR is the cost of equipment, being approximately £7k for a basic system, and increasing with functionality.

Binley et al (2001), considered the possibility of cross-borehole GPR to monitor moisture migration in a sandstone aquifer, since it offers a higher spatial resolution than typical electrical resistivity imaging. Two boreholes were drilled into the ground approximately 5m apart, the maximum distance between boreholes was limited by the conductivity of the soil. A transmitter was placed in one borehole, and the receiver in the other. Two types of measurement were taken, multiple-offset gather and zero-offset profile. Using multiple-offset gather the transmitter is moved to multiple vertical locations within the borehole while the receiver remains in a stationary position. The receiver is then moved to a new position and the transmitter is moved through a range of positions again. From the resultant data a tomogram can be derived, but a large amount of post-processing is required. Using zero-offset profile both the transmitter and receiver move relative to each other, and the emitted waves move in a straight line between the two. This method provides a one-dimensional profile between the two boreholes at multiple vertical locations between boreholes. This method is much faster as far fewer measurements are taken, and little post-processing is required. Binley noted that when the reciprocity of measurements was taken it was found to be very repeatable, with values differing by approximately 2%. They concluded that the technique allowed for the monitoring of subtle contrasts in lithology, and the ability to see wetting fronts through the sandstone, noting a rate of approximately 2m per month.

While GPR offers excellent spatial resolution, and quasi-continuous measurements, its main disadvantages are decreasing measurement depth with increasing conductivity and the cost of the hardware. It is also not suited to small scale applications since currently available hardware is based on geophysics applications, and would need redesigning to work at the individual plant scale, which is expensive and outside the scope of this research.
X-ray

X-ray is a hard-field modality typically associated with the medical industry (Gregory, 2003), in which electromagnetic radiation waves are emitted from a source and pass through the medium under test. X-ray waves will be absorbed as they pass through a medium, relative to its density. Directly opposing the emitter is a detector, which is used to measure the loss in magnitude of the x-ray waves and attribute this loss to the density of the material. A very dense material will absorb more of the X-rays, and as such only a small amount will be detected. In the medical industry X-rays are used in a wide range of applications, for example, to determine bone fractures. In soil based applications, one aim is for x-rays to determine the location of fine roots within the soil based on the different densities between soil and root structures.

Hard-field measurements are frequently considered advantageous over soft-field, such as electrical resistance measurements, as the propagation of waves through the medium under test are in straight lines through the body and are independent of the material outside this region. In contrast, field strength at an arbitrary location within soft-field measurements is a function of distributed properties throughout the body, and it is inherently more difficult to determine the electrical properties (Polydorides, 2002). For example a highly conductive area will draw the flow of electrical current towards it as the current will flow through the path of least resistance. Because of these distortions, determining the cause of the field fluctuations is difficult, with no unique solution. For example, for a multi-layered soil sample, each with a unique conductivity, differing conductivities of layers could produce the same value of measured electrical resistance.

Gregory used X-ray micro tomography to image crop roots within soil, from which they were compared with destructive measurements obtained through use of a flatbed scanner. Gregory aimed to create a system capable of resolving roots at 150 µm in diameter. Using a silver-target X-ray source with a focal spot of 80 µm they measured the growth of wheat and rape seed over the period of 8-10 days. Results were found to be within 10% difference of the destructive method for root mass and length measurements. Their spatial resolution was found to be capable of ‘seeing’ roots having diameter 0.48-1.22 mm. Bayer (2004) considered a different application, in which they used X-ray absorption to measure the soil water retention curve in soil. For experimental purposes a sand based measurement was performed within a PVC column of dimensions 10 cm tall, and 8.15 cm radius.
One of the main advantages of X-ray is that hard field measurements travel in straight lines and do not suffer from the typical complications associated with soft-field measurements, which create an ill-posed inverse problem. Another advantage is the spatial resolution of X-ray measurements, where it has been discussed how X-ray has been used to distinguish roots of only 150 μm in diameter (Gregory, 2003).

The main disadvantage of X-ray is that while the technique is able to distinguish fine roots, it is only possible within small volumes of soil. In order to distinguish roots of 150 μm, a maximum sample diameter of 25 mm was possible. This is caused by the dense nature of soil when compared to those experienced in medical applications. This will result in an increased absorption of X-ray waves and require more powerful machines for measurement on larger volumes, which further increases equipment costs. Because of the disadvantages presented, the use of X-ray is not proposed.

Magnetic Resonance Imaging (MRI)

Alongside x-ray, MRI is also a technique most commonly associated within the medical industry (Tanaka, 2005). The technique relies on a large magnetic field around the test object, and a second radio frequency magnetic wave to excite the nuclei within the test object. It is used as MRI provides a good contrast between the different soft tissues in the body. It has rarely been the focus of research outside of the medical industry due to its size, associated limitations, and equipment cost. However, Amin (1993) implemented MRI to monitor the time-varying spatial distribution of water in several soil samples. They found that soils rich in iron presented a problem due to the magnetic fields, but that they could provide information relative to the porosity of the soil in a non-destructive system. However, it should be noted that while they claim the soil sample is non-destructive, they have to excavate a large sample to place within the MRI equipment. It is not possible to place an MRI machine in a field and test soil non-destructively. While MRI may offer lab-based measurement data, it is not suitable for field-based measurements. Due to the cost and size constraints MRI is not the chosen technology for this research.


**Capacitance Methods**

Simple capacitance methods have been explored for detecting changes in crop properties by analysing change in capacitance. Campbell (1961) created an electronic instrument for the automated estimation of pasture yield by placing two parallel-plates above the ground surface, between which crops would grow and change the measured capacitance value. Prior to this, estimations of pasture yield for cattle required manual sampling through cuttings. However, destructive sampling leads to a reduction in pasture available to animals and variance between test samples depending on the spatial resolution of samples. Difficulties were also encountered through grass touching the bare electrodes which were subsequently covered by placing them behind a Perspex sheet. Campbell’s predictions from capacitance measurements were shown to be in the order of 10% error of prediction, estimated to reduce to 2-3% in a higher sample yield and assuming random errors.

While capacitive sensors on the surface showed potential, they also suffered from the possibility of interference from undesired objects between the sensors. However, the principle of measuring the capacitance is applied to geophysics studies through dielectric sensors (Kinzli, 2012). Dielectric sensors work in much the same was as manual capacitance measurements, but consist of a standalone unit which is inserted into the soil. The soil then acts as the dielectric between two parallel plate electrodes, from which the dielectric permittivity can be measured. This is possible due to the large difference in permittivity between soil (≈4) and water (≈80).

Kargas (2012) implemented a capacitance sensor to determine the accuracy and precision of the sensor relative to permittivity in liquids with known dielectric properties, and to establish a soil electrical conductivity limit for the sensor. The sensor utilised a 70 MHz oscillator, and found that for liquids the measured dielectric was overestimated for all tests, but within the operating limits of the equipment. They also note that for soil based measurements the sensor required calibration for each soil type in order to obtain accurate absolute values of permittivity.

It is the high frequency, approximately 70 MHz, and calibration requirements for soil type of capacitance sensors that lead to a decision not to implement this technology for analysis of soil, pertaining to moisture content. Both of these factors create additional costs, in a cost-sensitive application. For higher frequency measurements more expensive hardware is
required, and in order to calibrate multiple soils, repeat testing is required which increases overall test time and expenditure.

Time Domain Reflectometry (TDR)

While time domain reflectometry is not a capacitance measurement, it does utilise the dielectric properties of the soil to infer water content. Dalton (1984) are regarded as the first to apply the TDR technique to soil measurements. It was a technique that originated from a measurement to obtain the frequency dependence of liquids. Here, TDR is based on the velocity of propagation and reflections of impulses down a probe inserted in the ground, which occur due to the dielectric properties of the soil. If the dielectric properties of the soil can be measured, then an empirical equation (Topp, 1980) can be used to relate dielectric constant to soil water content. Topp found that a single polynomial function described the relationship between volumetric water content and permittivity in four mineral soils.

A high frequency impulse is injected down the probes of the sensor. Variations in soil conditions will affect the reflections, with wetter soil causing smaller wave velocities. The TDR equipment emits a voltage step and also measures the reflected wave. The time taken for reflections can be used to estimate the permittivity of the soil, which is predominantly dependent on its moisture content. Since the equipment will be characterised, and should not change with changing soil properties, the only section of interest in the reflected waveform is the section which occurs when the waveform reaches the probes located in the soil. At this point, energy is dissipated into the soil which slows propagation velocity. Energy not dissipated returns to the source through the probes as a reflection. The time taken for the reflection to return to the emitter can be used to determine the relative permittivity of the soil, and infer the soil moisture content.

The dielectric between the rods is a function of soil, air and water. The permittivity of the water is the dominating factor, being approximately 80, compared to 3-5 for soil materials, and unity for air, and therefore changes in water content have a far greater influence than soil and air. The TDR device is typically capable of measuring soil moisture content for soils
in the range of 0 to 0.5 m$^3$ m$^{-3}$ (volumetric water content) and can be as accurate as 0.01 to 0.02 m$^3$ m$^{-3}$ without calibration (Evett, 2003).

TDR is relatively insensitive to salinity when compared to the majority of electrical based measurements, with the salinity having little effect on the relative permittivity of the water. However, increased soil salinity does still have a negative effect on measurements. In highly saline soils the transmitted wave may be conducted between probes which will also lead to compounded change in the reflected signal. It will be difficult to extract the individual components responsible for the reflected wave as it will be seen as a single reflection.

One of the main restrictions with TDR is caused by the relatively small sphere of influence of measurements, at approximately 1-2cm, as only the area between soil probes is measured. Measurements are therefore best suited to localised and not field scale. This small sphere of influence leads to the requirement to insert probes into areas such as root bundles to determine soil moisture content. This may be too invasive in certain applications as the insertion of the probes into the soil may damage the root system or cause compaction unless pilot holes are drilled, which is time consuming and labour intensive, (Robinson, 2003). Pre-drilling holes can also lead to ambiguity in measurements from over-drilling which can lead to small reservoirs of air or water at the tips of measurement probes, skewing measurement data. Probes could be inserted prior to planting, but will rely on the accurate estimation of root growth location, and may also suffer from a lack of soil-probe interface as the soil dries and shrinks. Another disadvantage is the possible preferential flow of water along the rods which will cause localised wetting of soil. While TDR is a very capable technology for measuring soil moisture content in the laboratory, it is not suited to mass measurements at multiple locations as it would require multiple probes placed in the soil, which would be invasive and costly.

**Gypsum Resistance Blocks**

Gypsum resistance blocks allow a basic electrical resistance measurement that is predominantly dependent on soil moisture content (Stenitzer, 1993). A small block of
porous material, typically Gypsum, is attached around two wires of a defined separation distance, and inserted into the ground. When placed in soil, moisture is absorbed into the block from the soil until equilibrium is reached. As the moisture content of the blocks fluctuates the value of resistance between the two wires will also change, from which the soil moisture content is estimated. The measured value of resistance, however, is not purely dependent on moisture content, but is a function of other parameters such as salinity, temperature, soil compaction, texture and porosity, making determination of soil moisture content from resistance more difficult than a simple linear relationship. It is for this reason that calibration of soils is performed with electrical resistance measurements.

Gypsum blocks are an inexpensive method of estimating the soil moisture content and due to their low cost offer the ability to insert multiple measurement blocks throughout a field and obtain large amounts of measurement data. Buried gypsum blocks also allow temporal measurements of soil moisture as once placed within the ground they require no additional disruption to the soil which would affect measurement data. The material gypsum is used for measurement blocks in an attempt to counter any effects of salinity change in the soil, which will affect the measured value of resistance and the estimated value of moisture content. Gypsum is susceptible to degradation over time due to the creation of calcium sulphate each time the blocks are wetted, and therefore the blocks have a finite life. In unfavourable conditions of frequent wetting and drying, the blocks have a much shorter life span, possibly requiring annual replacement. However, Stenitzer claims that blocks can last for “many years” under the soil surface. Therefore, while not a significant concern for short-term laboratory testing, the use of materials with a finite lifespan may inhibit long-term field based testing which could be pursued in future work.

Resistance blocks have a very wide measurement range of approximately -30 to -1500 kPa, compared to -85 to 100 kPa for tensiometers. This allows gypsum blocks to determine the moisture content for soils even at wilting point, which tensiometers are not able to achieve. Stenitzer compared estimated values of soil moisture from gypsum blocks to measured data from a neutron probe. He found that when blocks were calibrated to soil types the technique was capable of achieving measurements of moisture content that were comparable in accuracy to that from a neutron probe. He also noted that gypsum blocks had an additional benefit over neutron probes by allowing semi-permanent measurements due to the ability to be kept in the ground between measurements, as opposed to the required removal of neutron probes between tests.
Gypsum blocks have several advantages over other methods of estimating soil moisture which have been previously discussed. They are inexpensive, with the cost of the blocks and simple resistance meters being typically less than £100. This low cost allows for multiple sets of equipment to be placed within a field which will increase spatial resolution and since they can be left in the ground semi-permanently they allow temporal measurements to be taken, unlike expensive TDR probes. They also provide an advantage over neutron probes as no radioactive materials are used and unlike X-ray and MRI, no specialised training or expensive equipment is required.

Despite these advantages, gypsum blocks have several disadvantages which make them unsuitable for the application chosen for this research, which is laboratory based measurements of soil moisture at a plant scale. The absorption of water from the soil into the blocks removes moisture that may have been available to plants and can skew measurement data. In large field measurements this may not be a concern, but as measurements are scaled down the absorption into the blocks can cause a significant change in moisture content. Gypsum blocks also have a small sphere of influence, much like TDR, with only the soil moisture immediately around the blocks affecting measured values of resistance. The blocks are also invasive, with a portion of the soil requiring to be removed in order to house the resistance block, which can be detrimental to plant root growth. It was also mentioned that the value of measured soil resistance will depend on several factors other than just soil moisture content. However, during laboratory based measurements the effect of other factors such as salinity, temperature and compaction have a lessened effect as the soil used during testing is well characterised, unlike field-based testing.

Despite the presented disadvantages, gypsum resistance blocks offer a promising solution to estimating soil moisture content through electrical resistance measurements on soil. In the following sections other applications are discussed which attempt to estimate soil moisture content through measurement of soil resistance by injecting an electrical current into the soil and measuring the resulting resistance value. This increases the sphere of influence to encompass a larger volume of soil without the requirement to physically move measurement probes throughout the soil.
2.2.3: Electrical Resistance Methods

It was previously discussed that the chosen measurement technique for the research should be cheap, reliable, non-destructive and suitable for laboratory trials, with a possible future aim of greenhouse and field trials. Invasive measurements could be pursued, depending on the level of invasiveness, if it was required to have intimate contact at the soil-electrode interface. The previously discussed modalities were merited, primarily, based on their ability to estimate the moisture content of soil, with the overall aim to enable estimation of root water uptake and provide the possibility of rapid phenotyping of crops. It was suggested that while gypsum blocks suffer inherent limitations, the technique of electrical resistance measurements may satisfy the criteria for the research as hardware costs are low, they are only moderately invasive and are suited to temporal measurements. The aim of this section, therefore, is to improve the understanding of electrical resistance methods, particularly relating to the measurement of soil moisture content. The section will also discuss any potential limitations of the technique.

Direct Contact Resistivity Methods

Direct contact methods aim to establish the soil electrical resistivity distribution of the volume of interest (Knodel, 2007). Changes in soil structure, porosity, texture (particle size distribution), organic matter, temperature, water content, water conductivity and bulk density/compaction will affect the measured resistivity. In geophysics applications, four metal electrodes are typically required to achieve measurements of electrical resistivity. To measure the electrical resistivity of soil, an electrical signal is injected into the ground via a direct current (DC) or low frequency alternating current (AC) between one pair of electrodes while a second pair of electrodes is used to measure the resulting potential voltage, which is dependent on the soil properties and magnitude of the injected signal. Four electrodes are utilised to reduce the effect of polarisation effects, the accumulation of charge which can result when both the current injection and voltage measurements are performed on the same pair of electrodes. Electrode polarisation and the associated effects are discussed in detail later within this section. Typically the four measurement electrodes
are placed in a linear formation along the soil surface, with the outer electrodes being current injection, and inner electrodes used to measure voltage potential. For a homogeneous medium, ohms law and current density can be used to establish the voltage change from the single electrode to some point under the soil surface (Knodel, 2007), and is given by;

\[ V_r = \frac{\rho I}{2\pi r} \]  

Equation 2.6

where \( r \) is the distance in metres between the electrode and point of measurement, \( \rho \) is the resistivity in \( \Omega \cdot m \), and \( I \) is the measured current in amps (A). Equation 2.6 assumes the second current receiving electrode is placed an infinitely large distance from the current injection electrode, however, this is not possible to achieve due to a finite measurement space available. Instead, the current receive electrode is placed much closer to the current injection electrode where the effect of this is that the current flowing from the electrode no longer flows in radial lines, but instead flows between electrodes with a regular geometric shape (Samouelian, 2003). Voltage potentials also no longer follow radial lines and become more complex to determine. For the case of a homogeneous earth, but with the two current injection electrodes placed a closer distance, the resulting current field lines and electrical potentials can be seen in Figure 2.9 for a 4-electrode measurement, with \( P_1 \) and \( P_2 \) being potential electrodes, and \( C_1 \) and \( C_2 \) being current injection electrodes.
For a four-electrode measurement, the potential difference ($\Delta V$), can be calculated as follows (Knodel, 2007).

\[
\Delta V = \rho I \left[ \frac{1}{2\pi} \left( \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right) \right]
\]

Equation 2.7

where $r_1 = C_1 P_1$, $r_2 = C_1 P_2$, $r_3 = C_2 P_1$ and $r_4 = C_2 P_2$. The square brackets can be removed and the value $1/K$ used in its place. The parameter $K$ is known as the geometric or configuration factor and is a numerical value derived from the electrode separation distances of the survey (Ward, 1990). Therefore the resistivity for a homogeneous half space is;

\[
\rho = K \frac{\Delta V}{I}
\]

Equation 2.8
Since the earth is not a homogeneous half space, the resistivity value measured is a function of many different parameters, and is therefore termed the apparent resistivity ($\rho_a$), as it is a value representative of the heterogeneous soil between electrodes.

There are four commonly used array types used to measure soil apparent resistivity namely the Wenner, Schlumberger, dipole-dipole, and pole-dipole arrays (Ward, 1990), with each array having specific strengths and weaknesses. In all cases two electrodes are used for current injection and two for voltage measurements. For pole-dipole, however, one of the current injection electrodes is placed at a large distance, effectively infinity, in order to try reducing the effects of interference from current injection electrodes (Yadav, 1988).

Generally, the spacing of the outer current injection electrodes determines the measurement depth, and the measured potential occurs at the inner electrodes. The sensitivity matrix is used to determine the sensitivity of each element of the model to changes in resistivity. A general trend with surface electrode measurements is that as the electrode spacing increases the measurement depth also increases. However, this leads to a lower resolution with increasing measurement depth. The sensitivity matrix will establish the contribution of each measurement to each element of the model (Knodel, 2007).

When adjusting either electrode configuration or spacing one must consider the geometric factor constant associated with it. The geometric factor is a numerical representation of the expected potential differences to be achieved from the electrode configuration. A high geometric factor will indicate that lower potential differences will be measured, requiring more sensitive measurement equipment. Therefore, when performing a survey, a lower $k$ value is preferred. Wilkinson (2006) researched two strategies to attempt to find the maximum spatial resolution in ERT surveys using only a limited number of four-electrode configurations. They found that both their strategies offered better optimisation when compared to a previous model. The improved strategies utilised a first-order estimate of the model resolution to assess the suitability of the electrode configuration, first by adding the effects of new configurations directly while the second method looked at a goodness function to estimate which configurations would be beneficial to include. With multiple electrode configurations available, the sensitivity matrix is used to determine the sensitivity, and which locations in the volume will have most effect on measured values of resistivity. For example, in a surface array type measurement, the sensitivity will be greatest towards the soil surface, and reduce in deeper soils, meaning it is more difficult to determine the soil properties with accuracy in deeper studies. For borehole studies the
sensitivity will be constant with increasing depth (Perri, 2012), however, boreholes come at the expense of being invasive.

When measuring the soil resistivity it is common to refer to its inverse, the apparent electrical conductivity of the soil ($\sigma_a$). $\sigma_a$ is a measure of the ability of the soil to conduct an electrical current between measurement electrodes. Since soil is predominantly sand, silt and clay (United States Department of Agriculture, 1999) it is not a good electrical conductor. The air gaps between soil particles are also an insulator, having an assumed infinite resistivity. However, when water is added to the soil it allows good conduction of electrical currents. The conduction of electrical currents through the soil is predominantly ionic in the soil water particles, rather than electronic as found in a copper wire, apart from a small amount of conduction from adjacent clay particles (Shainberg, 1975). Ionic conduction is a function of ion concentration, and as such only a finite current can be conducted through an ionic material, dependent on this concentration. When utilising an AC current the ionic conduction through the pore solution is purely resistive, in-phase, whereas the ionic conduction through the soil and air particles and at the electrode-soil interface leads to a complex resistance, reactance, (Kemna, 2000). This reactance can lead to polarisation at the soil-electrode interface.

To perform typical soil resistivity measurements the electrodes need to be placed in direct galvanic contact with the soil. Failure to achieve sufficient galvanic contact will result in a large measured resistance due to the electrically insulating air gap between the electrode and soil. Slater and Binley (1995) state that one method of countering measurement inaccuracies, which may result from difficulties in achieving a consistent contact, is to perform both repeated and reciprocal measurements. Repeated measurements will highlight any possible non-contact issues. Reciprocity, however, is the process of reversing electrode polarities. In an isotropic system with perfect reciprocity, a measurement will have matched values for the magnitude of the measured impedance regardless of the direction of current flow. However, actual measurements in soil will suffer from anisotropy, where the measured impedance will vary dependent on the direction of current flow. Through reciprocity measured values can be averaged to provide more accurate data. One side effect of reciprocal measurements is that increasing the number of measurements also increases data acquisition time. If a four-electrode system is used, eight measurements are required to achieve full reciprocity. This means that each data frame will take eight times longer, a significant increase for time critical applications.
Measurement electrodes are typically placed at the soil surface to avoid being invasive, yet still require minimal insertion to ensure good contact at the soil-electrode interface, typically less than 0.5m. However, surface arrays of electrodes suffer from decreasing resolution with increasing measurement depth. Therefore, arrays of electrodes can be placed linearly in vertically drilled boreholes. Borehole arrays have a uniform resolution with depth, but disrupt the soil due to the intrusion of boreholes in the excavated holes. Slater (2000) discuss the use of borehole arrays of electrodes in a 3m deep experimental tank, used to detect the movement of a saline tracer in soil. They found that the borehole method was invasive, and created areas of preferential water flow close to electrode arrays, a side effect which does not occur with surface electrodes. Kim (2010) used borehole and surface ERT to monitor infiltration through a 1m x 1m undisturbed soil column. Two boreholes of 90 cm depth were created, with ring electrodes placed in the boreholes at 10 cm intervals and at the same intervals across the surface between boreholes. Multiple excitation strategies were used from borehole-to-borehole, surface-to-borehole and borehole-to-surface to improve spatial resolution. Results show a range of resistivity values from 50 - 5 kΩ, and clearly showed a wetting of the soil as water infiltrates down from the surface over a 20 day period. Of particular note was the observation of preferential flow, often a problem in undisturbed soil columns typically caused by cracking from soil shrinkage as it dries, and can lead to roots being unable to obtain the water, as it moved down through the soil too quickly. Both surface and borehole electrodes have strengths and weaknesses, it is the decision of the end user as to which modality to implement.

Daily (1992) focused research on the use of ERT, and the flow of water in unsaturated soil. While the flow of water in saturated soil can be estimated using Darcy’s Law, unsaturated flow is more difficult to estimate, especially within a medium as heterogeneous as soil. Daily implemented a system with multiple boreholes between 17 and 30 m deep within soil. Inserted poles with vertically mounted electrodes were used for cross-hole resistivity measurements. The measurement system produced good temporal images, with the plume of water clearly visible as it propagated through the soil. The speed and shape of the plume could be obtained through the images. Their chief finding was that the rate at which water travelled through unsaturated soil was far greater than expected. They found that the water travelled down to the water table 24 m below the surface within 24 hours. Some difficulties arose, mainly with the high contrast between resistivities at the upper electrodes, where the wetting front and dry soil interfaces existed.
For large scale geophysical measurements electrodes are usually constructed from stainless steel rods (Rucker and Gunther, 2011), which are driven into the ground to ensure good electrical coupling with the soil. If there is restricted contact at the soil-electrode interface the measured resistance will be incorrect due to the high resistance of air. As soil dries, this air gap can increase due to shrinkage and subsequent cracking, especially found with soils that are high in clay content, further compounding the problem. Clay soils suffer from swelling and shrinkage due to the ability of clay to absorb water, whereas sand is unable to absorb water and therefore has very little, if any, swelling and shrinkage. Water can be placed around the electrodes to wet the soil and ensure good local contact at the soil-electrode interface. Samouelian (2003) found that the use of a conductive fluid with copper/copper sulphate electrodes provided good galvanic contact between soil and electrodes and also reduced electrode polarisation, however, the complexity and cost of these electrodes makes them not ideal for field applications, or where arrays are used due to multiple electrodes.

It may not always be possible to obtain sufficient access to drive electrodes into the ground. For example, farmers may not want interruption to land for fear of damage to crops, or the survey area may be in an urban environment where it is not possible to drill down through a ground covering such as concrete. In these cases flat planes of electrodes can be placed on the surface. Athanasiou (2007) compared the quality of measurement data from surface electrodes to regular surface electrodes which slightly penetrate the ground. The surface electrodes comprised a 7cm x 7cm copper base of thickness 1cm, and utilized a water and salt based electrolyte to ensure good electrical coupling between the ground surface and electrode. The electrode surface area was comparable to that of a typical rod driven into the ground to reduce differences due to surface area. One significant challenge was that the ground closest to surface electrodes is generally the driest and consequently has a larger resistance. When regular rod electrodes are driven into the ground they reach into deeper soil with a lower resistance. It was found that the inversions from flat surface electrodes produced RMS errors that were 2-3% more than for conventional rod electrodes. However, the results obtained were in good agreement and showed that non-penetrating surface electrodes could be used as an alternative to penetrating surface electrodes.
Electrical Resistivity Imaging of Soil

In the preceding discussion, only individual measurements have been considered for a four-electrode measurement, providing a single value of electrical resistance, termed the apparent resistivity. Individual measurements of the soil through a 4-electrode measurement will provide only a bulk measurement of soil properties in one localised region between electrodes. A more complete ‘view’ of the soil is achieved through physical movement of the electrodes above the ground to change the region of soil being measured (Samouelian, 2005).

If the separation distance between current injection electrodes is increased the current will flow deeper into the soil, providing a voltage potential relative to the soil properties at an increased measurement depth. However, to achieve data for a greater measurement depth, an increased electrical current must be provided to ensure a measurable voltage. Increasing the electrode spacing is known as vertical electrode sounding, where the centre point is kept in the same location and resistivity is measured at various depths (Knodel, 2007). The measured depth is referred to as the pseudo-depth as it is an estimation of the depth based only on the electrode spacing, and not factoring the soil lithology beneath the surface. Highly conductive soils will provide a shallower depth than highly resistive soils as the current will flow through the top-most soil due to its lower resistance. Only after inversion of the measurement data is the pseudo-depth converted to actual depth.

Sounding is used to determine horizontal boundaries beneath the soil surface. In sounding surveys, it is typically assumed that the sub-surface soil is constructed from multiple discrete horizontal layers, each of a defined depth and resistivity. However, while some layering will exist, there is often a gradual change between soil layers. Loke (2001), Barker (1981) and Dahlin (1996) are examples of work which has used 2-D resistivity surveys in environmental applications.

When electrode separation distance is kept constant, but the array is moved along the surface of the ground, multiple measurements can be taken to create a map of the soil resistivity at a fixed depth. This is known as profiling, and allows the user to create a 2D reconstruction of the soil to determine vertical boundaries and changes in the soil properties at a constant depth (Knodel, 2007). As the electrodes are moved through the field vertical transitions between soil types, rocks and air pockets will be seen.
A combination of both profiling and VES can create a 3D image of the soil bulk properties below the ground. The user must decide the resolution to which they would like to measure by adjusting the step size of electrode space changes.

The original method for interpreting sounding and profiling curves was to match measured curves empirically with theoretical curves, such as that by Mooney and Wetzel (1956). However, the arrival of low-cost computing power has led to the popularity of inversion techniques to interpret sounding data. This inversion is required to convert the resistivity at the pseudo-depth, where the depth is estimated only from estimations based on the electrode spacing, to that at the effective depth. This inversion provides a quantitative value of resistivity of the ground at each specified location tested. Dey and Morrison (1979) and Barker (1992) discuss the techniques used for a 2D resistivity survey inversion with the use of computers.

**Spectroscopy**

So far the focus has been on the use of direct current, or very low frequency alternating current as the source of the artificial current injected into the ground, with higher frequencies only mentioned as a method of overcoming electrode polarisation. However, spectroscopic impedance measurements, commonly known as electrical impedance spectroscopy (EIS), can be used to determine more soil properties through analysing spectroscopic real and imaginary impedance. Generally, soil moisture measurements require prior calibration to determine the soil type, soil moisture can then be obtained from electrical measurements. Tetyuev (2006) implemented spectroscopic measurements on an extracted soil sample to characterise soil type before measuring soil moisture. They extracted soil and placed it in a container which allowed electrical connections to the soil, while allowing it to dry from the outside through air vents. The soil was saturated and allowed to dry in a controlled environmental chamber while performing spectroscopic measurements of complex impedance. They were able to characterise 5 soil types based on previous knowledge of soil types, therefore can be seen as an empirical solution. Once the soil has been classified through spectroscopic analysis, regular electrical resistivity measurements could be used to determine other factors, such as the soil moisture content.
Buehler (2007) considered the use of impedance spectroscopy to determine the water and ice content of simulated martian soils. They utilised an impedance spectrometer to allow measurements over a range of 1Ω to 3 GΩ. Spectroscopic measurements showed that methods of electrical conductivity differed between water and ice. For water the conductivity was dominated by the concentration of salts, whereas for ice the conductivity was determined by the concentration of hydronium.

Pluta (2009) considered EIS as a non-destructive and non-invasive method of measuring the density and moisture content of soils between 300 kHz and 40 MHz. They found that the empirical soil model they used was subject to large variance in the gradation of the soil, due to the large variation in surface area for different soil types. This led to the requirement for soil characterisation, which improved accuracy by 119% between uncharacterised and characterised soil measurements.

Limited research has been performed with regards to impedance spectroscopy in soil, due to the relatively frequency independent nature of soil and water. The majority of spectroscopic work has been performed on root systems. The following sections discuss some potential areas for concern when implementing direct contact resistivity measurement techniques.

**Polarisation Effects**

When a metallic conductor is placed within an ionic conductor, such as an electrolyte or wet soil, a polarisation will occur at the electrode-electrolyte interface caused by the uneven charge distribution across its surface (Serghei, 2009, McAdams 1995). This polarisation will cause a double layer capacitance at the electrode interface, and subsequent impedance, which is termed as the contact impedance. Figure 2.10 shows an electrical model of the double layer capacitance where $C_P$ is the polarisation capacitance rising from the double layer and $R_P$ is the polarisation resistance from the contact impedance.
For systems utilising DC signals, the boundary potential and contact impedance are constant, as there are no frequency variations. $C_P$ is an open circuit, and therefore all contact impedance is frequency independent and caused by $R_P$. It is therefore possible to characterise the associated impedance and subtract its effects from the measured value of resistivity. However, when AC signals are used, the boundary potential changes relative to the frequency. Because of the double layer capacitance the frequency of the injected current determines the reactance, and as such, higher frequencies will have a lower value of contact impedance (Schwan, 2006). The total contact/polarisation impedance is given by the formula:

$$Z_p = R_p + \frac{1}{\jmath \omega C_P}$$  \hspace{1cm} \text{Equation 2.9}

where $Z_p$ is the total impedance relative to polarisation effects, $R_p$ is the polarisation resistance, and $C_p$ is the polarisation capacitance. The relative magnitude of the electrode impedance can be significant when compared to the overall sample impedance, and its effects are particularly pronounced at low frequencies and with higher conductive fluids. The resistive element of the impedance, found at the surface, can range from mΩ to hundreds of Ω, decreasing with frequency. Typical capacitive values range in the μF region at 1 kHz. While the polarisation charge on the electrode-soil interface will decay over time, if only one pair of electrodes is used for both current injection and measuring voltage potential, the measured voltage will be subject to any charge at the electrode-soil interface. Electrode polarisation occurs in the current injection stage of the measurement, and causes a significant problem if the subsequent measurement occurs too quickly without allowing the polarisation effects to disperse. For this reason, the majority of soil based surveys utilise the four-electrode design as previously outlined. Since the current

![Figure 2.10: Electrical model for the double layer capacitance.](image)
injection is separate to the potential measurement, the charge build up is of limited effect. While the four-electrode design reduces polarisation, Yoke-Lin and Chee-Earn (2008) discuss how two-electrode designs can be ideal for smaller applications in which space is limited.

According to McNaughtan (1999) electrodes should be small, less than a few mm in size, to ensure a steady state current over the electrode surface. Due to the steady state current, the contact impedance will be easier to characterise, leading to the possibility of a simple subtraction to determine the contact impedance. However, there are only limited applications where such small electrodes are feasible. As such, larger electrodes must be used which do not feature a steady state current and therefore the impedance will change and cannot be subtracted from the measured value. Alternatively the frequency of the source may be increased to a level at which the double layer capacitance cannot be established due to inertia of ion transport mechanisms (Grieve, 2002). With increasing frequency, however, one must consider the effects caused by parasitic capacitance at frequencies above 1 MHz in which capacitance between elements of the measurement equipment can cause undesired effects due the reduced value of reactance with increasing frequency. A value of parasitic capacitance between electrical conductors can cause feedback loops and interference. Therefore, a compromise is typically made between electrochemical effects and parasitic capacitances. Besides the use of four electrodes, Schwan (2006) outlines a number of techniques that are available to correct for electrode polarisation. Substitution techniques require the replacement of the medium under test with a sample medium of known electrical properties. An impedance measurement is then taken, and the known sample properties are subtracted, leaving the remaining impedance being the polarisation impedance. However, care must be taken as the test medium may affect electrode polarisation in a different way to the sample medium. This technique would be available for laboratory based measurements on soil, where a known sample could be used. However, for field based measurements it would not be possible to substitute the soil non-destructively. Another possibility is to implement electrode distance variation techniques, in which the cell geometry or electrode distance is changed to find polarisation effects. For two different cell constants, the following equations apply;

\[ Z_{M1} = Z_P + Z_{S1} \]  

*Equation 2.10*
\[ Z_{M2} = Z_p + Z_{S2} \]

and therefore;

\[ Z_{M1} - Z_{M2} = Z_{S1} - Z_{S2} \]  \hspace{1cm} \text{Equation 2.11}

where \( Z \) represents the impedance and subscripts \( s, p \) and \( M \) denote sample, polarisation and measured total impedance. Calculation of the difference is independent of the value of \( Z_p \). This method is accurate if the polarisation impedance does not change with cell constant. This technique would be possible to utilise in a typical geophysics survey where the electrode spacing can be easily adjusted.

Frequency variation techniques, again detailed by Schwan, are commonly used where cell dimensions are fixed or characterised mediums cannot be used. They require the analysis of resistance and capacitance with varying frequency, where the capacitance of the sample should be constant for varying frequency when compared to the polarisation capacitance. If the sample capacitance is known, the polarisation capacitance can be subtracted from the value of \( C_{\text{TOTAL}} \).

Typically, DC characteristics of metal electrodes have been considered with the aim to establish a non-polarisable electrode. However, it cannot be assumed that a 'good' DC electrode will perform well with an AC signal. For example, Schwan (2006) states that while a platinum electrode is suitable for AC applications, it is a poor for DC studies.

The most robust method of stopping electrode polarisation is to cover the electrode with an insulating covering which provides a capacitive layer of known properties, which can be subtracted from the total measured impedance. This is discussed in detail in section 2.2.4.
Corrosion

Corrosion of electrodes, due to the soil in which they are within intimate contact, can lead to a changing value of polarisation over time which will be difficult to characterise as it is not constant. The corrosion of electrodes is predominantly dependent on the electrode material, with steel and zinc being susceptible to corrosion in soils (Kear, 2006). Kear also presented work in which the corrosion of electrodes was considered, with the aim to infer corrosion rates based on the change in electrode polarisation. They found, however, that large variation between visual and electrochemical measurement data led to an inability to predict corrosion rates.

In the case of plant growth studies which take place over a long period measured values of resistance can cause incorrect analysis of data assuming a constant polarisation effect. Also, corrosion can lead to the requirement to replace electrodes once they become too corroded. In a situation where the electrodes are placed in a remote location, or within boreholes in a semi-permanent fashion for example, the replacement of electrodes is costly both with regards to time and expense. Since the characterisation of corrosion showed little correlation between visual and electrochemical data it is therefore desired that the corrosion of electrodes can be eliminated by other means. One such method would be to cover the electrode surface with a material which would not be susceptible to corrosion, such as a dielectric material. However, doing so would inhibit direct current being passed at the soil-electrode interface.

This section has discussed the basic principles applied to electrical resistivity imaging techniques to determine the electrical properties of soil. While the technique of electrical resistivity has so far largely fulfilled the research criteria, in that it provides a cheap, reliable and simple measurement system from which the soil moisture content can be inferred, two major limitations have been presented. First, the creation of a frequency dependent contact impedance due to polarisation at the electrode-soil interface which can cause a measurable effect. Characterisation or removal of the contact impedance and polarisation effects is required. The second limitation is of corrosion to the electrode surface, caused by the intimate contact at the electrode-soil interface. This corrosion will change the electrode polarisation over time, leading to difficulties in characterisation. These two limitations must be considered before implementing the technique. However, the following section first provides a more detailed summary of examples from other research in which electrical
resistivity imaging is predominantly used to determine the electrical properties of soil and plants at the individual plant scale rather than the typical field scale of geophysics studies. It should be noted that not all methods presented are based on electrical resistivity measurements. For those which aren’t, a brief summary of strengths and weaknesses is provided. Following the literature review of electrical resistivity measurements at the plant-scale the discussion is focused on the adaptation of the electrical resistivity technique to overcome the discussed limitations.

2.2.4: Measurements on Soil, Plants and Roots at the Individual Scale

The literature review so far has focused on the use of electrical measurements to determine the electrical properties of soil, and has outlined several limitations found in typical direct contact studies. This section discusses various methods used to determine the properties of plant roots, and establish relationships which may exist between plants, their root system, the soil in which they grow and also electrical properties. Following a summary of various non-electrical techniques, the review focuses on the adaptation of the technique to be performed on an individual plant scale, which requires knowledge of the plant system, both how the root system is expected to grow, and how, if at all, it may affect electrical measurements.

Destructive Methods of Measuring Root Density

One of the aims of the research is to determine the soil moisture content within the rhizosphere. From this it may be possible to infer the effect of roots, and possibly root mass. Manual methods of determining root mass are the most accurate method, yet they are destructive as they require the full root bundle to be removed from the soil for measurement. It is also very time consuming to measure a full root system due to the extent of the root system. Udawatta (2005) states that for an established maize plant, the average total root length from a sample volume of 1 m$^3$ was approximately 890 m. In an
effort to reduce data analysis time, Newman (1966), suggested a method of measuring root density for only a small sample size and scaling findings to estimate the density of the full root bundle. The method utilised a sample section of root viewed within a small rectangle area, viewed through a microscope. Through one of the eye-pieces a slide is placed which includes several straight lines arranged in a ‘random’ formation. A longer root will cross the ‘random lines’ more times than a smaller root. From the number of times the root crosses the lines the total sample root length can be estimated. The new technique took half the time of the direct measurement and had a variance of 7.7, compared to 15.9 for the direct measurement when scaled up to the full size of a root.

Despite Newman’s method being able to reduce analysis time, it is still relatively slow to determine root mass, and is also destructive. It was previously mentioned how X-ray has been used to determine the root structure of a plant, and was found to be able to detect roots to within 150 μm diameter. However, the limitations of X-ray have already been expressed, predominantly the hardware cost. While electrical resistance measurements do not offer the resolution that X-ray does, they do offer the availability to include multiple electrodes located close to the rhizosphere to provide a large sphere of influence, and afford temporal measurements. This may be useful in inferring the root water uptake through monitoring the locations in which the water is removed from the soil. If a 3D image was constructed for soil water movement, indicating the areas in which soil moisture was moving, it may be possible to infer that the root system is the cause of these water movements, and relate this to measurements of the plant above the surface.

However, since electrical resistance measurements are soft-field, the interaction of the electrical signals and the root structure becomes significant. Therefore it is required to understand how the root structure may affect electrical measurements. The following sections discuss electrical measurements performed on plants, and how the root properties can be better understood.
Electrical Models of Plants and Roots

In order to fully understand the interface between roots and soil, the complex internal cell structure must be considered. A plant system is constructed from millions of individual biological cells, separated by insulating phospholipids (walls) (Hayden, 1969). When an AC electrical current is passed through the cells a complex impedance, dependent on frequency, is obtained. This is due to the cells acting as multiple capacitors both in series and parallel. Because of this frequency dependency the measured impedance of plant cells will form a sigmoid shaped curve, with a large impedance at low frequencies (less than 10 kHz), increasing to a much smaller impedance at higher frequencies (more than 10 kHz). This response is labelled as β-dispersion (Schwan, 1994), and is typical of all living tissue, Figure 2.11.

Figure 2.11: Dielectric constant $\varepsilon$ (increasing) and conductivity $\sigma$ (increasing) as a function of frequency – Known as β-dispersion (Schwan, 1994).

Hayden (1969) and Zhang (1991) both created electrical models to represent the internal cell structure of potato plants. Both use discrete components to simulate the internal cell structure, and as with all models, assumptions were made. In the Hayden and Zhang work, the assumption is that all living cells are isodiametric and therefore a simple network of
resistors and capacitors can accurately represent the potato plant. However, as Hayden indicates cells are not truly isodiametric, having equal diameters or axes, yet care was taken to ensure chosen components offer a close electrical representation. Both the Hayden model and the Double Shell model can be found in their relative academic papers previously referenced. A basic analysis of the circuit shows that at low frequency the current passes through the cell walls, due to the reactance of the membrane being so high. However, as frequency increases the reactance of the membrane decreases, and more current begins to flow through the cell membrane and cytoplasm than the cell wall. At high frequencies the reactance created by the capacitance of the insulating layer is reduced to such a point that the impedance through the cells becomes lower than through the cell walls.

The Double Shell model is similar to the Hayden model, but the components are attributed to different factors within the cells. At low frequency the current flows through the apoplast, which is the free diffusional space between the vacuole and the cell wall. This is due to the high resistance from the insulating layer between cells as mentioned for the Hayden model. Again, similar to the Hayden model, as frequency increases the reactance of the capacitive elements reduces and current begins to flow through the cytoplasm and vacuole. There are other models of plant cells, but they are not discussed here as they are refinements to the two mentioned and the present work does not focus on the specific internal structure of plants, but instead a general understanding of how electrical signals will pass though plants.

The response of the electrical models for the plant cells is similar to the β-dispersion previously mentioned, the frequency response of all living cells. Since a low impedance is most desirable to allow current flow through the plant it is advisable to perform measurements at those frequencies greater than 10 kHz. One disadvantage with electrical models is ambiguity. It is possible, when performing spectroscopic measurements, to have many models which result in a good fit. Therefore care must be taken when considering the model; Intuition regarding expected values, examination of measured data to check for consistency with model data and inspection of resistance and capacitance values to check for realistic values. Despite knowledge of β-dispersion it is difficult to establish absolute values as all plants are different. Both the Hayden and Zhang models conclude that while
the membrane acts as an insulator at lower frequencies, it becomes very conductive to electrical signals at higher frequencies.

Aubrecht (2006) characterised the root system by the diameter of roots and the outer surface material, which define its functionality. Thinner roots, of diameter less than 2 mm, were labelled as absorbing roots, and responsible for absorbing the water and nutrients into the plant system. Roots with a diameter greater than 2 mm were regarded as woody roots, with an insulating outer surface. They provide the ability for the plant to transport the water and nutrients from the absorbing roots through the stem to the leaves and also provide anchorage for the plant. These roots are known as conducting roots. Aubrecht also presented the theory behind the earth impedance method (EIM). An artificially generated electrical current is fed into the plant, and their hypothesis is that the current will exit the roots in certain locations. The number and location of exit points for the electrical current will be relative to the size of the plant, and provide information pertaining to the size of the plant root system. To pass electrical signals through a plant system there must be a way of injecting current into the plant. In Aubrecht’s work, and in others that are discussed later, the basic premise behind this is to insert an electrode into the stem of the plant and another one in the soil close to the stem. It is suggested that roots are populated with many small “absorption zones“ through which water and nutrients are absorbed. It is also through these absorption zones that electrical signals will enter and exit the root. The soil-root exchange surface can be determined by the following equation:

$$S = \frac{\rho_{\text{wood}} L_{\text{mean}} I}{U}$$

Equation 2.12

Where $S$ is the total root absorption surface in m$^2$, $\rho$ is the resistivity of the water conducting tissue, $L$ is distance from the stem in m, $I$ is current flowing through the wood stem, root system and soil and $U$ is the potential difference between the stem boundary and soil potential electrode. In a follow up paper by the same group, Cermak (2006) outlines a method of verification to the Aubrecht paper, in which actual measurement data confirm the root absorption zone theories. The Aubrecht/Cermak method utilises an electrode to be placed in the soil at an arbitrary distance from the plant stem in order to determine the root size and properties.
Sperry (1998) comments on how the ratio of root absorbing area to transpiring leaf area is of fundamental importance. If a relationship can be determined, the leaf area will be an indicator of root size. Measurements of the leaf area will be easier to perform as they are above ground and can be performed non-destructively. Sperry’s method offers no quantitative data, but only an estimate based on the leaf canopy area. However, the leaf canopy size can be used to estimate the distance the roots may cover beneath the soil and be used as an estimate for the location of the soil electrode.

Cao (2010b) performed destructive testing on willow tree samples to assess the root surface area through electrical resistance methods. Their results confirmed that the resistance decreased in relation to an increase in the contact surface area of the roots with the solution. Their results also conclude that capacitance was more useful than resistance for estimating root size. However, the results do not confirm whether Aubrecht was correct in his hypothesis of root absorption zones, or whether electrical signals are emitted along the full length of root branch. It should also be noted that for both the Cao and Aubrecht work the principles are applied to ‘woody roots’ typically found in trees. Aubrecht discusses the difference between soft conducting roots of plants, and hard insulating roots of trees. It should therefore be noted that the findings may not be applicable to plants with soft conducting root surfaces.

All papers were in agreement that the resistance of plant tissues decreases as frequency increases. This change in resistance was found to begin at approximately 3-10 kHz and stops at approximately 1 MHz.

**Electrical Impedance Measurements of Soil, Plants and Roots**

The following section discusses those methodologies which are both invasive and non-invasive in order to utilise spectral measurements to monitor the effects of cell walls and root growth on electrical impedance measurements. For invasive measurements, intimate contact ensures that the electrical properties of the plant are measured, however, the placement of an electrode in the plant does increase the chance of causing damage to the plant system. Therefore, some of the work discussed in this section utilises non-invasive
measurements of the soil rhizosphere in order to infer electrical properties of plant systems without the requirement for invasive techniques.

Chloupek (1977) implemented a method to estimate the size, weight, volume and surface area, of a plant’s root system from capacitance measurements. In order to estimate the root size measurements needed to be taken sub-surface. A system was devised which utilised the insertion of an electrode into the petiole of a carrot stem. A second electrode was placed in the soil surrounding the plant root, within 5-15 cm away from the centre, and at a depth of 10 cm, similar to the Aubrecht/Cermak method. The two electrodes were connected via a capacitance bridge. A 1 kHz signal, at 15 mA, was used to measure the capacitance between electrodes. The premise behind the work was that the presence of a plant root would induce a change in electrical capacitance measured. Significant correlations between root size and electrical capacitance were achieved. Chloupek also noted the sensitivity to soil type, water content and plant species. Because of this, he concluded that the root capacitance was sensitive to soil electrical conductivity, which is a function of soil moisture content, texture and structure.

Rajkai (2005) also looked at the electrical capacitance of roots, particularly relating to root media and impedance measurements at frequencies between 30 Hz and 1 MHz. Their aim was to simplify the method with which root systems are analysed, and improve measurement data. Root impedance measurements were taken on an 18-leaf sunflower within capillary-saturated soil, a washed root independent of soil and a standalone soil sample capillary saturated. They found that the electrical impedance of the soil was almost constant across the frequency spectra used. For the standalone root, there was a large decrease in resistance from 13.6 to 10.6 kΩ between 500 Hz and 5 kHz, typical of the β-dispersion previously discussed. When the root was placed within soil there was decreasing resistance, but not as steep as the stem measurement. A reduced initial resistance of 1.6 kΩ which further reduced to 1.3 kΩ again between 500 Hz and 5 kHz was measured. The difference in resistance was assumed to be due to the mixture of both soil with a constant resistance and root with a changing resistance. Capacitance measurements were also taken across the same frequency spectrum for soil, root and a mixture of both. They found that the magnitude of change for capacitance and resistance of the stem decreased by a similar amount as frequency increased. However, unlike resistance, soil capacitance also decreased with frequency, making it more difficult to quantify whether changes in capacitance were due to soil or root.
Rajkai also considered the use of clamp electrodes when compared to needle electrodes for monitoring roots. Needle electrodes have been predominantly used in root tests, allowing the electrode to be directly inserted into the xylem sap. However, clamp electrodes do not have the requirement for direct contact, and so differ in measurement technique and experimental data. Clamp electrodes generate an electric field which penetrates the stem despite no physical penetration made. However, this electric field penetration is significantly less than for a needle electrode, which causes a lower capacitance reading from the clamp electrode. The benefit of the clamp electrode however, is that due to no penetration of the plant it is completely non-invasive.

Dalton (1995) presented a conceptual model for in situ capacitance methods of measuring roots. The experimental procedure utilised a small electrode inserted into the stem of the plant, and another into the soil. Dalton used a 28 gauge stainless steel electrode in the stem, rather than the previously used silver chloride electrodes, and compared measurement data for changing vertical positioning of the electrode. Experimental data was performed on hydroponically grown tomato plants, in order to visually confirm results. Dalton found that a good relationship exists between capacitance value and root mass, and that temporal measurements are accurate enough to provide valid data regarding plant growth. Dalton also notes the significance of the vertical placing of the electrode, stating that poor measurement data is most likely to occur due to inaccurate and inconsistent electrode positioning.

Ozier-Lafontaine and Bajazet (2005) further progressed the work. They attempted to estimate the root size of a tomato plant through a measurement system similar to Chloupek and Dalton, by invasively placing an electrode into the stem of a plant. The second electrode was again placed within the soil a short distance from the plant stem. Although invasive, by inserting an electrode into the stem, the measurement is non-destructive to the plant and root system and no detrimental effects were observed when the electrode was inserted correctly. Multiple tests were conducted regarding electrode placement both within the plant stem and in the soil. They found that the soil electrode placement was relatively insensitive to placement. However, the stem electrode was very sensitive to placement height, causing large changes in impedance spectra magnitude. They also found that the resistance of the plant was affected by frequency. For tomato plant it was found that at low frequencies, 10 to 100 Hz, the resistance of the plant was high, approximately 120 kΩ. At higher frequencies, 100 kHz to 1 MHz, the resistance had
reduced significantly, to approximately 20 kΩ. It is suggested that the high resistance at low frequency is due to the resistance of the extracellular space associated with β-dispersion. As frequency increases, however, the current begins to bypass the cells which in turn generate a capacitance and resistance. Once the frequency is significantly high the capacitance due to cellular membranes is cancelled and cells are crossed completely by capacitance, and resistance reduces further. However, it must also be noted that the change in resistance with frequency was more prominent in ‘younger’ plants. They found that as plants age the change in resistance was less sensitive to frequency. While being an invasive measurement, due to the electrode in the stem, both Ozier-Laurentaine and Chloupek created systems which were non-destructive, in-situ and quick when compared to manually removing the root from the soil. They conclude that spectroscopic measurements are necessary to increase knowledge of the behaviour of the root system.

Repo (2005) measured the impedance of the roots of willow cuttings, suspended in hydroponic solution. Two electrodes were used, one placed within the stem and the second within the solution. 488 impedance measurements were taken between 40 Hz and 340 kHz, twice a week over the period of a month. An electrical model was created, aimed at simulating the root structure. They found that as the root mass increased, the measured resistance decreased. However, they could not authenticate which proportion of the increase was due to the root mass increase, of the root surface area increase. They also discuss the model, constructed from resistors and capacitors, and the time constants associated with them. They state that multi-frequency measurements may provide more information regarding the root, and interfaces present.

Cao (2010b) looked at the electrical resistance of willow cuttings again within a hydroponic solution. In this case hydroponics is favoured due to the ability to visually assess the root structure. Cao connected an electrode to the stem of a willow cutting, just above the surface, and another within the hydroponic solution. All root offshoots were covered in black insulating plastic, except one, which was incrementally lowered into the solution. Cao found that the resistance measured when only the root apex was inserted was high at approximately 3-4 MΩ, but as the root was lowered in the resistance began to decrease. Upon the whole root entering the solution the resistance had dropped to 100–700 kΩ. If the stem was further lowered, so that it completely entered the solution, the resistance halved again from that of the whole root. There was little difference in resistance measurements between stem only, and stem/root. The sharp decrease in resistance when the stem enters
was thought to be due to the cut surface entering the solution. The high influence on resistance measurements due to the presence of the stem makes it difficult to interpret results, and further work would be required to quantify better the effect of the stem, and confirm the causes, rather than suspecting the cut surface.

The use of stem electrodes has advantages that the signal is forced through the plant structure, and the measured signal is therefore a function of plant properties. Measured values of complex impedance have shown that there are correlations between impedance values and plant size, and that the plant cells create a high value of impedance at low frequency. Despite their advantages, the use of stem electrodes is either invasive or possibly destructive, for needle electrodes and time consuming for collar electrodes. Therefore, while the work discussed has provided an overview of electrical properties in plants, it was decided to only utilise surface electrodes to reduce invasiveness and labour intensity from placement of collar electrodes around the stem. The following paragraphs discuss the use of electrical resistivity measurements to determine soil properties at the centimetric scale.

Samouelian (2003) utilised electrical resistivity methods to determine the location and magnitude of cracks commonly found from soil drying. They discuss how other methods require destructive sampling to determine cracking severity and location, but that resistivity imaging can provide non-invasive and non-destructive measurements. They implemented a 1.5cm electrode spacing, which required a copper/ copper sulphate (Cu/CuSO₄) electrode to ensure adequate contact at the soil-electrode interface. They were able to detect mm width artificial cracks which represent those typically found when soil dries and shrinks. Electrical resistivity methods are well suited to this application due to the requirement for a constant current path through the soil. A crack in the soil would break this path and through 2D resistivity imaging and inversion of data it was possible to establish both when these cracks were present and their location. However, data inversion requires increased solution time and complexity.

Al Hagrey (2004) found that electrical surveys can distinguish between conducting (absorbing) roots and woody (water transportation) roots. Al Hagrey (2007) utilised GPR, electrical and seismic methods in both the vadose zone and the trunk of olive trees is discussed. For 2D electrical measurements they used a Wenner and dipole-dipole array of electrodes with a spacing of 0.5m, while soil moisture was correlated with data gathered from two TDR probes placed in the soil. For 3D measurements a star-array was used, with a
smaller electrode spacing of 0.2m. GPR readings were collected in 0.1m intervals, and results compared. They conclude that both GPR and electrical methods are very sensitive to soil moisture changes, but further confirm that GPR suffers from high attenuation in highly conductive soils. Both GPR and electrical methods in 2D and 3D were able to resolve targets of individual roots and overall root envelopes beneath the soil. Temporal measurements were able to determine water movement over time throughout the soil.

Amato (2008) discussed the quantitative relationships between soil electrical resistivity and root mass density (RMD). Amato used a linear Wenner array of 48 electrodes. The measurement system produced over a thousand unique measurements, and took approximately 60 minutes from start to completion. Their findings suggest that a large portion of the variability in resistivity measurements was due to the root density within the soil suggesting that despite no intimate contact with the plant, the effect of roots could be measured. Their data concludes that a resistivity range from 7 to 700 Ωm was measured and that they are confident in their results concluding there is a definite relationship between RMD and soil resistivity. They struggled however, to achieve favourable data in measurements where RMD was low, where experimental data could not differentiate between root mass and soil.

Werban (2008) presented a measurement system which featured 970 data points for 220 cm$^3$ soil. They were able to detect irrigation events, and observed only small change in soil moisture through a diurnal evening cycle, due to reduced transpiration in the ‘night’ period. They also found that the majority of diurnal soil moisture changes were located in the area closest to the roots, suggesting increased water movement is due to root water uptake.

Grieve (2009, 2010) looked at the possibility of using electrical impedance tomography (EIT) to provide a safe, low-cost, non-invasive subsoil imaging system using a measurement system designed for in-process duties. EIT measurements were performed on soil cores located within vessels, around which were placed two concentric rings of 16 electrodes. Measurements were taken every 5 minutes over a growth period of 8 weeks. The plants were located within controlled chambers and placed on a 12/12hr diurnal cycle and featured a single water feed per day at a set time. Four test vessels were used; two measurement and two control. Results show that conductivity values in measurement vessels displayed a clear, repeatable pattern where conductivity increased sharply after the feed, and then remained stable until the day cycle. During the day cycle, the plants began
to use the water through transpiration, which was shown by a decrease in conductivity as the soil dried. For control vessels, there was a sharp increase in conductivity also at the feed, but this decreased sharply due to run-off as the soil was at saturation point, from limited water usage. During the day cycle the control vessels conductivity continued to increase despite no additional water. It was hypothesised that this was due to additional heating from the lights within the chamber and the positive correlation between electrical conductivity and temperature. The second element of the research was to utilise X-ray computerised tomography to verify EIT data. Sample images showed that X-ray was capable of observing moisture movement within the soil, alongside the placement of fine roots. One limitation was that the X-ray system could only be used for plant samples <3-4 weeks old due to size constraints. While X-ray has proved to be capable of determining location and mass of root structures alongside the moisture content of soil, the technique is not appropriate for this research due to the expense, and limited ability to measure plant root systems at more than 4 weeks old. However, the work performed by Grieve, alongside the others mentioned in this section, have provided confidence that EIT measurements can be used to determine soil moisture content.

The research discussed in this section has shown that small scale measurements on plants and soil can provide beneficial results. Research has shown that the electrical properties of a plant can be related to characteristics which could be used to infer health, and possibly inform for rapid phenotyping. However, when intimate contact is required it can be detrimental to a plant system, and also requires increased manual intervention in order to both place the stem electrode carefully, and frequently monitor the electrical contact at the stem-electrode interface. Therefore, it is the preferred option that non-invasive measurements are pursued. Another shortfall for invasive measurements was highlighted by Dalton, who claimed that poor electrode placement caused large variation in measured impedance. The benefit gained from invasive placement of electrodes is negated by the complexity of electrode placement within the stem. Considering the electrode placement, it is proposed that a fixed array of electrodes can be implemented to ensure electrode geometry is kept constant. Despite the requirement for temporarily redundant electrodes when using an array formation, it would reduce any errors caused by electrode placement since the electrodes location is fixed relative to one another.

Measurement data from research discussed within this section has shown that the plant and root system have a spectroscopic impedance signature. At low frequencies the plant
and root system is an electrical insulator, due to the cell structure within the plants. However, as excitation frequency is increased, the insulating cell structure within the plant system becomes a conductor, and electrical impedance reduces. While the plant has a frequency dependent impedance, soil was shown to be frequency independent. Therefore, spectroscopic measurements have the potential to allow discrimination between roots and soil. The next section of the literature review considers the use of rhizotrons, test cells in which the visual observation of soil and roots is performed.

**Rhizotrons**

Due to the nature of soil, it is difficult to visually observe the growth and development of plant roots. Test cells in which visual observation of the soil is permitted are termed *rhizotrons* which feature a clear window through which qualitative measurements of the plant and soil can be made (Klepper, 1993 and Busch 2005). Repo (2005) boldly claimed that the only method of non-destructive measurement, besides electrical impedance measurements, with any merit is the use of mini-rhizotrons. Mini-rhizotrons are small diameter glass tubes which are inserted into the soil in the region of interest. Small cameras are placed within the tubes to observe the root intersections along the glass surface (Majdi, 1996). Majdi notes how the use of mini-rhizotrons can provide qualitative information relating to frequency of root growth, root colour and branching characteristics. Such information would only be attainable through X-ray methods, which have been concluded to be too expensive for this research. Majdi also noted how insertion of the tubes into the soil can cause effects of up to a year for the soil to re-equilibrate with the roots.

Repo also states that the small sphere of influence in mini-rhizotrons does not provide adequate data. The consideration of visual verification was also implemented by Garre (2011), who utilised 3D ERT imaging in a large lysimeter, soil column, of height 1.5 m and internal diameter of 1.16 m. The soil core was extracted from a field with minimal disruption to ensure an accurate representation of field soil was achieved. 212 electrodes were placed around the lysimeter in six horizontally spaced rings of 32 electrodes, and four vertical transects of 5 electrodes. Four small Perspex tubes were placed into the soil core at
various heights and a microscope was placed down the tubes as a visual verification of ERT measurement data. Twenty TDR probes were also inserted at various heights to measure water content. They found that they were able to determine the soil moisture content through electrical resistivity with an in-situ calibration, based on the values obtained from the TDR sensors. However, they also state they were only able to determine soil moisture if the presence of roots did not influence measured resistivity.

While mini-rhizotrons are placed within standard soil cores, laboratory scale rhizotrons are purpose built vessels in which the dimensions are confined along one axis, to create a tall, thin vessel, to encourage root growth along the clear window. They are favoured as they still allow soil to be the growing substrate, required for the support it provides to roots, but allows roots to be visually observed on a larger scale than mini-rhizotrons. James (1984) notes that one distinct advantage is the ease with which the side wall of the vessel can be removed, allowing for easy removal of the root for post-test analysis. However, this ‘advantage’ can also highlight another issue, that the visual observation alone is not an adequate method of measuring plant root systems, but requires destructive methods to be implemented post-test.

Lobet (2013) utilised scanning techniques to measure and vectorise the root system, based on plants which had grown within a rhizotron. Grown plants were removed from rhizotrons, and destructively sampled to provide a vectorised image of root growth, which could be analysed by computer to provide morphological, topological and geometrical information for a complete root system, rather than relying on the visual observations at the soil surface. They found that they were able to completely image a root system for a 20-day old maize plant, which informed of relationships between roots and soil. However, the technique is both labour intensive and destructive, requiring careful removal of the plant system from the soil for vectorisation.

While rhizotrons allow visual observations of roots, they suffer particularly from a small sphere of influence in that only a small proportion of the roots can be seen as the rest are within the restricted soil core. The flat viewing windows can also offer preferential root growth along the surface and the thin soil core does not allow a true representation of root growth. Taylor (1976) compared the use of regular glass window rhizotrons to those with acrylic windows. A test was conducted in which the growth of Soybean plants was observed over time. They found that the plastic-soil interface was more susceptible to cracking when monitored over time due to the combined effect of flexibility of the plastic and soil
shrinkage. This exaggerated the cracking at the soil-plastic interface causing preferential root growth, thus voiding the results obtained as the root was not growing in a way similar to that of natural growth within soil. Therefore only rhizotrons with glass windows were recommended to minimise preferential root growth, and ensure root growth is normalised. However, it can be argued that even a glass window rhizotron would limit the plant to non-typical growth due to its thin profile, yet they still offer a visual observation which is unattainable in other measurement techniques.

The above research is only a small section of the rhizotron research available, however, of those studied they all cite the same limitations, that data which are visually observed are qualitative in nature only. To achieve any quantitative data, destructive sampling is required, which is labour intensive, and therefore costly. Limitations are also expressed in the form of the confined volume of the vessel, which allows roots to grow, but does not allow root growth to be representative of that experienced within non-confined soil cores.

Despite the benefits of visual observation of the soil and plant roots offered by rhizotrons, it should be considered that the data are only qualitative, unless destructive testing is performed, which limits temporal testing. It is proposed that electrical resistivity measurements are combined with rhizotrons in order to quantitatively measure soil properties alongside the quantitative measurements from visual verification. There are two possibilities for electrical resistivity measurements within a rhizotron. First is to place a linear array of electrodes along the top surface, and interrogate down into the soil. This would provide good spatial resolution at the surface, but as the plant root system extended deeper into the soil core the surface electrodes would only provide a coarse resolution. Also, the use of surface electrodes would require an inverse solution in order to convert apparent resistivity into estimated values of resistivity at discreet locations within the soil. Another disadvantage of surface arrays of electrodes is that they can inhibit water penetration through the soil as they cover the surface closest to the plant stem. While this may not be a significant problem in laboratory testing, it would represent a problem in field based measurements as the electrodes would limit the soil penetration in the area surrounding the roots. The final disadvantage of a surface array within a vertical rhizotron is that only a linear array could be implemented, which would offer only vertical electrode sounding, due to the physical constraints of the vessel.

The second method is to place a rectangular array of electrodes along the back plane of the rhizotron, and perform electrical resistance measurements only on adjacent pairs of
electrodes, therefore requiring no inverse solution. Another benefit is that the spatial resolution would be the same throughout the vessel, so even soil at the bottom of the vessel could be measured with the same resolution as the top most surface.

The use of electrical resistivity measurements offers the possibility of temporal measurements to be performed in the soil core, being able to measure the electrical resistivity over time, in a formation which offers only limited invasiveness to the soil and plant. This temporal resolution, coupled with the spatial resolution of a rectangular array, is particularly relevant to the determination of soil moisture movement and plant growth over time. It is anticipated that as soil dries the electrical resistivity of the soil will increase.

A search of the current research has indicated that no other research has coupled the connection of an array of electrodes to a rhizotron vessel in order to provide good spatial and temporal resolution measurements of electrical resistivity, coupled with visual verification through the rhizotron window. Therefore, the rhizotron is chosen as the vessel used within this research.

2.2.5: Capacitively Coupled Contactless Conductivity Detection (C4D)

This section discusses the use of capacitively coupled measurements to determine the electrical conductivity of a medium under test. It is proposed as a solution to the polarisation, contact impedance and corrosion effects typically found within electrical resistance measurements. By placing an insulating layer between the electrode and the medium under test, it is anticipated that corrosion will be inhibited, and the well-defined insulating layer can be characterised easier than a polarised layer at the soil-electrode interface.
C4D in Electrophoresis

C4D provides measurements of electrical conductivity through an insulating layer that is placed between the electrode and medium under test. Originally, the methodology was motivated by a desire to detect the conductivity of saline solution during the electrophoresis process (Gas, 1980). Typically, ultraviolet (UV) absorptivity is used to determine the electrophoresis process, which requires a clear section in the capillary pipe in order to visually detect progress. However, in certain applications some processes do not return sufficiently high absorption in order to be detected, which lead to the consideration of electrical impedance measurements as an alternative. In an application such as electrophoresis, which utilizes capillaries with internal diameters between 25 and 75 μm, creating a contact-based conductivity sensor would be very difficult to achieve. As such, contactless measurements were proposed through electrodes mounted around the external surface of the capillary. The technique requires the use of electrically insulated electrodes adjacent to the fluid flow, and hence capacitively coupled. As an AC signal is presented on the excitation electrode the fluid passing through the capillary will alter the measured AC signal on the detection electrode by changing the electric field that propagates through the fluid. From measured admittance, the conductivity of the solution can be obtained. In the case of electrophoresis the separated chemical compounds are represented as peaks which occur at different times when the conductivity is plotted against time on what is known as an electropherogram.

The earliest work utilizing C4D for electrophoresis was published by Gas (1980) who implemented a four-electrode design. In direct-contact conductivity measurements a four electrode design reduces the influence of any polarization effects as the current injection and voltage measurements are performed on different pairs of electrodes. However, since there is no direct contact, only two electrodes are required for C4D. As an example, Fracassi da Silva and do Lago (1998) used an axial arrangement consisting of two tubular electrodes around a capillary and found that while frequency had a substantial effect on sensitivity they were able to achieve comparable results with a four-electrode system.

Another distinct advantage for the use of contactless-conductivity detection in electrophoresis is the non-invasive nature, specifically the removal of requirements to clean any equipment after use, since no fluids come into contact with the electrodes. The non-invasive nature is also of particular interest for electrophoresis as contact-electrodes
could also have effects on fluid flow through the capillary, creating unwanted preferential flow. Zemann (1998) concluded that the technique was viable for electrophoresis having a sensitivity which allows for detection in the range of 200 ppb for cations and anions. It was also noted that physical arrangement of the test setup was ideal due to simplicity and flexibility.

A simple electrical model, Figure 2.12, can be used to represent the C4D system. The two capacitors, $C_w$, represent the capacitively coupled electrodes, and the resistor, $R_s$, represents the fluid passing through the circuit. As the conductivity of the fluid changes, the value of $R_s$ will also change. Any changes to the fluid conductance have no effect on the capacitance $C_w$, therefore once the value is known it can be subtracted and conductivity can be inferred.

![Figure 2.12: Equivalent circuit for a C4D system](image)

**C4D in Non-Electrophoresis Applications**

Wang and Huang (2010) utilised the C4D method, but instead of implementing for electrophoresis they were attempting to detect the presence of a plastic pipe within a water filled phantom, much more typical of an industrial ERT process, and somewhat closer to the application used here of a rhizotron and soil-water detection. The system was similar to that of an electrical capacitance tomography (ECT) system, with 12 large copper electrodes, 150mm x 25mm in size, around the periphery of the vessel of 110mm diameter. They note that between any two electrodes, when the vessel is filled with a conductive fluid, the impedance can be represented by the same model as in Figure 2.12. The resistance $R_s$ would change dependent on the conductance of the fluid and the distance
between electrodes, and as such a forward model could be created to predict values of resistance. A reconstruction image can be created, to show where values differ from those of the forward model and measured values, allowing the detection of objects of differing conductivity within the vessel. The system built by Wang et al proved a working principle, however, they do note that there are still problems that must be addressed. They have problems with the RC time constant and the injection frequency leading to larger measurement error. They noted that the electrode covering must be as thin as possible to ensure maximum sensitivity to any changes in conductivity by increasing coupling capacitance. Such a thin insulating layer may easily be breached. They also note that a resonance element should be considered by adding a series inductor.

Huang (2009), from the same research group as Wang, noted that in a capacitively coupled measurement the resistance of the conducting fluid was small in magnitude when compared to the reactance of the coupling capacitors on the insulating layer of the pipe. They note that it is possible to increase frequency or electrode size in order to reduce the reactance value, however, it serves only to reduce it, and not remove it. They therefore suggest a method of removing the reactive element through the addition of an inductive element in series with the capacitance. The addition of a series inductance allows for a resonance effect to take place. At resonance, the capacitive effect of the insulating barrier will be cancelled out by the inductor, leaving a purely resistive element in the circuit. With only a resistive element any changes in conductivity will be easier to measure (i.e. the sensitivity will increase). The circuit detailed by Huang includes an inductor placed in series with the AC source and the excitation electrode as shown in Figure 2.13. Huang found that the inclusion of the series inductor ‘significantly’ improved the sensitivity of the system with conductivity detection range being much extended. They also state a series resonance, rather than parallel, is far easier to implement due to the resonance being independent of the solution impedance and can therefore be determined in advance. The relationship, therefore, between Z and R is linear, unlike with a parallel resonance method.

![Equivalent circuit for C4D with a series inductor placed in series. RL is the resistance associated with the inductor L](image)

Figure 2.13: Equivalent circuit for C4D with a series inductor placed in series. RL is the resistance associated with the inductor L
Huang also considered the use of an electrical shield between the two electrodes to reduce stray capacitance, which occurs through the air between electrodes. The shield was constructed of brass and was claimed to have removed all stray capacitances while leaving the electrode capacitances unchanged. The focus area for Huang’s research was much more typical of an electrophoresis application, the monitoring fluid through an insulated pipe, however, it was applied to ERT by further work within the same group (Wang, 2012a and 2012b), who considered the electrical model previously presented, and applied an inductance through a quartz crystal in series with each capacitively coupled electrode. At resonance the RC components were completely cancelled, leaving only a small resistance associated with the quartz element, and the resistance of the fluid under test. Since the fluid resistance was far higher than the quartz resistance, the measurement system was able to determine the fluid conductivity. Limited results are presented in the work presented by Wang, but they do conclude that the series resonance method was capable of determining the location of one or two 20 mm diameter plastic rods within a 100 mm diameter pipe filled with water. One limitation to the series resonance method in relation to the research discussed within this thesis is that the plant root systems were found to have a value of impedance which was frequency dependent, where at low frequencies the impedance was high, and as frequency increased the plant system tended towards being a conductor. A series resonance circuit does not allow for spectroscopic measurement data to be performed, which is unsuited to plant measurements of impedance.

Wang (2013) presented further work on the C4D system. It was noted that previous work had performed non real-time measurements with an impedance analyser. This latest work demonstrates that real-time measurement can be performed, alongside the implementation of a FEM to determine the sensitivity matrix within the pipe vessel. Of note was that this work did not feature the use of series resonance elements, which were previously claimed to improve performance by removing the capacitive element from the network. It is suspected that this may be due to the added complexity of the hardware required for series resonance, and the ability to measure at only one frequency. The FEM model was created within COMSOL Multiphysics, and was analysed in the 2D plane, with vertical fringing effects not considered due to the length of electrodes used. Simulated data concludes that the pipe permittivity needs to be high, in order to provide a favourable ratio of real and imaginary components, in which the real, resistive, part of the measurement dominates the total impedance. Simulations also determined that the thinner walls would be advantageous. The hardware specification, based on FEM simulations, was that the pipe
had a relative permittivity of 6 and a thickness of 2 mm, while a 100 kHz excitation signal
was implemented. With their data acquisition system, a rate of 30 frames/s was achieved,
which was able to determine the location of a plastic pipe within a water filled vessel, and
also show changes relative to size difference of different diameter pipes.

**Alternatives to C4D – Based on Similar Principles**

A method similar to capacitive-coupling measurements is inductive-coupling. Alder and
Drew, (1979) utilized inductive coupling to measure changes in conductance through a
glass tube. Measurements were taken at high frequency (115 MHz), where the change in
charge, caused by changes in the resistive component, was used. They found that they
could successfully detect changes in potassium chloride in water down to 2ppm, with a
linear response over three orders of magnitude of concentration. They also note that the
design is cheap and robust, and as such would be ideal for long-term applications where
temporal data was needed, much like the rhizotron to be used in this work.

Huang (1995) looked at the implementation of a contactless-conductivity probe to monitor
soil contamination, simulated by passing diesel through sand. The probe used low
frequency electromagnetic (EM) methods, due to high dispersion of soil causing GPR and
high frequency EM to be inadequate. Their results indicate that absolute EM
measurements are not sensitive enough to detect contamination, having no sharp
boundary between clean and contaminated sand. However, temporal measurements on
propagation and induction would improve data as trends could be observed over time.
They also suggest that findings indicate diesel can filter through soils with larger particles
(sand) much faster than those with finer particles (clay based). The disadvantage to their
method was that soil samples must be removed for analysis in a Perspex tube therefore
being destructive.

Kuras (2007) implemented a technique they termed capacitive resistive imaging, in which a
towed array of capacitively coupled electrodes was pulled along the ground surface with
the aim to determine the resistivity distribution below the surface. The technique was
aimed primarily at measurements of resistivity below artificially created surfaces such as
concrete or wood found in urban environments, in which typical resistivity measurements would not be able to obtain the galvanic contact required. They were able to obtain a centimetric spatial resolution, while pulling the towed array at speeds in the order of 2.5 km/h. Comparison with a regular contact-based electrical resistivity technique showed that both methods were in good agreement, and that the use of capacitively coupled measurements would provide a benefit in those environments where galvanic contact measurements could not be taken. Despite the favourable results, towed arrays of electrodes do not provide a suitable solution to rhizotron based studies at the laboratory scale, and are instead best suited to urban environments.

Despite the alternative methods of coupled measurements, it was decided that the high excitation frequency was a limiting factor. The use of C4D allows for low frequency measurements to be taken at less than 50 MHz, which is both an advantage for laboratory based measurements, but also for future potential hardware as lower frequencies will assist with keeping the price of hardware to a minimum.

C4D Conclusions

In summary, the capacitively coupled method of measuring the conductivity of a medium seems like an attractive proposition for soil based measurements. The most beneficial aspects are that the insulating layer between the electrode and soil will remove the possibility of electrode corrosion from the saline soil. The dielectric layer will also reduce electrode polarisation, as a well-defined dielectric layer will be used at the boundary, from which its electrical properties are easier to determine than a double layer capacitance typically associated with electrode polarisation. The use of capacitively coupled electrodes does not significantly increase hardware costs or complexity, but does present some measurement complexities as outlined by the quoted work. It was determined that the use of series resonance did not suit the application of soil and plant analysis, as it requires measurements to be performed at only the resonant frequency, while previous research indicated that spectroscopic measurements on plants are advantageous. However, it should be noted that Wang indicated that in order to reduce the reactance of the insulating
layer the frequency must be increased above 30 kHz, and therefore the spectrum available is limited even for non-resonance measurements.

Despite the advantages of capacitively coupled measurements, disadvantages still exist. The implementation of an insulating layer increases the general complexity of the measurement data as measurement vessels must be characterised to remove the effects of the insulating layer, while also reducing measurement sensitivity as low values of coupling capacitance reduce the sensitivity of the system. In its simplest form, C4D requires only a pair of insulated electrodes and an impedance analyser, as was initially proposed in the research discussed by Wang (2010), in which electrodes were placed on the external surface of the pipe vessel. However, for soil based measurements it is proposed that the electrodes are placed in a rectangular array along the back plane of a rhizotron vessel. There is a requirement to automatically switch between electrode pairings for a rectangular array of electrodes to perform the required excitation strategies for all electrode pairings.

Since the insulating layer is required to be thin, placing the electrodes on the external wall of the rhizotron vessel is unlikely to reduce the reactance enough to allow the resistance of the soil to be determined. Therefore, it is anticipated that a thin insulating layer will need to be added to the electrode surface to provide a capacitively coupled measurement. One area of expected complexity arising is the robustness of a thin insulating layer. If a weak insulating layer is used, coarse soil particles may pierce the layer and cause galvanic contact between the soil and electrode which will remove the capacitive coupling. Therefore, consideration must be given to what is a suitable insulating layer. If the insulating layer is damaged it would require removal of the soil from the vessel to repair the damaged electrodes. Conversely, it is anticipated that damage to only a few electrodes would not completely compromise measurement data, but instead data could be interpolated from adjacent electrode pairings to allow the test to continue with only limited disruption.

The final conclusion to the use of C4D is both a strength and a weakness of the technology. Because so little work has been done by others within the field there is little in terms of research, where information could be gained from other groups. However, this is also advantageous, as it is currently believed that no other groups have utilised C4D within soil based measurements, and particularly based on the rhizotron vessel, with a rectangular array of electrodes.
2.3: Literature Review Conclusions

The literature outlined in this review has considered several key areas relating to root growth and measurements in soil. It was previously found that many techniques are currently available to estimate the soil moisture content. Techniques such as TDR, Neutron Probe and tensiometers provide a quantitative value of soil moisture content, however only offer a very small sphere of influence, are invasive and often expensive. GPR is non-invasive, but is performed on a scale much larger than the required scale of individual laboratory rhizotrons and equipment is again expensive. Direct contact electrical measurements offer significant benefits over those mentioned. The technique can be mildly-invasive, requiring electrodes to be placed at the soil surface only, and when configured correctly can be used to measure resistivity of the soil at multiple depths and locations as the array geometry is adjusted and moved across the surface. While laboratory test equipment costs may be comparable with some other technologies mentioned, it is anticipated that with future work the hardware costs of electrical resistivity measurements could be significantly reduced to approximately £100-200 per unit rather than equipment costs of greater than £5000.

Rhizotron vessels were discussed as a feasible method in which electrical resistance measurements can be performed on a soil column with limited invasiveness. The clear viewing side of the rhizotron allows for both root growth and soil properties to be visually verified. As a purely visual technique rhizotrons offer limited benefit as they provide qualitative data only. Therefore it was decided to place a rectangular array of electrodes along the back plane of the rhizotron from which adjacent pairs of electrodes could take resistance measurements with a higher spatial resolution than surface only measurements. Alongside improved spatial resolution is a well-defined geometry arising from the fixed locations of the electrodes, in a soil core of limited volume. However, the use of an array of electrodes also requires the implementation of switching electronics in order to interrogate multiple excitation strategies which does increase the measurement system complexity. It was felt that the complexity arising from this requirement was outweighed by the advantages gained with simple measurements and high spatial resolution. The rhizotron and electrode array system also offers excellent temporal resolution as the electrodes are placed in contact with the soil, but suffer only limited invasiveness and will allow electrical resistance measurements during long term plant growth tests.
Despite the advantages of electrical resistivity measurements within laboratory specification rhizotrons, it was anticipated that limitations would exist, particularly relating to electrode polarisation and corrosion. The final section of the literature review discussed the use of C4D in order to remove galvanic contact between the soil and electrode and as such aim to remove electrode polarisation and corrosion effects. C4D is a new methodology in regards to measuring soil moisture content and as such no work has been found directly where insulated electrodes have been used for measurements in soil. Within C4D, several methods were discussed to reduce or remove the reactance of the insulating layer, which is a result of capacitive coupling. Series resonance methods were suggested as a method, however, their added complexity and limitation to only one excitation frequency led to the decision to not be implemented here. The chosen C4D method requires a thin electrode layer, with a high relative permittivity, to increase sensitivity to the measured resistance value and an excitation frequency typically greater than 30 kHz. The use of spectral excitation signals may allow for observation of effects of spectroscopic impedance from plant tissues, which have been shown are an insulator at low frequencies, and a conductor as frequency is increased, due to the β-dispersion of living cells. Therefore, it may be possible to perform spectroscopic measurements in order to differentiate between roots and soil structure, which shows frequency independent impedance.

In summary, the final proposed vessel and methodology is to perform C4D electrical resistance measurements on a rectangular array of electrodes placed along the back plane of laboratory scale rhizotron vessels. These measurements will aim to measure moisture movement through the soil over time, to infer root water uptake and assist with rapid phenotyping through strong genetic traits exhibited by certain strains of crop. While hardware costs of laboratory tests are comparable to other technologies such as GPR or entry level X-ray, the future aim is that hardware costs can be significantly reduced in future work which would allow field or greenhouse-based tests to be performed in parallel.

With the chosen methodology and test vessel configuration confirmed, the research focused on the simulation of data to determine the feasibility of insulated electrodes being used to determine electrical resistivity data.
3: Insulated Electrodes – Analytical and Numerical Analysis

In this chapter the process of simulating measurement data using insulated electrodes method is discussed. First, the adaptation from electrophoresis applications to soil moisture measurements is considered, followed by the discussion of the proposed electrical model. Once the electrical model is known, an analytical solution is determined, followed by an analytical simulation, performed in MATLAB, to determine the ability to measure changes in bulk material resistance with insulated electrodes. This is followed by a second approach in which an FEM model is created based on the physical properties of the test cell and the complex admittance is simulated. This second approach is performed with the COMSOL Multiphysics software package.

After these simulations the limitations of the insulated electrode technique are considered. This is followed by a discussion focusing on the way in which the computational challenges of simulating very thin layers can be accommodated in FEM. Finally, a new FEM model based on a small section of the rhizotron is simulated with COMSOL. The simulations are designed to explore the feasibility of using insulated electrodes for measuring soil moisture change from changes in bulk resistance.

Two software packages were used throughout this section of the research in order to perform the simulations, MATLAB (MathWorks, 2013) and COMSOL (COMSOL, 2013). MATLAB is a software package used for the manipulation of numerical values, and is a non-physics based package. Therefore, an analytical solution is determined from the electrical model proposed for parallel-plate measurements. MATLAB is then used to simulate the complex impedance of the analytical solution based only on the derived equation and parameter values entered. The second software package is COMSOL multi-physics, a physics based application in which a FEM model is constructed through three-dimensional geometries. The parameter values of the FEM model are entered and the complex impedance is calculated based on the FEM model geometry and model materials.

For simulations presented in this research the COMSOL AC/DC physics module was required, from which the complex admittance can be determined. COMSOL will only output the complex admittance, unlike MATLAB which can output either the complex impedance or admittance, therefore admittance is converted to complex impedance through the use of a script file to allow comparison between both MATLAB and COMSOL.
simulations. The use of a FEM allows COMSOL to be used to determine the impedance of more complex electrode arrangements when compared to the MATLAB analytical solution, which is only applicable to parallel-plate formation.

The MATLAB software is also used to produce all plots seen throughout this thesis, and create the various script files used to automate processes such as the conversion of complex admittance to impedance for COMSOL simulated data. Where script files are used they are referenced in their appropriate sections.

3.1: A new model for Capacitively Coupled Electrodes

Capacitive coupling techniques are proposed for determining soil moisture through non-galvanic contact measurements. The literature discussed in chapter 2 outlines the use of capacitively coupled measurements to determine the conductivity of an electrolyte passing through a capillary pipe. In the present work capacitive coupling is proposed to circumvent the problems that are typically associated with direct-contact methods of soil based measurements.

Previous work has reported the use of the C4D technique in an electrical tomography application (Wang, 2012), to determine fluid conductivity within a pipe. Wang implemented a simple electrical model, as seen in Figure 3.1, to represent an electrical system for electrodes connected around the periphery of an insulating pipe containing a conductive fluid. Capacitances $C_1$ and $C_2$ approximate the capacitance of the dielectric of the pipe wall, and the resistance $R$ represents the conductive fluid passing through a pipe network.

![Figure 3.1: Electrical Model for C4D as Proposed by Wang (2012)]
An important development in the present work is that the Wang model is extended to include the resistive and reactive components of both the insulating layer covering the electrodes and the bulk. This model was originally proposed by Dr. Frank Podd, within the Sensing, Imaging & Signal Processing (SISP) group at the University of Manchester. Rather than using the boundary of a capillary pipe as the dielectric material, it was proposed that a thin dielectric film should be placed over the surface of a metal electrode to inhibit galvanic contact. While the dielectric inhibits DC, it allows AC to pass. To verify the model, measurements were proposed on a bulk material sandwiched between two insulated parallel plate electrodes. The two-dimensional block diagram and equivalent electrical model for a parallel-plate configuration insulated electrode system can be seen in Figure 3.2. This features three parallel-RC networks connected in series, representing the impedances of the dielectric insulator on each electrode, or wall, and the bulk material. The resistive and capacitive components $R_B$ and $C_B$ depend on the bulk material. The impedance of the walls, $R_{W1}$, $R_{W2}$, $C_{W1}$, $C_{W2}$ do not change. Since only the complete impedance of the system can be measured, the challenge is to extract the bulk impedance from the total impedance and eliminate the effect of the insulating layer. If a bulk material of fluctuating conductivity is considered, the complex impedance, $R_B$ and $C_B$, will change relative to the fluctuations. However, the impedance of the wall, $R_{W_1-2}$ and $C_{W_1-2}$, will remain unchanged. The aim is to extract the bulk material impedance by isolating the impedance of the wall.

![Figure 3.2](image-url)
Since the electrical properties for each electrode are, in principle, identical it is possible to combine the impedance of the insulating layers into a single value to simplify the analytical solution. The simplified electrical model is comprised of only two parallel-RC networks connected in series, one representing the impedance of both insulated electrodes combined, $R_W$ and $C_W$, and a second representing the bulk material, $R_B$ and $C_B$, Figure 3.3.

![Simplified equivalent electrical circuit with both electrodes combined](image)

Figure 3.3: Simplified equivalent electrical circuit with both electrodes combined

The following section discusses the simplified electrical model, the basic principles of the analytical solution and how it was derived.

### 3.2: Understanding the Insulated Electrode Model

One of the benefits of performing an analytical solution is the ability to separate the electrical model into individual sections, which will allow for analysis of each section to determine how it contributes to the total electrical impedance for a parallel-plate configuration. Here the electrical model is separated into two sections, the dielectric wall and the bulk material. Figure 3.4 shows the separation of the electrical model into the two sections where it can be seen that both the wall and bulk material are simply parallel-RC networks. The following discussion considers the complex impedance of each of the two sections individually and how the analytical solution for each is derived. This is followed by a discussion on the combined complex impedance of the whole electrical model and the analytical solution for the measurement system.
For all simulations, the spectroscopic impedance is plotted for frequencies between 1 Hz and 20 MHz, mimicking the frequency limits of the impedance analyser which will be used for laboratory testing. A frequency sweep was required to determine the spectroscopic signature of the insulated electrode system. For the section representing the bulk material, tap water is used as an example to demonstrate the spectroscopic response.

![Separated elements of equivalent electrical model](image)

**Figure 3.4**: Separated elements of equivalent electrical model. a: insulating layer, b: bulk material

### 3.2.1: Analytical Solution of the Electrode Insulating Wall

The first element to be discussed is the dielectric material covering the measurement electrodes, which is referred to as the *insulating layer*, Figure 3.4a. The insulating layer is used to inhibit galvanic contact, and therefore DC current flow through the electrodes into the bulk material. Since it is a dielectric it will have both a capacitance and resistance associated with it. Using Ohm's law, the analytical solution can be derived for the parallel-RC model for the insulating layer. Ohm's law dictates that the current flow through a circuit is proportional to the voltage applied, relative to the resistance, or in this case impedance since an AC signal is used and there is a capacitive element. Therefore;

\[
I = \frac{V}{Z} = \frac{V}{R} + j\frac{V}{X_C}
\]

Equation 3.1
where $I$ is the current, $V$ is the voltage, $Z$ is the impedance and $X_C$ is the reactance associated with the capacitance $C$. Since $R$ is purely resistive, its impedance is frequency independent. Inductance is not considered here as the insulating layer placed across the electrode will have no inductance. The reactance is the opposition of current from the capacitive element, and is frequency dependent. The reactance $X_C$ is calculated as follows;

$$X_C = \frac{1}{2\pi fC} \tag{Equation 3.2}$$

where $f$ is the simulated measurement frequency. Since the electrical model is a parallel network, the voltage across the resistance and capacitance will always be equal, and can be removed from calculations. From Equation 3.1;

$$Z = \frac{R(-jX_C)}{R - jX_C} = \frac{RX_C^2}{R^2 + X_C^2} - j \frac{R^2X_C}{R^2 + X_C^2} \tag{Equation 3.3}$$

From this equation the complex impedance can be calculated from the values $R$ and $C$, independent of knowledge of the voltage or current. An important, but perhaps often misunderstood point is that the real part of the resulting complex impedance has a contribution from the reactive component and the imaginary part from the real component. These real and imaginary components of the overall complex impedance must not be confused with the resistive and reactive elements of the parallel-RC network which are also designated the real and imaginary impedance. Therefore the real and imaginary components of the complex impedance will be termed as the real impedance of the solution and the imaginary impedance of the solution from which the complex solution is derived. With the analytical solution derived for the wall impedance, the bulk material is considered.
3.2.2: Analytical Solution of the Bulk Material

The electrical model for the bulk material, Figure 3.4b, is also represented by a parallel-RC network exactly the same as the insulating layer, but with different parameter values. Equations 3.2 to 3.3, used to determine the analytical solution for the insulating layer, are also applicable for finding the analytical solution of the bulk material. As with the insulating layer, the complex impedance can be determined independent of knowledge of the current and voltage.

Since both sections use the same formula to calculate impedance, designators will be used to differentiate between them. For the insulating layer the subscript \( W \) will be used as the layer is also referred to as the Wall, and for the bulk material the subscript \( B \) will be used. Therefore, the impedance for the insulating layer is;

\[
Z_W = \frac{R_W X_W^2}{R_W^2 + X_W^2} - j \frac{R_W^2 X_W}{R_W^2 + X_W^2} \tag{Equation 3.4}
\]

While the impedance for the bulk material is;

\[
Z_B = \frac{R_B X_B^2}{R_B^2 + X_B^2} - j \frac{R_B^2 X_B}{R_B^2 + X_B^2} \tag{Equation 3.5}
\]

Having derived the analytical solution for both the insulating layer and the bulk material, the next step is to determine parameter values for resistance and capacitance of each section in order to simulate spectroscopic impedance.
3.3: Deriving Simulation Parameters

This section details the process used to derive all simulation parameters of the electrical model for use in the MATLAB analytical solution, to find the typical spectroscopic response for varying bulk materials. At the end of this section all parameter values are tabulated for future reference.

For all simulations and laboratory based measurements, a 3 x 3cm electrode is used, providing a surface area of 9cm$^2$. The electrode size was chosen based on the dimensions of the rhizotron test cell, and in particular the back plane area. The rhizotron back plane allowed for an array of 10 x 6 electrodes, with a 2cm horizontal and vertical spacing. More details of the rhizotron vessel and electrode array formation are provided in chapter 4.

First, the parameters used for the electrical properties of the insulating layer in the simulation are derived. Since the electrical properties of the electrode insulator do not change, only one set of values was required for all simulations. Only if a new insulating layer was used, or a change to electrode size was implemented would the parameters $R_W$ and $C_W$ change. The electrical properties of the insulating layer were taken from the datasheet of the laminate mask used during laboratory testing. The dielectric mask has an electrical resistance of more than $1\times10^{12}$ Ω, relative permittivity of 3.56, and thickness of 75 μm, defined by the datasheet. Since the resistance is provided, only the capacitance $C_W$ must be calculated. From the thickness of the insulating layer, and the electrode dimensions, $C_W$ can be calculated. The capacitance is calculated from the parallel-plate capacitor formula;

$$C_W = \frac{\varepsilon_0 \varepsilon_r A}{d} = 378\text{pF}$$  \hspace{1cm} \text{Equation 3.6}

where $\varepsilon_0$ is the permittivity of free space having a value of $8.854\times10^{-12}$ F/m (farads per metre), $\varepsilon_r$ is the relative permittivity of the material with a value of 3.56. The variable $A$ is the surface area of the parallel plates having a value of 9cm$^2$ (0.0009m$^2$) and $d$ is the distance between plates having a value of 75 μm. The above values are for a separate dielectric layer on each electrode. As previously mentioned the electrical model was
simplified, combining the impedance of both electrodes in series. Since measured resistances in series are simply added together, the total resistance $R_W$ is $2 \times 10^{12}$ Ω. Capacitances connected in series, however, are added reciprocally to give $C_W = 189$ pF.

With the electrical parameters calculated for the insulating layer, it was decided to compare the analytical calculations with the actual measurements to determine the accuracy. This was required as inaccuracies in parameter values of the wall impedance would lead to inappropriate conclusions being drawn as to the applicability of the system to be used for measuring soil resistance, and may also lead to inaccurate estimates regarding bulk resistance since the wall impedance may be subtracted from the total impedance.

A measurement cell was created based on the proposed test specification to match the electrical parameters in the analytical model for a parallel-plate measurement. A preliminary test was conducted in which the spectroscopic impedance of tap water was measured between 10 Hz and 10 kHz using a HP 4192a impedance analyser. The impedance was not measured below 10 Hz due to limitations of the available equipment. More information regarding the spectroscopic response of the insulated electrode model across the full simulated frequency spectrum is found in section 3.5. A detailed description of the measurement technique and equipment used is found in chapter 4. The analytical solution was based on Equation 3.4.

![Figure 3.5: Comparison of analytical solution and measured real impedance for tap water measured in a parallel-plate configuration. Simulation parameter $R_W = 2 \times 10^{12}$Ω.](image)
Figure 3.5 shows the real impedance up to 10 kHz for both the calculated and measured real impedance of the solution. It can be seen that the results are very different. For the analytical plot the impedance at 1Hz is approximately 360 kΩ, which decreases with frequency until approximately 50 Hz where it plateaus at 5 kΩ, the impedance of tap water. For the measured impedance, at 10 Hz the impedance is approximately 1.5 MΩ. There is a subtle decrease in impedance between 10 Hz – 500 Hz, from 1.5 MΩ to 700 kΩ. Between 500 Hz and 10 kHz the measured impedance decreases more rapid, from 700 kΩ and tending towards the value of 5 kΩ, the impedance of tap water. It is clear from this comparison that either one or both of the simulation parameters $R_W$ and $C_W$ are not correct. It is assumed that at lower frequencies, the analytically calculated value of real impedance would increase to $2 \times 10^{12}$ Ω. However, available laboratory equipment does not allow for measurements at such low frequencies, and therefore the analytical model was also not considered at these low frequencies.

Through empirical modelling it was possible to adjust the values used in the analysis until the spectroscopic impedance best matched that seen in the measured values as shown in Figure 3.6. In this simulation, only the value $R_W$ was changed, all other parameters were kept the same. When $R_W$ was set to 1.5 MΩ it can be seen that the simulated and measured impedance are very similar.
Through empirical methods the resistance $R_w$ has been found to be approximately $1.5 \, \text{M} \Omega$ when compared to the value of $2 \times 10^{12} \, \Omega$ as quoted from the product datasheet (Bungard, 2013). The large difference between the estimated parameter value and measured value was determined to be due to the inability of the impedance analyser to measure at such high impedances as those presented by the insulating layer. The operating specification of the HP 4192A impedance analyser suggests a maximum impedance value of $1.3 \, \text{M} \Omega$ can be measured, slightly below the measured value for tap water in a parallel-plate test cell. Despite this limitation, it is not a cause for concern since the low frequency impedance is not used to determine the electrical properties of the bulk material. For all future simulations the value of $R_w$ will be set to $1.5 \, \text{M} \Omega$ with the aim to match that which would be expected for actual measurements.

With the electrical parameters determined for the insulating layer, the electrical parameters for the bulk material were calculated. To avoid complicating factors associated with soil, for instance texture and structure, water was used for initial simulations. Once the simulation was verified to be able to distinguish the changing impedance of the water, the bulk material parameters would be adapted to represent soil.

The parameters used for the calculation of $R_B$ and $C_B$ were derived from typical values of relative permittivity and conductivity of tap water (Lenntech, 2013). The relative permittivity of water was taken to be 80, and the conductivity was 0.0255 S/m, based on a mid-point value from a range of typical tap water conductivity. To calculate the value of $R_B$ and $C_B$, the vessel internal dimensions must be known. The cross-sectional area of the simulated vessel was 3 x 3cm, determined by the surface area of the electrode. The internal cell dimensions were 3 x 3 x 5cm, however, the electrode was 2mm thick and so the distance between the electrode faces was reduced to 4.6cm. With the distance between electrodes known, the values $R_B$ and $C_B$ were calculated to be 5 kΩ and 13.9 pF respectively.

Using the above methods, values were also calculated for the resistance and capacitance of both distilled water and a saline solution representing sea water. These values were calculated to observe the performance of the insulated electrode method, and whether any limits of operation were experienced for very low and high conductivity water. For all water simulations a relative permittivity of 80 was used. For distilled water a conductivity of 5.5 μS/m was used, and for saline solution a conductivity of 5 S/m was used. These values of conductivity provide a resistance of $9.3 \times 10^6 \, \Omega$ for distilled water and 10.2 Ω for
saline solution. The calculated values for resistance and capacitance for all three water types are seen in Table 3.1.

<table>
<thead>
<tr>
<th>Bulk Material</th>
<th>Conductivity (S/m)</th>
<th>Permittivity</th>
<th>Resistance (Ω)</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>5.5x10⁻⁹</td>
<td>80</td>
<td>9.3x10⁹</td>
<td>13.9</td>
</tr>
<tr>
<td>Tap water</td>
<td>0.0255</td>
<td>80</td>
<td>5x10⁻⁵</td>
<td>13.9</td>
</tr>
<tr>
<td>Saline solution</td>
<td>5</td>
<td>80</td>
<td>10.2</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Table 3.1: Calculated resistance and capacitance values for distilled, tap and saline solution based on the proposed dimensions of the parallel-plate test cell.

The values for resistance and capacitance were also calculated for a bulk material representing soil. With soil being such a complex material, electrical resistivity and permittivity values can vary significantly for varying texture. When water is added the values will vary even more so due to the high permittivity of water and the creation of a conducting electrolyte from the salts contained in the soils. The values chosen provide three typical values for soils, ranging from dry to approximately saturation point, and are taken from Smith (1993) and agree with von Hippel (1954). Smith tested soils at twelve sites in England and Scotland at gravimetric moisture contents ranging from 0% to 28%. They are approximations taken from graphs and used to represent typical values one would encounter in measuring soil electrically. Soil at various moisture contents was chosen over different soil types due to the larger dependency of soil permittivity on water content. While the three levels of soil moisture content provide a comprehensive range of typical properties they are not exhaustive and used only for simulation purposes.

The method of calculating resistance and capacitance for each soil moisture content is the same as that used for calculating the bulk parameters of tap water. Table 3.2 shows the selected resistivity and permittivity of the three soil samples, and the calculated resistance and capacitance for each based on the dimensions of the parallel-plate test cell.
Table 3.2: Calculated resistance and capacitance values for three soil types based on the dimensions of the parallel-plate test cell. Values taken from Smith (1993).

Table 3.3 shows the calculated resistance and capacitance values for all simulation parameters, both water and soil alongside the designators used to differentiate between bulk materials. Once all parameters were calculated for the bulk material, analysis of the MATLAB analytical solution could be performed.

Table 3.3: Calculated resistance and capacitance values for all simulation parameters for the analytical solution.
3.4: Mechanical and Electrical Limitations of the Insulating Layer.

This section discusses the main limitation of the insulated electrode system, namely the thin covering placed on the electrodes. As previously discussed, the complex impedances of each electrode are added in series to provide a single value of resistance and capacitance. Series capacitances must be added reciprocally where the smallest capacitance in the circuit will dominate the total value of capacitance. If the capacitance of the insulating layer is lower than that of the bulk material the measurement will become insensitive to changes in bulk material properties. Table 3.4 shows two examples in which the lowest values of capacitance dominate the total value when added reciprocally.

<table>
<thead>
<tr>
<th>Capacitance (pF)</th>
<th>C_W</th>
<th>C_B</th>
<th>C_W</th>
<th>C_TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>100</td>
<td>10</td>
<td>10</td>
<td>4.8</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>10</td>
<td>10</td>
<td>4.9</td>
</tr>
<tr>
<td>200</td>
<td>10</td>
<td>200</td>
<td>10</td>
<td>9.1</td>
</tr>
<tr>
<td>200</td>
<td>20</td>
<td>200</td>
<td>10</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Table 3.4: The influence of C_B and C_W on C_TOTAL.

When the capacitance C_W << C_B, the value C_TOTAL tends towards the value C_W/2 and changes very little for a large change in C_B. However, when the value C_W >> C_B, the value C_TOTAL tends towards C_B and changes a large amount for a large change in C_B. Therefore, the capacitance of the insulating layer needs to be significantly higher than the bulk material. For a parallel-plate capacitor the plate separation significantly reduces capacitance and vice versa.

Since the electrode size is determined by the rhizotron measurement system, the high capacitance for C_W is achieved by ensuring that the insulating layer is as thin as possible. The insulating layer used in simulations, and proposed for testing, is a PCB soldermask laminate sheet which is applied to the electrodes (Bungard, 2013). Despite the quoted resistance of more than 2x10^{12} Ω for the insulating layer, testing determined that the impedance analyser limited the measurable value of resistance to 1.5 MΩ. However, for the capacitance the impedance analyser was operating within specification and was found to be approximately 378 pF, as the data sheet suggested.
The effect of using a thicker insulating layer is illustrated below. An increase in insulator thickness from 75 μm to 10 mm would decrease the capacitance of $C_W$ from 378 pF per electrode to 2.8 pF, and for both electrodes added in series this value halves to 1.4 pF. The capacitance of the bulk material when simulated for water was calculated to be 13.9 pF. The total capacitance, therefore, of the bulk and scaled wall are;

$$\frac{1}{C_{TOTAL}} = \frac{1}{C_W} + \frac{1}{C_B} = \frac{1}{769\epsilon_0} = 1.3 \text{ (pF)}$$  \hspace{1cm} \text{Equation 3.7}

Therefore it becomes impossible to extract the bulk capacitance from the measured capacitance value since the insulating wall now dominates the total capacitance. The effect of this can be seen in Figure 3.7, which shows the calculated real impedance for two both the standard insulating layer at 75 μm, and the second at 10 mm. All other wall parameters remained unchanged. While this would not be possible to achieve in real word testing it allows for a comparison of impedance when only capacitance is changed. From the calculated real impedance two main effects can be seen. Firstly, there is no plateau region for the wall of 10 mm thickness, this is due to the wall capacitance being low and dominating the total capacitance value. The second effect is that the decrease in impedance has been shifted along the x axis, which represents frequency. For a 75 μm insulating layer the minimum frequency at which the resistance can be estimated is 1 MHz, whereas for the 10 mm layer the minimum frequency would be approximately 100 MHz. As measurement frequency increases, so too does the cost of equipment required to take measurements making a thicker insulating layer impractical for testing.
While the thin electrode covering seems ideal due to its high capacitance, it will be more susceptible to mechanical damage from coarse materials, such as sand. Since it is crucial that a high capacitance is achieved, this is one aspect in which a compromise must be made. Therefore care must be taken during measurements that the insulating layer is not damaged, which would allow galvanic contact to be made between the electrode surface and bulk material and void measurements.

3.5: Analytically Calculated Impedance of the Electrical Model

Once the simulation parameters were determined it was possible to analyse each of the electrical model sections independently. Once completed, the two sections could be combined and the complete analytical solution determined and analysed. Commented versions of the MATLAB scripts and GUI used for the analysis can be found in appendix A1.1 and A1.2 respectively. The first section to be considered was the insulating layer on the electrodes.
3.5.1: Spectroscopic Impedance of Individual Sections

It was previously determined that the parameters for $R_W$ and $C_W$ were 1.5 MΩ and 189 pF respectively, and that the impedance for insulating layer was calculated in equation 3.4. A plot of the real, imaginary and absolute impedance of the analytical solutions for the insulating layer can be seen in Figure 3.8. It can be seen that below approximately 500 Hz the real and absolute impedance of the solution are, essentially, constant and independent of frequency, point A. This is due to the reactance of the insulating layer being so high that the majority of current flow is through the resistive element. As frequency increases above 500 Hz, point B, the reactance decreases until the impedances of both the resistive and reactive parts are equal. Above approximately 600 Hz the reactive impedance reduces below the resistive impedance, and the majority of current flows through the reactive element rather than the resistive element.

![Simulated spectroscopic complex impedance of the dielectric coating.](image)

**Figure 3.8:** Spectroscopic complex impedance of the insulating layer.

$R_W = 1.5 \text{ MΩ}$, $C_W = 189\text{pF}$.  

124
Figure 3.9 shows the complex current through the resistive and reactive elements, where it can be confirmed that at low frequencies the majority of current flows through the resistive element. As frequency increases, the reactance decreases and subsequently current through this element increases until the point at which the majority of current flow occurs in the reactive element. It can also be seen that the resistive current flow is frequency independent, due to being a purely resistive element, whereas the current through the reactive element changes with frequency. At low frequencies the calculated total current flow is approximately 1 μA, compared to 10 mA at 20 MHz, since the reactive element offers so little impedance to current flow at high frequency.

The next simulation considered the complex impedance and current flow for the bulk material using the parameters for tap water, where \( R_B \) and \( C_B \) were set to 5 kΩ and 13.9 pF respectively. Plots of the complex impedance and current can be seen in Figure 3.10 and 3.11 respectively. Below 1 MHz the real and absolute part of the complex impedance solution is approximately 5 kΩ, matching the value of the parameter \( R_B \). Below 1 MHz the imaginary part of the solution is very low and increases with frequency. At approximately 2 MHz the impedance of the real and imaginary parts are almost equal, meaning equal current will flow through each element. Above this point the reactive impedance decreases, causing a decrease in absolute impedance since the value is the product of both the real and imaginary part, and is predominantly determined by the lowest impedance.
Figure 3.11 shows the current flow through both the resistive and reactive elements of the bulk material. Below 1 MHz the majority of the current flows through the resistive element and despite the reactive impedance decreasing, the ratio of current through the reactive element compared to the resistive element is low. Only as frequency approaches 1 MHz does the current flow through both elements become approximately equal. As frequency continues to increase, the total current flow increases due to the extra current through the reactive element alongside the static current flow through the resistive element. The current through the resistive element does not change since it is resistive only, and independent of frequency.

Figure 3.10: Simulated spectroscopic complex impedance of tap water as bulk material. $R_B = 5 \, \text{k} \Omega$, $C_B = 13.9 \, \text{pF}$.
Figure 3.11: Simulated spectroscopic current flow through the resistive and reactive elements for tap water. 

\[ R_B = 5 \, \text{k}\Omega, \quad C_B = 13.9 \, \text{pF}. \]

3.5.2: Spectroscopic Impedance of Combined Sections.

Until this point, only the complex impedance of individual sections of the electrical model has been discussed. This section gives a brief overview of the expected spectroscopic signature for the full model. Methods for analysing the total complex impedance will be discussed in the following sections. This section of the thesis does not consider the changing of the simulation parameter values, \( R_W, C_W, R_B \) and \( C_B \). Instead, a sample set of parameters are provided and the subsequent response is discussed. The key features of the resulting spectra are discussed, and will remain the primary discussion areas for the analytical solution found in section 3.4. With the complex impedance of the series connected combination. The simplified electrical model is repeated in Figure 3.12.

Figure 3.12: Simplified electrical model for insulating layer of both electrodes combined and bulk material.
First, the analytical solution must be derived, after which the impedance spectra are calculated using MATLAB. Since the complete model comprises the individual sections combined in series, the full analytical solution can be determined by adding real and imaginary components of the solution. The complete analytical solution is given in Equation 3.8.

\[ Z_T = Z_W + Z_B = \frac{R_W X_W^2}{R_W^2 + X_W^2} + \frac{R_B X_B^2}{R_B^2 + X_B^2} \]

\[ -j \left( \frac{R_W X_W^2}{R_W^2 + X_W^2} + \frac{R_B X_B^2}{R_B^2 + X_B^2} \right) \]

Equation 3.8

Figures 3.13 and 3.14 show the complex impedance and current for the complete analytical solution respectively using the previous parameter values for the insulating layer and tap water.

Figure 3.13: Simulated spectroscopic complex impedance of the full analytical solution for tap water. Point A represents the Plateau region created by the insulating layer. Point B represents the plateau region created by the bulk material. \( R_W = 1.5 \, \text{M} \Omega \), \( C_W = 189 \, \text{pF} \), \( R_B = 5 \, \text{k} \Omega \), \( C_B = 13.9 \, \text{pF} \).
The combined impedance is a series combination from both the insulating layer and bulk material. The aim of the insulated electrode system is to determine the real component of impedance of the bulk material. The goal is to estimate the resistivity of water, but ultimately in laboratory or field based measurements the goal is to estimate the resistivity of soil and how this changes in relation to water content. Analysis of the results in Figure 3.13 shows that the real part of the complex impedance has a plateau between approximately 1 Hz and 500 kHz (point A). The real impedance of this plateau region is 1.5 MΩ ± 2%, corresponding to the impedance of the insulating layer. This then decreases between approximately 500 Hz and 10 kHz, during which the reactance of the insulating layer is decreasing below that of the resistance. At approximately 10 kHz another plateau occurs until approximately 1 MHz, point B, with an impedance of 5 kΩ ± 2%, the parameter value of resistance for the simulated tap water. At higher frequencies the real impedance decreases again as the reactance of the water decreases below its resistance. While the imaginary complex impedance and the absolute impedance both provide information relative to the overall impedance of the system, they do not allow for a simple estimation of the resistance of the bulk material. It is possible that the resistance of the bulk material could be estimated from the absolute impedance, but only in a very small bandwidth at approximately 1 MHz. Even at this frequency the calculated impedance is only within 10%
of the simulation parameter. Therefore, the bulk material resistance here is estimated only by measuring the value of the real impedance of the solution within the plateau region at point B. It was anticipated that for all future analysis and measurements, only the real part of the complex impedance will be used. This provides the clearest plateau region, and most simple method of determining the bulk material impedance.

The complex current plot of Figure 3.14 shows current flow through the resistive and reactive elements of the bulk material. The resistive current is no longer frequency independent as the impedance of the insulating layer and tap water are combined. At low frequency, Figure 3.14 point A, very little current flows through the insulating layer, therefore current flow through the bulk is also low. However, as current through the reactive element of the circuit increases so the current through the bulk will increase point B.

This section has provided a brief overview of the analytical simulation of the insulated electrode model. It has provided an example of the typical spectroscopic signature which should be experienced for an insulated electrode measurement, and the key elements to consider when analysing the impedance plots. Following these experiments, it was anticipated that this spectroscopic signature would be similar if the bulk material were soil. It is known that the increase of water content in soil will reduce its impedance. This change in impedance will be presented by a plateau region which changes according to the change in impedance of the soil. It was also anticipated that soil moisture content is not the only parameter which might change the impedance of the soil. Determination of the other parameters, and the effects they may have on soil impedance, was discussed in chapter 2, and the results of testing performed in this research are found in chapter 5.

The next section covers the analytical simulation for various simulation parameter values of bulk impedance, simulated and analysed to determine whether the resistivity of the bulk material could be estimated through an insulated electrode measurement. It was hypothesised that for all water types and soil moisture contents, a spectroscopic plot of the real impedance would be similar to that shown previously, and that the wall impedance would not vary regardless of the bulk material resistance.
3.6: Analytical Solution for Varying Bulk Materials

The full analytical solution as given in Equation 3.8 is based on the electrical impedance of two parallel-RC networks connected in series. The analytical simulation for varying bulk materials was separated into two areas. First, three water types were analysed; distilled and tap water and saline solution. The second section is the analysis of data for a soil based bulk material at three moisture levels; 0%, 14% and 28%. For all analyses attention is focused on the real part of the complex impedance, however the real, imaginary and absolute values are all plotted to confirm that the real part of the complex impedance is the most appropriate parameter to use.

3.6.1: Analytical Solution for Water

This section discusses the simulated impedance for water placed between two insulated electrodes. Table 3.5 shows the parameters used for the resistance and capacitance of the parallel-RC model, previously determined.

<table>
<thead>
<tr>
<th>Bulk Material</th>
<th>Conductivity (S/m)</th>
<th>Permittivity</th>
<th>Resistance (Ω)</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>5.5x10^-6</td>
<td>80</td>
<td>9.3x10^6</td>
<td>13.9</td>
</tr>
<tr>
<td>Tap water</td>
<td>0.0255</td>
<td>80</td>
<td>5x10^3</td>
<td>13.9</td>
</tr>
<tr>
<td>Saline solution</td>
<td>5</td>
<td>80</td>
<td>10.2</td>
<td>13.9</td>
</tr>
</tbody>
</table>

Table 3.5: Calculated resistance and capacitance values for distilled, tap and saline solution.

The first bulk material to be considered is tap water. The real, imaginary and absolute impedance can be seen in Figure 3.15. From the results it is proposed that the impedance of the bulk material can be estimated from the real impedance of the complex solution in the plateau region from 40 kHz to 1 MHz. The plateau regions used in this analysis are estimated from visual observation only and determine the frequencies at which the real
impedance of the complex solution can be used to estimate the resistance of the bulk material. The data was also interpreted by means of numerical analysis, determined by observing at which frequencies the calculated impedance was within 2% error of the simulation parameter value.

Analysis of the numerical results shows that the value of impedance extracted from the plotted data is within 2% error of parameter values for the bandwidth 70 to 300 kHz. These values of frequency are slightly lower than the estimated bandwidth through visual observation alone. Outside these frequencies the real impedance of the solution cannot be used to determine the bulk material resistance. While the visual observation of the cut-off frequencies is slightly inaccurate, it still offers a rapid method of estimating resistance since it would be wise to estimate resistance from the real impedance in the middle of the plateau region, and not close to the upper and lower limits. It can also be seen that estimating the resistance of the bulk material from the imaginary and complex impedance is again not possible. Only at approximately 300 kHz to 2 MHz does the absolute impedance appear to produce a plateau region. The numerical value of absolute impedance at 1 MHz was found to be 4.98 kΩ, an error of only 0.4%. However, since the plateau region is poorly defined, it is advantageous to estimate the bulk resistance from only the real impedance of the complex solution.

Figure 3.15: Simulated real, imaginary and absolute complex impedance for tap water. 

\[ R_W = 1.5 \text{ MΩ}, \ C_W = 189 \text{pF}, \ R_B = 5 \text{kΩ}, \ C_B = 13.9 \text{ pF}. \]
Figure 3.16 is a plot of the real, imaginary and absolute spectroscopic impedance calculated for distilled water. The spectroscopic impedance is very different to that of tap water. The reason is that the value of resistance of the distilled water is greater than that of the insulating layer. Therefore, it does not appear possible to determine the resistance of the bulk material when it has a resistance higher than 1.5 MΩ, from a ‘typical’ plateau.

However, observation of the real and absolute impedance at low frequencies shows that the impedance between 1 to 100 Hz is a plateau, point A. Observation of the numerical data for this plateau shows that the real and absolute impedance was 10.8 MΩ. This value is the sum of both the wall resistance, 1.5 MΩ, and bulk resistance, 9.3 MΩ, combined.

Since the wall resistance is known it can be subtracted from this total impedance to provide the bulk material resistance. From the imaginary impedance it is not possible to determine the bulk resistance since no distinguishing features correlate to the resistance value used for the simulation.

Finally, a saline solution was considered having a conductivity representing sea water. Results are shown in Figure 3.17. The visual estimation of the plateau region occurred at frequencies between 1 to 20 MHz, indicated by point A. Through numerical analysis of the real impedance it was found that an error within 2% was achieved between 2 to 10 MHz. It can also be noted that the plateau has shifted along the x-axis, meaning that the plateau for measuring resistance increases frequency for decreasing bulk resistance. This suggests...
that for such conductivities equipment will need to be capable of measuring at higher frequencies in order to determine the impedance within the plateau.

Figure 3.17: Simulated real, imaginary and absolute complex impedance for a saline solution.

\[ R_W = 1.5 \, \text{MO}, \, C_W = 189 \, \text{pF}, \, R_B = 10.2 \, \Omega, \, C_B = 13.9 \, \text{pF}. \]

Figure 3.18 shows the calculated spectroscopic real impedance for all three water types. It demonstrates how the low frequency impedance of the wall is unchanged between saline solution and tap water, and that the reactive element of the insulating layer is the cause for the decreasing impedance at low frequencies, as seen by point A in Figure 3.18. However, the distilled water has a greater resistance than the insulating layer and at low frequencies the impedance is the product of both the insulating layer and the bulk material. It can also be seen that as resistance of the bulk material decreases, the low frequency cut-off for the plateau shifts along the x-axis, therefore increasing in frequency. This occurs as the real impedance only plateaus when the impedance of the bulk material is greater than the reactive element of the insulating layer. Therefore, bulk materials of high conductivity will have a plateau which occurs at higher frequencies. The higher frequency roll-off is caused when the reactance of the bulk material decreases below its resistance. Beyond this point the impedance is dominated by the reactive element and will not allow for estimation of bulk material resistance from the real impedance.
Analysis of the insulated electrode model suggests that the resistance of the bulk material can be estimated within certain criteria. The resistance must be estimated from within the second plateau region. Below this plateau region the real impedance of the solution is dominated by the reactance of the insulating layer on the electrodes. In circumstances where the bulk resistance is significantly higher than the insulating layer resistance, the low frequency real impedance may be used to estimate bulk resistance. In this scenario, it must be assumed that the impedance of the insulating layer is unchanging, characterised to be 1.5 MΩ, and must be subtracted from the total impedance to provide the bulk resistance. At frequencies greater than the upper cut-off of the plateau, the real impedance is dominated by the reactance of the bulk material.

The next section considers the analytical solution for soil at three moisture contents to determine whether the insulated electrode system is a viable technique.

3.6.2: Analytical Solution for Soil

The previous section considered three values of resistance to represent distilled and tap water and a saline solution. A relative permittivity of 80 was assumed for all cases. For soil, both the permittivity and resistance were changed for each soil type. Impedance for three
soil samples of varying water content were calculated; dry soil with 0% moisture content, moderately wet soil of 14% gravimetric moisture content and saturated soil of 28% gravimetric moisture content. The simulation parameters for each soil type can be seen again in Table 3.6.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Resistivity (Ω/m)</th>
<th>Resistance (Ω)</th>
<th>Permittivity</th>
<th>Capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry (0%)</td>
<td>90x10^3</td>
<td>4.6x10^6</td>
<td>4</td>
<td>0.69</td>
</tr>
<tr>
<td>Moderate (14%)</td>
<td>900</td>
<td>46x10^3</td>
<td>25</td>
<td>4.33</td>
</tr>
<tr>
<td>Saturated (28%)</td>
<td>45</td>
<td>2.3x10^3</td>
<td>30</td>
<td>5.20</td>
</tr>
</tbody>
</table>

Table 3.6: Calculated resistance and capacitance values for three soil moisture contents based on values taken from Smith (1993).

The first calculations were for dry soil, and the complex impedance can be seen in Figure 3.19. The spectroscopic impedance of dry soil follows a similar pattern to that of distilled water, as expected, due to its very high resistance. At point A the total simulated impedance was 6.1 MΩ. As with the simulation for distilled water, if the wall impedance of 1.5 MΩ is subtracted from the total impedance at point A, the remaining impedance is 4.6 MΩ, the value used in the simulation. This method of subtraction shows that when the bulk material impedance exceeds that of the wall, the total impedance will be the sum of both the wall and bulk material together.
Figure 3.19: Simulated real, imaginary and absolute complex impedance for dry soil. 
\[ R_W = 1.5 \, \text{M} \Omega, \, C_W = 189 \, \text{pF}, \, R_B = 4.6 \, \text{M} \Omega, \, C_B = 0.69 \, \text{pF}. \]

Figure 3.20 shows the real, imaginary and absolute impedance for the moderately wet soil sample which again follows the typical spectroscopic impedance. From visual inspection the plateau region extends from approximately 8 to 300 kHz. Numerical analysis suggests that for an error value within 2% of the simulation parameter, the plateau region is 20 to 40 kHz.

Figure 3.20: Simulated real, imaginary and absolute complex impedance for moderately wet soil. 
\[ R_W = 1.5 \, \text{M} \Omega, \, C_W = 189 \, \text{pF}, \, R_B = 46 \, \text{k} \Omega, \, C_B = 4.33 \, \text{pF}. \]
Results for saturated soil are shown in Figure 3.21. The visually estimated plateau is between 60 kHz to 4 MHz. Numerical analysis determined that an error of less than 2% occurred in the plateau between 100 kHz and 700 kHz.

For comparison, Figure 3.22 shows the real impedance for all three soil samples. This suggests that the resistivity of the bulk material can be estimated, even for dry soil. However, the spectroscopic response shows that a measurable plateau region only occurs for the moderately wet and saturated soil sample, based on the operating limits of the HP4192A impedance analyser. For dry soil, it was possible to subtract the wall impedance at low frequency to determine the impedance of dry soil. However, this relies on the maximum impedance limits of the impedance analyser used, which in the present case has been shown to be limited to 1.5 MΩ. It can therefore be expected that for bulk materials of very high impedance, such as dry soil or deionised water, the insulated electrode method cannot be used to determine its impedance for laboratory based measurements.
3.6.3: Summary of Analytical Solutions for the Insulated Electrode System

Figure 3.23 shows the spectroscopic real impedance for all six bulk materials that have been considered. The plots of impedance suggest that it is possible to estimate resistance of the bulk material for all simulation conditions. For a bulk material of very high resistance, results might be determined by subtracting the insulating layer resistance from the total low frequency impedance. For actual measurement data this is limited, however, by the operating specifications of the impedance analyser. If the maximum measurable impedance is 1.5 MΩ, then the subtraction method would not work.

For all bulk materials with a resistance lower than that of the insulating wall, a plateau region occurs, from which it was found that bulk resistance could be estimated to within 2% error of parameter values from visual observation alone. For bulk materials of low electrical resistance, the limits of operation are determined by the maximum frequency of the measurement equipment used. For the saline solution the lowest frequency of the plateau occurs from 2 MHz upwards. If the operating specification only allowed a measurement at excitation frequency of 1 MHz, there would be an error in the estimated value of bulk material impedance.
The analytical solution, performed for all six bulk materials representing both water and soil, have shown that under theoretical conditions the insulated electrode system can provide a method of determining the resistance of a bulk material without galvanic contact DC based methods. The main limitation exposed so far is specification of the equipment used for measurements which it is anticipated could not determine the impedance of deionised water or dry soil.

![Graph showing real impedance of the complex solution for the full analytical model for all bulk materials.](Figure 3.23)

**Figure 3.23**: Comparison of simulated real impedance of the complex solution for the full analytical model for all bulk materials.

### 3.8: Analytical Solution Conclusions

Analysis of the simulation parameters determined that the insulating layer must be as thin as possible to ensure its capacitance is high and does not dominate total measurement values. However, one side effect of the thin covering is the possibility of causing damage when performing laboratory based measurements. Therefore care must be taken to ensure the integrity of the insulating layer against scratches from coarse material during testing.

Analytical simulations have suggested that bulk material resistance can be estimated when a non-galvanic measurement is performed for a variety of water types and soils of varying moisture content. When the bulk material has a very high resistance, the low frequency
real impedance of the solution is a product of both the insulating layer and the bulk resistance. Simple subtraction can be performed to remove the impedance of the insulating layer, leaving only the bulk resistance. This is only possible for simulations, however, due to limitations in the maximum measurable impedance from the impedance analyser.

As resistance of the bulk material decreases below the resistance of the insulating layer, a plateau in the real impedance solution occurs across a frequency bandwidth relative to the bulk material properties. The impedance of this plateau represents the bulk material resistance, and within this plateau simulations show that bulk resistance can be estimated to within 2% of the simulation parameter value from visual observation of the spectroscopic impedance. As resistance of the bulk material further decreases, the magnitude of the plateau not only decreases accordingly, but also has an increasing shift along the frequency axis. Therefore, a bulk material with a very low resistance, such as the saline solution, will require equipment which can measure at approximately 1-2 MHz or higher. For a bulk material with an even lower resistance than saline solution, the measurement equipment will need to be capable of measurements at an even higher frequency.

The analytical solution is based on a simple electrical model, an approximation based on the parameters of two series parallel-RC networks. While a simple analytical solution exists for parallel-plate measurements, the ultimate goal is to perform measurements between electrodes on the same surface, in what is termed as adjacent-plate measurements. A simple analytical solution does not exist for adjacent-plate measurements, and therefore numerical modelling techniques must be used.

3.9: Finite Element Modelling of Insulated Electrodes

COMSOL, is an FEM software package through which the electrical properties of any physics based system can be simulated. The following sections discuss how COMSOL was used to verify the analytical solution for parallel-plate simulation data. Once verified, COMSOL was used to produce a FEM for adjacent-plate measurements which would
provide a simulated data set which could be compared to actual measurement data from the rhizotron cell. The COMSOL AC/DC electric currents physics module was used to simulate the spectroscopic admittance of the FEM model across the same range of 65 frequencies, between 1Hz – 20 MHz, as performed for the analytical calculations. As a software package, COMSOL provides values of electrical fields and voltages based on the dimensions of the FEM created and the defined electrical properties of the materials used. From the simulated voltage values, the complex electrical impedance can be calculated and plotted.

As COMSOL is a FEM software package, a model representing the parallel-plate test vessel was constructed. The model dimensions were based on those derived previously for the MATLAB analytical solution, with a 3x3 cm metal electrode, 4.6 cm electrode spacing and 75 μm insulating layer placed over the electrode. The COMSOL model features a 3 mm Perspex outer vessel, comparable to that of the actual test vessel used for measurement data. An isometric view of the COMSOL model can be seen in Figure 3.24a. Once the geometry of the FEM model is created in COMSOL, the model is converted into a mesh, seen in Figure 3.24b. The mesh is used to discretise the model into a large number of smaller elements from which the admittance of each element will be calculated. The total admittance will then be the product of the mesh elements combined. The complex admittance is then converted to impedance for analysis with a MATLAB script for easier comparison between analytical and numerical simulations.

Figure 3.24: a: COMSOL FEM model for parallel-plate test cell. b: COMSOL Mesh structure. Cell dimensions; 3x3cm electrode, 4.6cm electrode spacing and 75μm insulating layer.
COMSOL features a library of standard materials for use in the FEM. In the parallel-plate model four materials were used; copper, acrylic plastic, silicon and water. For all four materials the electrical conductivity and relative permittivity were required for the admittance to be simulated. COMSOL requires a value of electrical conductivity as the simulation parameter when using the electrostatics module, the resistance value used in the analytical simulations was converted first to resistivity and then to its inverse, conductivity. To convert resistance to resistivity the cell dimensions are required.

Since the wall resistance of 1.5 MΩ is the sum of the electrical insulating layer from both electrodes combined, the actual resistance for each wall is assumed to be half this value and therefore 750 kΩ. The separate value for each electrode is required as the COMSOL model does not combine both electrodes into a single value. For a cross sectional area of 9 cm² and layer thickness of 75 μm, the resistivity of the insulating layer was calculated to be 9 MΩ/m. Therefore the conductivity of the 75 μm thick insulating wall for a 3x3cm electrode was calculated to be 111.1x10⁻⁹ S/m and from the product datasheet the electrical permittivity is 3.56. For the first simulation the bulk material was tap water and the insulating layer was specified by the parameters previously derived. The parameters used are given in Table 3.7.

<table>
<thead>
<tr>
<th>COMSOL Material</th>
<th>FEM Model Component</th>
<th>Conductivity S/m (σ)</th>
<th>Relative Permittivity (ε_r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>Electrode</td>
<td>5.998x10⁷</td>
<td>1</td>
</tr>
<tr>
<td>Acrylic plastic</td>
<td>Vessel outer casing</td>
<td>5.5x10⁹</td>
<td>3.3</td>
</tr>
<tr>
<td>Silicon</td>
<td>Electrode insulator</td>
<td>111x10⁹</td>
<td>3.56</td>
</tr>
<tr>
<td>Tap water</td>
<td>Bulk material</td>
<td>0.0102</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 3.7: COMSOL Materials used, and associated electrical parameters. Values for a 75μm insulating layer and bulk material of tap water.
COMSOL was used to simulate the spectroscopic admittance for tap water in the cell. The numerically calculated complex impedance for a bulk material of tap water with a 75 μm insulating layer, compared to the simulated impedance from the analytical simulation with the same value of parameters can be seen in Figure 3.25. It can be seen that the numerical and analytical simulated real impedance plots are indistinguishable. Analysis of the numerical data from the simulation shows that for all frequencies the average percentage difference is 1.7% for all frequencies, with a standard deviation of only 1.3%.

![Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of tap water.](image)

**Figure 3.25:** Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of tap water. Note the two plots overlap.

The numerical analysis is a FEM simulation and as such there is a large computational demand in order to derive the complex admittance, when compared to the analytical solution. This is due to the intricacy of the model mesh which increases computational time. Modelling the insulating layer requires a very high number of mesh elements due to being very thin. The parallel-plate model is a relatively simple model, however, due to this thin insulating layer, the number of mesh elements, and subsequent simulation time, is very large at over one million mesh elements. While it is possible to simulate complex admittance for this simple model, it is not ideal as more complex models, such as the adjacent-plate electrodes as found in the rhizotron will incur increasing computational demands. For comparison, COMSOL is used to simulate an adjacent plate measurement, similar to that encountered in the rhizotron. Using a well configured PC it was found that
COMSOL was not able to simulate the complex admittance. Therefore a method was implemented to reduce the computational requirements of the COMSOL simulation. The next section discusses a technique in which the insulating layer thickness is increased in order to reduce the number of mesh elements in the FEM model.

### 3.10: Increasing Insulating Layer Thickness to Reduce Simulation Constraints

The possibility of increasing the insulating layer thickness was considered as this would significantly reduce the number of mesh elements in the model. However, if the layer thickness is increased, the electrical properties are no longer correct. Electrical parameters have also been scaled accordingly to provide the same conductivity and permittivity as a 75 μm insulating wall. COMSOL was used to determine whether scaling the insulating layer thickness was a viable method of reducing the mesh complexity for the insulating layer FEM. It would be considered a feasible technique if both the solution time was significantly reduced and simulated admittance remained accurate compared to the simulation values achieved for a 75 μm insulating layer. COMSOL simulations were performed for three wall thicknesses of; 75, 500 and 5000 μm. The scaled electrical conductivity and permittivity for all three walls are found in Table 3.8.

<table>
<thead>
<tr>
<th>Insulator thickness (μm)</th>
<th>Electrical Conductivity (σ) S/m</th>
<th>Electrical Permittivity (ε)</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>111x10⁹</td>
<td>3.56</td>
</tr>
<tr>
<td>500</td>
<td>740x10⁹</td>
<td>23.72</td>
</tr>
<tr>
<td>5000</td>
<td>7.41x10⁻⁶</td>
<td>237.2</td>
</tr>
</tbody>
</table>

Table 3.8: Scaled electrical conductivity and permittivity for 75, 500 and 5000 μm thickness insulating layer.

One of the advantages of creating a FEM is that the model parameters can be easily changed and simulations performed with simplicity. The parallel-plate vessel FEM model
and mesh structures for three insulating layer thicknesses can be seen in Figure 3.26 where it can be visually seen that increasing the insulating layer thickness significantly reduces the number of mesh elements around the electrode area.

![Fig 3.26: COMSOL FEM models and mesh structures for the parallel-plate test vessel using three values of electrode thickness; a-b: 75 μm, c-d: 500 μm, e-f: 5000 μm.](image)

### 3.10.1: Simulation Time for Increasing Layer Thickness

This section discusses the change to solution time for the COMSOL simulation for varying insulating layer thickness. If little benefit is achieved in terms of simulation time, from increasing the insulating layer thickness becomes insignificant. Table 3.9 shows the computational solution time and the subsequent number of mesh model elements for each insulating layer thickness, for a simulation of tap water in the parallel-plate test cell. The number of elements per second is
also provided, and presents a basic calculation to determine whether the number of mesh
elements and solution time is a linear relationship.

<table>
<thead>
<tr>
<th>Insulator thickness (μm)</th>
<th>Solution time (s)</th>
<th>Mesh elements</th>
<th>Elements per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>4473</td>
<td>1.07×10^6</td>
<td>239</td>
</tr>
<tr>
<td>500</td>
<td>154</td>
<td>35.8×10^3</td>
<td>232</td>
</tr>
<tr>
<td>5000</td>
<td>45</td>
<td>9.03×10^3</td>
<td>201</td>
</tr>
</tbody>
</table>

Table 3.9: Solution time, mesh elements and elements per second for a COMSOL simulation of tap water with three different thicknesses of insulating layer.

The mesh for a parallel-plate cell FEM with a 75 μm insulating layer has over one million
elements and takes approximately seventy five minutes to determine the spectroscopic admittance, compared to the thickest layer at 5000 μm, which only has 9000 elements and takes less than one minute. However, the elements per second calculation shows that solution time has an almost linear relationship with the number of mesh elements. For the most complex mesh structure the computer is capable of solving 239 elements per second, compared to 201 for the simplest mesh. While not absolutely linear, it shows that the COMSOL method of calculating the complex admittance is predominantly dependent on the number of mesh elements. It appears that the complex admittance is no more difficult to determine for a large mesh, but that the increased solution time is predominantly due to the increase in number of mesh elements. With a significant time advantage achievable for using a thicker insulating layer, the following section discusses the accuracy of the complex admittance for the increased thickness layers when compared to the original 75 μm layer.

3.10.2: Change in Accuracy for Increasing Layer Thickness

It has previously been determined that the values of impedance for both analytical and numerical simulations were in good agreement for a bulk material of tap water. Therefore, this section only discusses the change in simulated impedance for 500 and 5000 μm
insulating layer thickness when compared to data from 75 μm simulations. Therefore, the 75 μm simulation data is considered as the standard, against which the percentage difference will be considered, and referred to as the percentage error.

Figure 3.27 shows the simulated spectroscopic impedance for all three insulating layers for frequencies between 1 Hz – 20 MHz. The real impedance for the 75 and 500 μm plots overlap and are difficult to distinguish while the real impedance of the 5000 μm plot is slightly less at low frequencies, but in the plateau region also overlaps the 75 and 500 μm plots. Analysis of the numerical data from the simulation was performed to determine the percentage error at each frequency between the three layers, and also determine the standard deviation of the population of the error percentages between insulating layers. The average error between the 75 and 500 μm thickness layer was 0.8%, with a standard deviation of 0.91% while the average error between the 75 and 5000 μm layer was 4.9 %, with a standard deviation 5.56%.

Figure 3.27: COMSOL simulated real impedance for three insulating wall thicknesses. Note that the 75μm curve is not visible as it overlaps almost exactly with the 500μm curve.

Considering the calculated error percentage, standard deviation and simulation time, the 500 μm insulating layer appears to be a good substitute for the 75 μm layer. Using a 500 μm layer, the accuracy compared to the 75 μm layer is within 1%, while reducing the solution time by 96%. While the 5000 μm layer offered an improved simulation time over
the 500 μm layer, it was felt that the reduced accuracy between 500 and 5000 μm was too large for the benefit gained in simulation time. Therefore, for all future simulations a 500 μm insulating layer is used for the electrode layer.

3.11: COMSOL FEM Simulation for Varying Bulk Materials.

With the FEM simulation parameters determined for the insulating layer, this section discusses the numerical simulations performed for varying bulk materials. The same bulk materials used in analytical simulations are here used to allow comparison between both the analytical and numerical simulations. The electrical properties for the six bulk materials are again provided in Table 3.10 for reference. The previously calculated values of capacitance and resistance for each of the six bulk materials have been converted to conductivity and permittivity for the numerical simulations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (S/m)</th>
<th>Permittivity ($\varepsilon_r$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.0102</td>
<td>80</td>
</tr>
<tr>
<td>Tap water</td>
<td>$5.496 \times 10^{-6}$</td>
<td>80</td>
</tr>
<tr>
<td>Saline solution</td>
<td>5.011</td>
<td>80</td>
</tr>
<tr>
<td>Dry soil (0%)</td>
<td>$1.111 \times 10^{-6}$</td>
<td>3.98</td>
</tr>
<tr>
<td>Moderate soil (14%)</td>
<td>$1.111 \times 10^{-3}$</td>
<td>24.9</td>
</tr>
<tr>
<td>Saturated soil (28%)</td>
<td>0.022</td>
<td>30.0</td>
</tr>
</tbody>
</table>

Table 3.10: Calculated conductivity and resistance and capacitance values for all simulation parameters for the analytical solution.

If both analytical and numerical simulations are in agreement for the test cell, then it is suggested that COMSOL is suitable for exploring adjacent-plate measurements, which the analytical solution is unable to achieve. The simulated impedance from the FEM solution of the adjacent-plate formation of electrodes would provide a reference value for comparison between simulations and results of laboratory rhizotron testing. A COMSOL reference value would be used to provide confidence in expected results.
Figure 3.28 shows a comparison plot for the simulated real impedance of the saline solution from both a numerical and analytical solution. It can be seen that the real impedance is in very good agreement, with the plots overlaying each other. Analysis of the simulated data shows that the average percentage difference between both simulations is 2%, while the standard deviation of all frequencies is 1.4%.

![Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of saline solution.](image)

**Figure 3.28: Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of Saline Solution.**

![Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of sea water.](image)

**Figure 3.29: Comparison of MATLAB and COMSOL simulated real impedance. Bulk material is dry soil.**
Figure 3.29 shows the simulated real impedance again for both analytical and simulated, using dry soil as the bulk material. At frequencies below 20 kHz, they are in good agreement, and the simulated plots overlap. However, above 20 kHz the suggested real impedance from the analytical simulation is greater than that from the numerical simulation. It was previously discussed that this section of the plot is determined by the capacitance of the bulk material, and therefore its relative permittivity. Both analytical and FEM simulation parameters were checked for correctness and found to be accurate. Therefore, either the analytical or the FEM simulation is slightly incorrect with regards to high frequency impedance for dry soil. It should also be considered that it is likely that both the analytical and FEM solution are slightly incorrect. It is impossible to determine which is most correct with the limited electrical model used, however, this is not a large concern as the bulk material resistance is not estimated within this region. For completeness, empirical modelling was performed to determine the value of permittivity which would cause the two simulations to overlap. It was found that adjusting the value of relative permittivity in MATLAB from 3.98 to 5 would decrease the impedance to match that from COMSOL numerical simulation.

The comparison of real impedance for both analytical and FEM simulations, for all four of the remaining bulk materials, show a similar percentage difference margin to that shown for the saline solution and are not therefore plotted. However, the difference percentage and standard deviation for all six bulk materials can be seen in Table 3.11. For all simulation parameters, except dry soil, the difference between analytical and numerical simulation data is less than 3%, showing excellent agreement. It is currently unknown why the dry soil values are so different between simulations. Simulation parameters were confirmed to be correct, yet still a large difference between simulated values exists.
Since both the MATLAB and COMSOL simulations for five of the six bulk materials are within 3% error, disregarding dry soil, several conclusions can be drawn. First, the analytical solution can be considered accurate enough to provide a rapid simulation of expected spectroscopic impedance with relatively little computational power or simulation time compared to the COMSOL FEM method. Secondly, the COMSOL simulation provides confidence in its ability to determine complex admittance for a bulk material placed behind an insulated electrode. Therefore, the FEM model can be modified to explore adjacent-plate measurements, typical of those required for the rhizotron. The next section considers the use of COMSOL to determine the spectroscopic admittance of various bulk materials when placed in a cell that is representative of a rhizotron.

### Table 3.11: Percentage difference and standard deviation % between MATLAB and COMSOL simulations for all six bulk materials.

<table>
<thead>
<tr>
<th>Bulk material</th>
<th>% Difference between MATLAB and COMSOL</th>
<th>Standard deviation % between MATLAB and COMSOL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Distilled water</td>
<td>1.1</td>
<td>2.5</td>
</tr>
<tr>
<td>Saline solution</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Dry soil</td>
<td>20.6</td>
<td>24.6</td>
</tr>
<tr>
<td>Moderate soil</td>
<td>2.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Saturated soil</td>
<td>2.6</td>
<td>1.7</td>
</tr>
</tbody>
</table>

3.12: Comparison of 3x3 and 4x4 cm² Test Cell in COMSOL.

The analytical solution depends on a parallel-plate relationship between both the electrodes and the bulk material, and assumes a vessel with electrodes equal in cross-sectional area to that of the bulk material. However, it was impractical to construct a physical test cell with an internal cross-sectional area matching the electrode surface area due to the possibility of compromising the insulating layer on the electrodes. The insulating layer is tough, however, does suffer from brittleness. When the electrodes were cut to size
it was determined that the test cell should have a 0.5 cm border around the perimeter to ensure the insulating layer was not compromised. This change resulted in a test cell with an internal cross-sectional area of 4x4 cm, compared to the simulated cell of 3x3 cm. From here the two test cells will be referred to as the 3x3 and 4x4 cell, with the FEM of the 4x4 cell shown in Figure 3.30. This section discusses the simulated impedance, based on the FEM solution, for both the 3x3 and 4x4 test cells. The simulated values will then be compared to data from measurements taken in the actual test cell for a bulk material of tap water.

Despite the difference of only 0.5cm around the periphery of the electrode, the 3x3 test cell has a volume of 41.4 cm$^3$, compared to 73.6 cm$^3$ for the 4x4 test cell, an increase of approximately 180%. Therefore, it was expected that such a large difference in volume would be reflected in a measurable change in impedance. Figure 3.31 shows the plotted spectroscopic real impedance for both test cells. At lower frequencies the real impedance is very similar, due to the impedance of the insulating wall being unaffected by the larger test cell volume. However, the plateau region for the 4x4 cell has a lower value of impedance than the 3x3 cell. This is to be expected since a larger volume of water will allow more current to flow between electrodes, and result in a lower resistance.
The simulated impedance for the 3x3 cell was within 2% of the parameter value of 5 kΩ for tap water within the plateau region. For the 4x4 cell, the simulated impedance in the plateau region was averaged to be 37% less than the parameter value of 5 kΩ, at approximately 3 to 3.3 kΩ. However, the plateau region is still clearly seen, and from which a bulk resistance value can be acquired. While this value may not be the absolute impedance, it may be used to determine the changes in resistance over time relative to this initial value. Despite the difference in values of impedance, the simulation for both sizes of test vessel are in good agreement. While the value of the impedance in the plateau region is lower, the spectroscopic response is similar in shape and magnitude.

Figure 3.31: Comparison of real impedance for a 3x3 and 4x4 cm² test cell with tap water as the bulk material.

Figure 3.32 shows a plot of the measured real impedance compared to the simulated impedance for the 3x3 and 4x4 cell. It can be seen that the plateau region is closest matched to the 4x4 cell, showing that the FEM simulation for a 4x4 cell is more accurate than the 3x3 cell. It can also be seen that the spectroscopic impedance is different at low frequencies, with the measured impedance at 300 Hz being lower than both the 3x3 and 4x4 simulations, suggesting that the actual capacitance of the wall differs from the simulated value. It can also be seen that when the impedance at the plateau begins to decrease, the measured impedance values decrease at a faster rate than the simulated values. This again suggests that the capacitance value of the bulk material for simulations is
slightly incorrect. However, the overall trend of the measured data does closely follow that of the simulation, and a definite plateau region can be clearly seen.

The following section considers the use of COMSOL to simulate the complex impedance for the previously used six bulk materials, but in a FEM model which replicates a small section of the rhizotron test vessel.

![Comparison of COMSOL simulated real impedance and actual measurement data for varying test cell cross-sectional area. Bulk material of tap water.](image)

Figure 3.32: Comparison of 3x3 and 4x4 COMSOL simulated real impedance with measured real impedance of tap water. Measurements performed with HP 4192A impedance analyser between 10 Hz to 13 MHz. Measurement plateau region estimated to be 100 kHz to 1 MHz.

3.13: FEM Simulations for Adjacent-Plate Electrodes.

For adjacent plate electrodes there is no simple analytical solution. The aim of this part of the work was to construct a FEM model based on the rhizotron measurement system and simulate the complex impedance for adjacent electrodes for all six bulk materials previously used. This would provide a typical impedance signature to which future measurements can be compared.

A FEM model was created for a single pair of adjacent-plate electrodes, based on the dimensions of the rhizotron measurement system. The electrode surface area was identical
to that of the parallel-plate, at 3x3 cm². Electrode spacing was 2cm between electrode boundaries, and the rhizotron cell depth was 2.8cm. The model does differ slightly compared to the actual rhizotron cell, since a 500 μm insulating layer is used for simulations instead of the actual 75 μm layer. The FEM created to represent the rhizotron measurement system can be seen in Figure 3.33.

![Figure 3.33: COMSOL FEM for an adjacent-plate measurement, dimensions based on the rhizotron measurement system.](image)

Figure 3.34 shows the spectroscopic impedance derived from the FEM simulated admittance of tap water for both parallel-plate and adjacent-plate electrodes. It can be seen that at lower frequencies the parallel- and adjacent plate methods provide excellent repeatability, as expected since low frequency impedance is typically a result of the wall impedance only. However, above approximately 6 kHz the real impedance that is extracted from the adjacent-plate simulation is smaller than that of the parallel-plate. The real impedance in the plateau region for the parallel-plate simulation is approximately 5 kΩ compared to 3.4 kΩ for the adjacent-plate simulation. This equates to an inaccuracy of approximately 30% in the plateau-region.
The aim of simulating spectroscopic impedance was to determine and understand the behaviour of the insulated electrodes in the rhizotron. The simulation identifies a curve similar in shape to that found with parallel-plate simulations which suggests that capacitively coupled measurements can be used to determine the resistance. In parallel-plate simulations the real impedance in the plateau region mirrors the simulation parameter of $R_B$ to within 2%, while the adjacent-plate simulations appear to be 30% inaccurate, assumed due to the adjacent electrode formation. The inaccuracy between parallel- and adjacent-plate measurements may be constant, upon which a scaling factor could be applied to all adjacent-plate measurements to determine the resistance of the bulk material if required. If no scaling factor can be applied, the value of impedance in the plateau region for adjacent-plate measurements can still be used to determine a relative value of resistance from which changes over time can be measured.

Parallel-plate simulations, for a bulk material with very high resistance, showed a significantly different spectroscopic signature, with the low frequency impedance being the sum of both the insulating layer and bulk material. Distilled water and dry soil both show a similar spectroscopic response due to their high value of resistance. Figure 3.35 shows the spectroscopic real impedance of distilled water for both parallel- and adjacent-plate COMSOL simulations. The spectroscopic impedance shows a similar profile for both parallel- and adjacent-plate simulations, again suggesting that the resistance of the bulk
material could be estimated in the rhizotron test cell. Numerical data analysis shows that the average percentage difference between adjacent and parallel-plate in the plateau region is 31%, very similar to that of the tap water.

For simulated tap water, Figure 3.34, the difference between parallel- and adjacent-plate measurements is only significant within the plateau region, however, in Figure 3.35 it can be seen that the spectroscopic real impedance for the adjacent-plate measurements is always less than that of the parallel-plate. This is because the impedance is the combination of two sections in series, the impedance of the insulating layer and bulk material. For tap water, the resistance of the bulk material resistance is significantly lower than that of the insulating layer, and therefore never has a significant effect. As such the low frequency impedance is predominantly due to the wall and at higher frequencies it is due to the bulk. For distilled water, the bulk resistance is so high that at all frequencies the total impedance is significantly influenced by the bulk material. As previously explained, for bulk materials of very high resistance, if the resistance of the insulating layer is subtracted from the total impedance at lower frequencies, the bulk material resistance can be determined. Therefore, a plateau region can still be estimated as the region before which the real impedance begins to decrease, approximately 1 to 300 Hz.
The simulated impedance plots for the remaining four bulk materials are not plotted, however, they all show a similar trend in that the value of impedance in the plateau region is approximately 30% lower for adjacent plate than parallel-plate. The actual difference in percentage between parallel- and adjacent-plate simulations can be seen in Table 3.12.

<table>
<thead>
<tr>
<th>Bulk Material</th>
<th>Average % Difference in Plateau Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap water</td>
<td>30.3</td>
</tr>
<tr>
<td>Distilled water</td>
<td>31.0</td>
</tr>
<tr>
<td>Saline solution</td>
<td>30.6</td>
</tr>
<tr>
<td>Dry soil</td>
<td>38.0</td>
</tr>
<tr>
<td>Moderate soil</td>
<td>32.5</td>
</tr>
<tr>
<td>Saturated soil</td>
<td>33.7</td>
</tr>
</tbody>
</table>

Table 3.12: Average percentage difference between parallel- and adjacent-plate real impedance within the plateau region for all six bulk materials. FEM simulation data.

Despite this difference in the value of impedance, the decrease in resistance in the plateau region is somewhat constant. It is also worth considering that while the scaling factor may fluctuate at approximately 30-38%, real tests on soil will suffer from such heterogeneity that this scaling range may become insignificant. Even with the same soil type used the structure and porosity of the soil can vary significantly which will result in unpredictable conductivity through the soil as the structure will allow for multiple current paths, each unique. However, as has been previously mentioned the method of measuring resistance of the bulk material is still very much applicable to relative measurements performed over time in which the resistance changes in the soil can be attributed to changes in soil moisture.

### 3.14: SMP Graphical User Interface

It was previously discussed how empirical modelling could be used to fit the simulation parameters from measurement data for the insulating wall. Empirical modelling can be very time consuming due to the requirement to change parameter values between
simulations. Therefore a MATLAB GUI was created to decrease the time constraints of empirical modelling. The GUI was named Simulation Model Parameters (SMP) as it allowed the rapid changing of simulation parameters to empirically determine simulation values which provided a spectroscopic impedance which best matched measurement data.

Four parameters are used for the MATLAB analytical solution, $R_W$ and $R_B$ for the resistance of the insulating layer and bulk material respectively, and $C_W$ and $C_B$ for their capacitance. A screenshot of the SMP GUI is seen in Figure 3.36. The main plot section shows the simulated and measured spectroscopic impedance, while the four variable boxes on the right hand side are used to adjust the parameter values. Slider bars are also used to allow the user to increase or decrease the parameter values without the requirement to enter specific numeric values.

From the empirically derived values of complex impedance, the electrical conductivity and permittivity of the test data can be calculated.

![SMP GUI](image)

*Figure 3.36: SMP GUI created to allow empirical modelling and rapid analysis of effects of changing simulation parameter values.*

The SMP GUI uses a series of functions to create a live updating plot of simulated impedance as the user adjusts parameter values, seen by the red, solid line plot. The second plot is actual measurement data which the user must manually add to an array
within MATLAB, and is plotted as the blue hashed line. This measurement plot then becomes the base value, to which the user adjusts the simulation parameters until both overlap. Once both plots overlap, the simulation parameters will indicate the estimated values of the resistance and capacitance of both the insulating layer and bulk material. An example of empirically fitted data can be seen between Figures 3.36 and 3.37. While the data has been fitted, it is also clear that there is some discrepancy between measured and simulated data which is impossible to eliminate due to the simplicity of the electrical model. However, while the electrical model cannot provide a spectroscopic impedance identical to the measurement data, it can still be fitted enough to estimate the bulk material electrical properties with confidence, which is discussed in more detail in chapter 5.

Figure 3.37: SMP GUI with simulation data empirically fitted to measurement to determine electrical properties.

As was previously discussed, the plateau region is determined by the bulk material resistance, while the high frequency roll-off is determined solely by the bulk material capacitance. Therefore, from the empirical fitting, both the resistance and capacitance of the bulk material can be determined. If only the plateau region was considered, only the bulk material resistance could be estimated. While the bulk material resistance will provide a good indication of moisture content in soil based measurements, it will also be a function of parameters such as temperature, compaction, salinity and more. However, knowledge of...
the capacitance of the bulk will allow the calculation of the relative permittivity of the soil, which in soils is largely dependent on moisture content also since the relative permittivity of water is so large compared to that of soil.

The SMP GUI was also utilised several times during both the simulation and measurement period in which plotted data appeared incorrect. It was successfully used to provide a rapid analysis of the data and lead to correction of simulation parameter values if and when required. The SMP GUI proved invaluable as a rapid-simulation technique to determine both the effects of parameter changes and basic empirical modelling to allow the estimation of both the resistance and capacitance of the bulk material, something which regular modelling techniques could not achieve. Having the GUI also significantly reduced the time taken to understand the electrical model and correct or diagnose suspected errors in simulation parameters. The code for the GUI can be seen in appendix A1.2.

3.15: Using FEM to determine the region of influence and conductivity of soil from rhizotron test data

The thesis presents a technique for measuring impedance using electrodes having a thin insulating layer to counter the effects of polarisation. The aim has been to apply this to the estimation of water content in soil. Initial studies have involved measurements using a small rhizotron. Although these reveal sensitivity to moisture content, as presented in subsequent chapters, the results are “single point” and assume uniform conductivity distribution between each pair of adjacent electrodes. Future work will consider tomographic measurements which aim to identify conductivity distributions. This section addresses the interpretation of the impedance measurements in terms of the material properties in the region of a pair of electrodes. Firstly, what region is interrogated by a pair of electrodes in the x, y and z axes? Then, knowing this, what impedance value is measured for a given uniform conductivity within the region of influence. With this information the measured impedance can be calibrated to suggest the conductivity between each pair of electrodes, assuming uniform distribution. Finally, the effects of localised areas of contrasting conductivity are explored to determine the sensitivity to such areas, as real-
world tests in soil will feature inhomogeneities. Preliminary results from Finite Element Modelling (FEM) are presented.

COMSOL Multiphysics software and the associated ‘AC/DC – Electrostatics’ physics module has been used to explore the region of influence of a pair of adjacent measurement electrodes in the rhizotron. Figure 3.38 demonstrates an example of the COMSOL simulation results for adjacent electrodes on the wall of the rhizotron in a 2-layer arrangement. The layer closest to the electrodes has a low conductivity and the area farthest from the electrodes has a higher conductivity. The arrows display the current density, demonstrating that in areas of higher conductivity the current flow is more significant. The colour scale represents potential distribution, with the injection electrode having a value of 1V. For this example red represents a higher voltage, which varies through green towards blue which represents a potential of 0V. For the present results the “x” and “z” axes are indicated. The “y” axis is directed out of the page. As can be seen the current flows from the region of high potential near the left hand electrode, through the material and into the right hand electrode. For the rhizotron the field in the “z” direction is restricted by the upper, insulating, wall at a distance of 2.7 cm above the electrodes. However, in the “x” and “y” directions there is no barrier in the immediate vicinity. The aim of the present section is to explore how close material changes must be to have a significant influence on the measured impedance and therefore determine the ‘region of influence’ from adjacent-plate electrodes.

For all simulations a frequency of 1MHz has been assumed. This frequency was selected as it is the same frequency used during rhizotron testing. For determining the region of influence three values of electrical conductivity have been assumed as shown in Table 3.13. For all simulations “tap water” was selected as the primary bulk material and localised
areas of High and Low conductivity were introduced to determine the region in which they had an effect on the measured impedance.

<table>
<thead>
<tr>
<th>Region</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$5 \times 10^{-6}$</td>
</tr>
<tr>
<td>Tap Water</td>
<td>0.0255</td>
</tr>
<tr>
<td>High</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.13: Values of electrical conductivity used during FEM simulations to determine region of influence for adjacent-plate measurements.

The first section of this work provides results of simulations performed to determine the region of influence for adjacent-plate measurements. It explores the regions of influence in the x, y and z axes and attempts to approximate the volume around the electrodes which is interrogated during measurements. To explore the effect of material changes in the x, y and z directions, several models were created which allowed a boundary between different conductivities to be moved in 1cm intervals towards the electrodes. For the “x” direction, this was set to a distance of 15cm from the mid-point between the electrodes, illustrated in Figure 3.39, where an example layer is located at 12cm from the centre point between electrodes.

![Figure 3.39](image-url)

Figure 3.39: Model used to explore sensitivity as a boundary between different conductivities is moved along the X-axis. Contrasting layer set to 12cm from centre point of electrodes.
Figure 3.40 shows results of the predicted conductance between pairs of electrodes for different positions of the boundary. Tap water is the bulk material and results are shown for both Low and High conductivity materials beyond the boundary. The simulated conductance for a homogeneous vessel of only tap water is presented as a reference. In both cases the results suggest that beyond 5cm from the mid-point between the two electrodes the different material has negligible effect on the conductance. This equates to a distance of 1cm beyond the outer edge of an electrode which is also the mid-point in the gap between the next electrodes within the complete array of electrodes. Therefore, in the “x” direction, the region of influence is approximately bound to the volume of the electrodes under test, and material between neighbouring electrodes should have no measurable effect on impedance.

![Figure 3.40: Effect on conductance due to High and Low impedance materials being introduced along the x-axis. Marker demonstrates distance where contrasting layer has no measurable effect.](image)

The following section discusses the effect of material changes in the “y” direction, again based on a moving boundary of contrasting conductivity, to determine the region of influence. Due to the formation of the electrodes it was expected that the region of influence would differ in the x and y directions. It was proposed that in the y-direction the region of influence would extend outwards further than that experienced in the x-direction. The model created is seen in Figure 3.41, where an example layer is presented at a distance of 16 cm from the centre point of the electrodes. As with previous tests, the boundary layer
was moved in 1 cm increments from the centre point of the electrodes to a distance of 21 cm. As before, a reference conductivity of tap water was again used, and two tests were performed with values of high and low contrasting conductivity to determine the distance at which they influence the simulated impedance.

Figure 3.41: Model used to explore sensitivity as a boundary between different conductivities is moved along the Y-axis. Contrasting layer set to 16cm from centre point of electrodes.

Figure 3.42 shows results of the simulated conductance for different positions of the boundary. The reference value for homogeneous tap water is also presented. For both high and low conductivities the results suggest that along the y-axis, beyond 7cm from the mid-electrode point, the different material has negligible effect on the conductance. This equates to a distance of approximately 5cm from the edge of the electrode, a much greater distance than experienced in the x-axis. This was expected due to the nature of the current flow in the y-axis between electrodes, as is seen in figure 3.43, where the simulated current density arrows and potential distribution demonstrate that the current flows outwards from the electrodes extending further into the y-axis direction. A region of influence of approximately 5cm from the electrode edge means that in the rhizotron test vessel, where electrodes have a 3cm surface area and a 2cm spacing, the sphere of influence extends to the outer edge of the neighbouring electrode. The 5cm distance is highlighted in figure 6.
Figure 3.42: Effect on conductance due to High and Low impedance materials being introduced along the y-axis. Marker demonstrates distance where contrasting layer has no measurable effect.

Figure 3.43: Demonstrating the electric field in the y-axis. Boundary set at 5 cm from edge of electrodes and demonstrates the region of influence.

The previous two tests demonstrated that in the x-axis, the region of influence is approximate to 1 cm from the edge of the electrode, while in the y-axis, the region extends...
as far as 5cm. The final simulations to determine the region of influence consider the z-axis, the direction above the electrodes. In this direction the vessel limits the volume, due to the physical construction. To explore the effect of material changes in the “z” direction a model was created that allowed a boundary between contrasting conductivities to be positioned at distances of 0.7 cm, 1.4 cm and 2.1 cm from the surface of the electrodes. Larger distances were not explored as this is beyond the physical size of the present rhizotron. The model is shown in Figure 3.44, with an example layer placed at 2.1 cm from the electrode surface.

Results are shown in Figure 3.45. These confirm that as the boundary moves away from the electrodes the influence of the contrasting material reduces, as expected. At the maximum extent that is possible in the rhizotron it can be seen that changes in the conductivity of the material still have an effect on the measurements. Therefore it is concluded that the electrodes probe the entire space that is directly opposing them in the z-direction.
Simulated data suggests that the region of influence extends approximately 1 cm from the electrode edge in the x-direction, 5 cm in the y direction, and 2.7 cm in the z direction. Therefore, as an approximation, the volume of the region of influence which occurs from adjacent-plate measurements is $10 \times 13 \times 2.7$ cm in the x, y, and z axes respectively with a volume of $351 \text{cm}^3$, and can be seen located within a section of the rhizotron vessel in figure 3.46.
The model enables visualisation of the region which is interrogated during measurements. It can be seen that in the x-direction, measurements will not overlap with adjacent sets of electrodes, however, in the y-direction, the volume of soil measured will be ‘interrogated’ by two sets of measurements, from neighbouring electrodes. In the z direction, there are no sets of electrodes to influence the measurement data, however, the bounding nature of the rhizotron stops the sphere of influence extending beyond 2.7cm.

The next section of work considers the use of FEM to enable estimation of electrical conductivity of the bulk medium based on correlating simulated values of impedance against measured values acquired from rhizotron testing. Since there is no simple relationship available for converting measured electrical impedance to electrical conductivity for adjacent-plate electrodes, it was proposed that FEM can be used to relate a value of measured electrical impedance to a value of conductivity using simulated values, assuming a homogeneous medium under test. To achieve this, ten simulations were performed on a vessel featuring adjacent-plate electrodes. For each simulation the electrical conductivity of the bulk material varied. The range of electrical conductivities simulated were 0.001 – 0.028 S/m, with a step size of 0.003 S/m, chosen as they represent typical values of conductivity experienced in wetted soil. The resulting values of simulated electrical impedance could then be related to actual test data from the rhizotron measurement system to allow estimation of electrical conductivity within the rhizotron. It was suggested above that the region of influence extended 1 cm from the outer edge of the electrodes in the x-axis, 5 cm in the y-axis and 2.7cm in the z-axis. Therefore, a FEM of a new test cell was constructed matching this volume, with a single pair of electrodes, and can be seen in figure 3.47.
Figure 3.47: New test vessel with a volume representing the region of influence around the electrodes.

Figure 3.48 shows the simulated value of electrical conductance for ten electrical conductivities. However, since the conductivity will be estimated from values of impedance, the values were also converted to impedance and are shown in the same figure. It can be seen that as electrical conductivity increases, electrical impedance decreases, as expected. However, the relationship between electrical conductivity and impedance is not linear, but instead the change in electrical impedance decreases with increasing conductivity. With the simulated values of electrical impedance known, they can now be correlated from measured values in rhizotron testing to estimate electrical conductivity from electrical impedance.
To further explore the correlation of electrical impedance to conductivity, a sample data set of measured electrical impedance, acquired from the rhizotron test data over a period of 42 days, was considered and is presented in Figure 3.49. The data were taken from a vessel which was wetted to saturation and dried over a 42 day period due to plant water extraction. Therefore it represents a typical set of values experienced during rhizotron testing. It can be seen that over the period of 42 days impedance increases from approximately 1 kΩ to 25 kΩ as the soil dries. The second plot in the figure shows the simulated values of impedance from FEM for ten given conductivities. It can be seen that for the ten simulated conductivities the simulated impedances very closely match those experienced during plant growth tests within the rhizotron. From the figure it is possible to estimate the relationship between simulation points and from these calculate the value of electrical conductivity of the soil for all measurements after day 14. Prior to this point the soil conductivity is too high since the soil is saturated, and simulated values of impedance do not extend to these limits. Further simulations may extend the range of conductivities used, or conclude that the soil of most interest is the drier soil where water shortages may occur.
Two example estimations were performed to demonstrate the technique and are also shown in Figure 3.49. For measurement ‘1’, the measured value of impedance at day 19 was 8.58 kΩ. This value is correlated against that simulated, which returns a value of electrical conductivity of approximately 0.0045 S/m. For measurement ‘2’, the measured value of impedance at day 16 was 4.25 kΩ, which is estimated to correspond to an electrical conductivity of 0.01 S/m. The ability to estimate values of electrical conductivity allows us to estimate the material property of the soil independent of dimensions which will improve the ability to compare measurement data with theoretical data from other sources. Only ten electrical conductivities were simulated in FEM which provides a coarse relationship, however, it suggests that FEM can be used to help estimate values of electrical conductivity from measured values of electrical impedance in the rhizotron. In order to improve the technique more FEM simulations would be performed on a wider range, and smaller step size, of electrical conductivity.

Figure 3.49: Plot of Simulated electrical impedance for ten values of conductivity, and a plot of measured impedance over a 42 day period. Values of simulated impedance can be used to backwards estimate values of electrical conductivity, two examples shown.
The final research in this section explored the effect of localised conductivity contrast within the region of influence. Within the measurement vessel each pair of electrodes interrogates the region of influence and, in the absence of techniques such as those associated with tomography, it must be assumed that in each region the material is homogeneous. Areas of contrasting conductivity were only used to determine the region of influence. In real-world soil tests, the bulk medium would be inhomogeneous, featuring many areas of localised conductivity. This section attempts to establish what effects localised contrasting areas of conductivity may have on values of impedance in order to estimate an ‘error’ value. In order to achieve this, a new FEM test vessel, Figure 13, was constructed which featured a small object of dimensions 3x3x2.7cm positioned in three locations. The aim was to determine what effect the localised area of conductivity change would have on simulated impedance compared to that of a homogeneous medium.

The small cube had a volume of 24.3cm³, approximately 1/14th of the overall volume of the test vessel. For each position of the cube a set of simulations were performed. For all simulations, the bulk medium conductivity was set to that of tap water and the conductivity of the cube was adjusted between a range of ten conductivities. The same range of conductivities as shown in Figure 12 was used; 0.001 – 0.028 S/m, in 0.003 S/m steps, again chosen as they are typical values that may be experienced in wet soil. The simulated impedance for a homogenous test vessel filled with tap water was found to be 2.14 kΩ. FEM data were used to determine the change to this value due to the presence of the cube in various locations and at different conductivities. For the three positions of the cube, position 1 placed the cube directly between electrodes, figure 3.50. In position 2 the cube was placed between the electrodes and edge of the vessel in the y-direction. The cube was 1cm spacing from both the electrode edge and the edge of the vessel. In position 3 the cube was placed directly against the outer edge of the vessel, and therefore a 2cm distance from the electrode edge in the y-direction. Therefore, the cube was expected to have the largest influence in position 1 and the least influence in position 3.
Figure 3.50: Model used to explore sensitivity to localised regions of conductivity contrast, cube of localised conductivity in Position 1

Figure 3.51 shows plots of impedance for the test vessel featuring a localised contrasting cube at ten conductivities in all three positions. It also includes a plot to demonstrate the reference impedance for a homogeneous vessel filled with tap water. When the cube was set to a low value of conductivity, the expected effect was that impedance would be greater than the reference value. As the conductivity of the cube approached that of the bulk medium it was expected to have less influence, and as the conductivity of the cube exceeded that of the bulk medium it was expected to further decrease the impedance beyond the reference value. It can be seen that the cube location having the greatest influence is position 1, which is directly between the electrodes. In this location, when the cube has a low conductivity, the reduction in impedance is approximately 700 Ω, an increase in impedance of approximately 33%. At its most conductive, the cube results in an impedance of 2.07 kΩ, a reduction in impedance of approximately 4% against homogeneous. As expected, in positions 2 and 3 the cube has a much smaller effect on the value of impedance. At the lowest conductivity, in position 2, the cube causes an increase in impedance from 2.14 kΩ to 2.17 kΩ, approximately 1.4%. As the conductivity of the cube tends towards that of the bulk medium this effect decreases further.
Table 3.14 presents all values of impedance and the percentage difference between homogeneous and that from the inclusion of a contrasting cube. The percentage difference from the homogeneous value is here described as the ‘error’ since the localised conductivity is providing a value of impedance different from that experienced for a homogeneous test. The maximum error was 35%, when the cube was placed directly between electrodes and its conductivity was very low compared to that of the test medium. However, it could be argued that in position 1 the cube of contrasting conductivity is directly within the intended field of measurement, and not an artefact outside the electrode measurement area. In position 2 and 3 the cube represents an undesired area of contrasting impedance, but one which will still affects measurement data. In these positions the maximum error simulated was 3%, a small difference. Further research will continue to determine the effect of the cube in an increased set of locations within the vessel to further improve the knowledge of inhomogeneous conductivities.
<table>
<thead>
<tr>
<th>Conductivity of Cube (S/m)</th>
<th>Position 1</th>
<th>Position 2</th>
<th>Position 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Imped. (Ω)</td>
<td>Error (%)</td>
<td>Imped. (Ω)</td>
</tr>
<tr>
<td>0.001</td>
<td>2858</td>
<td>-35.1</td>
<td>2178</td>
</tr>
<tr>
<td>0.004</td>
<td>2639</td>
<td>-24.8</td>
<td>2155</td>
</tr>
<tr>
<td>0.007</td>
<td>2478</td>
<td>-17.2</td>
<td>2138</td>
</tr>
<tr>
<td>0.010</td>
<td>2360</td>
<td>-11.6</td>
<td>2126</td>
</tr>
<tr>
<td>0.013</td>
<td>2275</td>
<td>-7.6</td>
<td>2117</td>
</tr>
<tr>
<td>0.016</td>
<td>2211</td>
<td>-4.5</td>
<td>2110</td>
</tr>
<tr>
<td>0.019</td>
<td>2162</td>
<td>-2.2</td>
<td>2104</td>
</tr>
<tr>
<td>0.022</td>
<td>2124</td>
<td>-0.5</td>
<td>2099</td>
</tr>
<tr>
<td>0.025</td>
<td>2093</td>
<td>1.0</td>
<td>2095</td>
</tr>
<tr>
<td>0.028</td>
<td>2072</td>
<td>2.0</td>
<td>2092</td>
</tr>
</tbody>
</table>

Table 3.14: Simulated values of electrical impedance for all three positions of the cube, and the error percentage difference against the reference impedance of 2.14 kΩ.

In conclusion, real-world testing within the rhizotron vessel will perform measurements on adjacent pairs of electrodes which will feature multiple areas of localised conductivity contrast. Therefore the region of influence, and the effects of localised contrasting conductivities should be understood. In this work it was found that the region of influence extends 1cm in the x-axis, 5cm in the y-axis and 2.7cm in the z-axis from the electrode edges. It was also determined that knowledge of simulated values of impedance can assist with correlating measured values of impedance to dimensionless electrical conductivity. This is advantageous as it provides knowledge of the materials electrical property. Finally, through a small sample of FEM testing it was determined that localised areas of conductivity do have an effect on the measured impedance, which make it difficult to determine absolute values of conductivity. To overcome the limitations of such effects, one could consider the use of techniques utilised in tomography, particularly electrical resistivity tomography, using multiple electrode excitation patterns to estimate both the sensitivity of the measurement protocol, and a varying electrode excitation strategy to better understand the bulk medium. Such techniques were covered in the literature review, where it was discussed that despite the improved results which can be obtained, they come at an expense of increased complexity. It should also be considered that the rhizotron vessel, with a planar-array of electrodes is not ideally suited to a tomographic
application. However, future work would consider the possibility of utilising smaller electrodes in order to increase the possibility of tomographic techniques in order to better estimate the spatial impedance distribution within the rhizotron.

3.16: Conclusions to FEM Simulations

This chapter has discussed the use of two software packages, MATLAB and COMSOL, to determine the simulated spectroscopic impedance of capacitively coupled measurements in both the parallel- and adjacent-plate formation. The simulated values are used to determine whether the insulated electrode technique can be used to determine bulk material resistance, and if so, the limits of operation for the technique. Once confirmed the simulation data can be used to compare with measurement data for consistency.

The parallel-plate formation includes a bulk material sandwiched between two 3x3 cm² electrodes, with a spacing of 4.6cm. The thickness of the insulating layer was found to be of paramount importance to the capacitive coupling technique. An insulating layer of low capacitance will limit measurement sensitivity to changes in bulk material since the total impedance will be dominated by the impedance of the insulating layer and not the bulk material.

The electrical properties of the insulating layer on the electrodes were obtained from the datasheet of the product used in actual testing. Simulation parameters for the insulating layer resistance and capacitance were initially thought to be $2 \times 10^{12}$ Ω and 189 pF respectively. However, empirical modelling from a sample laboratory test showed that the combined insulating layer resistance was actually 1.5 MΩ.

For all simulations performed six bulk materials were used; tap and distilled water and saline solution, and dry, moderate and saturated soil. The electrical properties for each were taken from external sources and are referenced in the appropriate sections accordingly. They provide a sample of the most typical range of values which would be experienced in water and soil based tests.

The MATLAB analytical simulations showed that the real part of the complex solution typically produces a 'plateau region' in which the resistance of the bulk material can be
estimated to within 2% of the simulation parameter. For bulk materials of very high resistance no plateau region was found in the real impedance, however, the low frequency impedance was determined to be the product of both the insulating layer and bulk impedance. Subtraction of the impedance of the insulating layer provided a value of resistance which was, again, within 2% of the simulation parameter. The imaginary and absolute part of the analytically calculated complex impedance did not provide a consistent feature from which the bulk material could be estimated. Therefore, subsequent simulations largely discarded the imaginary and complex impedance.

Preliminary FEM simulations showed that both analytical and FEM simulation methods were in agreement, however the parallel-plate FEM model suffered from a long simulation time due to its complexity, resulting from the thin insulating layer. Therefore, COMSOL simulations also considered the possibility of scaling the insulating layer thickness to reduce simulation time constraints. A simple parallel-plate FEM model with a 75 μm insulating layer was found to have over one million mesh elements, and a simulation time of 76 minutes. When applied to the adjacent-plate measurements the simulation could not complete due to the complexity of the model. Therefore increasing layer thickness for simulation purposes was considered. Increasing the insulating layer to 500 μm, but with scaled electrical parameters, produced a model with a mesh size of approximately 35x10^3 elements, and reduced simulation time from 76 minutes to less than 3 minutes. The difference in simulation data was also found to be within 1%, and so all future COMSOL simulations utilised a thicker, scaled insulating layer.

COMSOL simulation data for a 500 μm insulating layer was found to be within good agreement of MATLAB data for all six bulk materials. Generally, simulation results were within 3% between programs. The dry soil simulation was found to differ by as much as 20% between MATLAB and COMSOL however. It should be noted that despite this large error, the difference was in the upper-frequencies of dry soil, an area not used to determine the resistance. Within the plateau region the difference was again within 3%.

Since FEM simulation data proved to be in good agreement with analytically calculated data, it was proposed that COMSOL be used to simulate the complex impedance for a FEM model representing the actual parallel-plate test cell which would be used in testing, a test-cell with a larger internal cross-sectional area due used to ensure electrode insulator integrity. It was found that simulation data for tap water closely replicated the
measurement data achieved in a preliminary test. Within the plateau region the simulation and measurement data were within 7% error.

The final simulations performed in this chapter were for a test cell which replicated a small portion of the rhizotron test cell, and therefore featured an adjacent-plate configuration. This test was required to be performed in COMSOL since no simple analytical solution existed for the adjacent formation of electrodes. Because of the confidence provided by previous simulations it was decided that COMSOL would be able to simulate an adjacent-plate measurement. One reason for this was to determine a typical spectroscopic signature for adjacent measurements, since this was unknown. It was found that the spectroscopic impedance was ‘similar’ to that of parallel-plate. A plateau region was still found when the spectroscopic impedance was plotted. At low frequencies the total impedance was predominantly caused by the insulating layer, and at higher frequencies caused by the bulk material. However, the plateau region impedance was found to be approximately 30–35% less than the simulation parameter. Therefore, a scaling factor could be applied to provide a vague estimate of absolute values, however, since the error is large a simple linear scaling factor is not advised. It is suggested that relative measurements be taken over time. The initial value can be used as a reference point to determine the changes in soil moisture over time as resistance increases and decreases due to moisture content changes.

This section also considered further utilising FEM to estimate the region of influence of adjacent plate measurements, and then determine whether backwards calculations could be performed to estimate conductivity of the soil from impedance measurements. It was found that the region of influence extended approximately 1.5 and 2.7 cm in the x, y and z axes respectively. With this region known, the impedance for ten values of conductivity was simulated. These values were used to backwards correlate measured values of impedance from the rhizotron to determine electrical conductivity. Finally, FEM was considered to estimate the influence that inhomogeneity’s had on measured impedance. It was found that within the direct location of the electrodes a localised contrasting conductivity could have as much of an effect as 35% on the value of impedance, within the simulation parameters used. However, outside the direct area of the electrodes the influence dropped to approximately 3% or less. Further work would consider more exploration into more accurate estimation of the effects of inhomogeneity within the measurement zone, alongside widening the simulation parameters used.
The simulations performed in this chapter have provided confidence that the simulated insulated electrode method can provide a method of determining the bulk material resistance for a parallel-plate measurement. For adjacent-plate measurements a relative value of resistance can be determined, from which measurements over time can determine the change in resistance relative to changes in the bulk material properties. These changes may be due to soil moisture, but also due to other factors such as the soil structure, texture, porosity, organic matter content, temperature and more. The following chapters will discuss the use of actual laboratory based measurements in both parallel- and adjacent-plate (rhizotron) test cells to determine the effects caused by these external factors, and whether they can be monitored with the insulated electrode measurement system.
The previous chapter discussed the use of software packages to simulate the spectroscopic impedance for both parallel- and adjacent-plate capacitively coupled measurements. The aim was to determine whether the technique could be applied to soil measurements, specifically with the aim of estimating soil moisture content from the measured total impedance between both parallel- and adjacent-plate measurements. It was found that the simulated data does indicate that capacitively coupled measurements can be used to determine changes in the bulk resistance for both parallel- and adjacent-plate formations, while negating those disadvantages associated with direct contact methods. While the technique may be able to monitor changes in bulk material resistance, the specific cause of the changes was unknown.

One of the major reasons for change in the bulk resistance of soil will be the moisture content. As moisture content increases, an increased number of conducting paths will be present in the soil, allowing more current to flow due to decreasing resistance. Also, since soil contains salts, even deionised water will become an electrolyte in soil and increase conductivity at a rapid rate. However, there are other factors which will also alter the resistance of the soil. For example, an increase in temperature is expected to reduce the bulk soil resistance, since the increase in temperature of the medium will increase water temperature also, which is positively correlated with electrical conductivity. Another example of causes for changing bulk resistance would be that the structure of the soil may vary, with heavily compacted soils featuring less pore space, and as such will have reduced resistance.

This chapter details the test procedures performed, and equipment used, throughout the remainder of the research. Laboratory based testing is required to determine the causes of changes to bulk resistance, and the effects of such changes. First, an overview of all equipment used is discussed, followed by details and procedures for parallel-plate cell tests. Within soil moisture testing, there are two main areas which are considered as the major contributors to soil resistance; soil compaction and temperature. Therefore the test procedure for each is discussed. After parallel-plate measurements, the use of adjacent-plate measurements is considered. The test procedure used for rhizotron testing, and specifically growth tests is discussed. All test results and discussions are found in the following chapter; chapter 5.
4.1: Test Equipment Used and Characterisation

This section provides a brief outline of all equipment used to perform laboratory based testing. It also details the preparation procedures, and specification, for the soil type used. For all tests soil from the same batch was used to improve repeatability between tests.

Impedance Analyser

For the majority of tests requiring the use of an impedance analyser, the Hewlett Packard (HP) 4192A was used to determine the total impedance of measurements (Aglent, 1981). The HP 4192A has a frequency range of 5 Hz – 13 MHz, with a user programmable measurement voltage or current. The impedance analyser has a measurement range of 1 Ω – 1 MΩ, outside this range the measured impedance will not be within the guaranteed specification of 0.15% accuracy. Two circuit modes can be used for impedance measurements, series or parallel. For all measurements throughout this research the parallel mode was used, as this more closely replicated the circuit being tested, since the electrical model was determined to be a parallel-RC network.

One feature of the HP 4192A is the ability to be remotely controlled via the Hewlett-Packard Interface Bus (HP-IB), often referred to as the General Purpose Interface Bus (GPIB). For the remainder of this work it will be referred to as the GPIB only. The GPIB is based on industry standards which allow for the connection of equipment and allow them to communicate through a known set of protocols. In this research the impedance analyser is connected to a desktop PC via a USB – GPIB converter.

The desktop PC communicates with the impedance analyser via two-way communications. First it sends commands to control the operation of the device, to allow aspects such as device configuration and when to perform measurements. The reverse communication allows the measured impedance to be sent to the PC and saved for future reference. A program was written and developed by Dr. Frank Podd in the SISP group at the UoM, called Tab Unique Measurement System (TabUMS). Tab is named due to the ability to control multiple devices via different protocols from each tab. Unique refers to the programs ability
to tailor the programs functionality for the required test specification since users can add and remove tabs as required. For example, the user may wish to communicate with an impedance analyser to perform regular measurements over time. At the same time the user may wish to monitor the weight of the medium under test, and can create a second tab to communicate with a balance, via a protocol such as RS-232, to determine the mass of the sample. Each tab can have an independent time period between measurements, so the primary measurement interval may be 10 minutes, while the secondary interval may be every 30 minutes. Since each device communicates via its own USB port multiple devices can communicate with the program simultaneously. One final feature of the TabUMS program is the repeat measurement options. Users can choose to perform a finite number of test iterations, or test indefinitely if the test end time is unknown. Once the test has ended the program saves all test data to a Comma Separated Variable (.csv) file, which can be opened in a spreadsheet program for analysis and manipulation.

While the HP 4192A impedance analyser is used for the majority of testing, for rhizotron based plant growth tests, the HP 4284A impedance analyser was used (Agilent, 2004), as these tests required long term use of the equipment, for which the HP 4192A was unavailable. While the 4284A impedance analyser has a lower value of maximum excitation frequency, at 1 MHz, it was capable of all the other functionality of the HP 4192A, and was deemed a suitable replacement.

**GPIB-USB Converter**

The Prologix GPIB-USB converter (Prologix, 2011) allows a desktop PC to interface with either impedance analyser, over the GPIB bus. The converter features two modes; controller and device. During this research, both modes are utilised. In controller mode the device allows commands to be sent from the desktop PC to the impedance analyser relating to measurement specifications set in the configuration file saved on the desktop PC. In device mode the converter can read measurement data from the impedance analyser and save it locally on the computer hard disk drive for analysis.
Conductivity Meter

The conductivity meter predominantly used throughout testing is a MettlerToledo SevenMulti (MettlerToledo, 2013) pH meter, with the additional conductivity meter attachment. The unit is a bench meter, with temperature calibrated conductivity measurements and a quoted range of 0.001 μS/cm to 1000 mS/cm, which equates to an electrical resistivity of 1000 MΩ/cm down to 1 Ω/cm. The meter was calibrated using Hanna conductivity calibration fluids. One disadvantage of the bench meter is that it was not always possible to measure the conductivity of a fluid as some tests were performed at a remote location from the laboratory bench. Therefore a handheld device was also used.

Handheld Conductivity Probe

A small handheld conductivity probe was required to measure the electrical conductivity of electrolyte solutions when use of the bench meter was not feasible. The handheld device was a Hanna HI 98130 Ph/Conductivity and total dissolved solids (TDS) tester (Hanna, 2013). Only the conductivity and temperature measurement functionalities were used, which offer a quoted operating range of 0 to 20 mS/cm once calibrated. Again, Hanna calibration solutions were regularly used to ensure the device was accurate to within specified limits. The conductivity probe was also used to determine temperature of the electrolyte sample to ensure minimal effects of temperature change during testing.

iButton Thermometer

The Maxim iButton range of products are small button shaped devices which can be used to passively measure conditions such as temperature or humidity, or be used as active devices to provide access control, asset tracking or electronic cash transactions Maxim Integrated, 2013). The devices have a small footprint, with a diameter of 16mm and depth
of 6mm, making it possible to place them within test vessels with relatively little concern. All temperature measurements during tests were performed with the DS1921L iButton thermometers (Maxim Integrated, 2003), which have a quoted temperature range of -40°C to +85°C to an accuracy of ±1°C. The temperature range used in all laboratory based tests lies within this quoted specification. For all tests where temperature is logged, one thermometer was placed loose within the environmental chamber, while a second was placed within the control or test vessel. In parallel-plate tests the thermometer was placed within a control pot, to reduce interference from the thermometer since the current flow through the bulk material would flow directly through the area where the thermometer was placed. For rhizotron tests the thermometer was placed within the rhizotron itself, as pre-testing showed that the iButton had no measurable influence on measurement data.

Since the devices are battery powered, their average operating life must be considered. When in standby they have a quoted consumption of “almost zero”. When taking measurements with a one minute sample time, at 40°C, the expected lifespan is approximately 5 years, and increases with decreasing temperature. Sample time can be varied between 1 to 255 minutes, and can log up to 2048 consecutive measurements. If required, the temperature can be set to roll-over and erase previous measurements, or set to end logging temperature when the memory buffer is full. For all tests a 30 minute sample time was used.

The temperature log is read post-test with a 1-wire USB reader (Maxim Integrated, 2011), connected to the PC. The time-logged temperature can be exported to a .csv file for data analysis.

Deionised Water

The deionised water used in testing is provided by the Millipore Direct-Q3 Ultrapure water system (Millipore, 2011). The device is hard-plumbed to the water mains within the laboratory and provides purified water with a quoted resistivity of 18.2 MΩ/cm at 25°C. To test the quoted accuracy, multiple tests were conducted with the Mettler Toledo SevenMulti conductivity meter on deionised water samples. Repeat tests showed that the
deionised water from the Millipore system had a conductivity range of 0.586 to 0.891 μS/cm, which converts to a range of 1.71 down to 1.12 MΩ/cm. While this value is only approximately 1/18 of the quoted value from the deioniser, it was consistent between repeat tests and provides a range with which the resistance of the deionised water can be estimated. The measured conductivity values were within the operating limits of the conductivity meter, so it is assumed that the deionised water equipment is not performing to within specification. While the cause of this is unknown, it causes no significant problems as it is a consistent error.

Both the analytical and numerical simulations, discussed in chapter 3, used a value of resistance and permittivity for distilled water, while the lab equipment provides deionised water. While deionised and distilled water are not the same, they both offer very high resistance, which was used to test the high-resistance limits of the parallel-plate method.

Soil Specification

The soil used for all tests during this research is known internally as 18-Acre soil, and provided courtesy of Syngenta at the Jealotts Hill facility. The PSD for the 18-Acre soil used can be seen in Table 4.1, where according to the USDA textural classification (USDA, 1999), the soil was classified as a Sandy Loam using the hydrometer method (Gee, 1986). The full soil characterisation report can be found in appendix C1.1.

<table>
<thead>
<tr>
<th>Particle Constituent</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>61</td>
</tr>
<tr>
<td>Silt</td>
<td>20</td>
</tr>
<tr>
<td>Clay</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 4.1: Particle Size Distribution for 18-Acre soil. Performed by Agvise Laboratories (Agvise 2013).
Soil Preparation

The 18-Acre soil used for testing was typically received in large bulk quantities, both sieved and unsieved. Therefore, the soil was required to be dried and sieved. Sieving the soil was a manual process, which involved taking smaller quantities of soil and passing them through a sieve with a known mesh size. For all tests, soil was manually sieved using a #10 sieve, with a mesh size of 2mm (2000 μm) using a Fieldmaster soil sampling sieve (Fieldmaster, 2013). Sieving the soil creates a more uniform consistency and helps to remove stones and other unwanted particles such as old plant growth remnants. Sieving the soil will improve repeatability of testing. Sieved samples were stored in plastic boxes until required, and were only dried immediately before testing.

Laboratory Oven

Soil samples were required to be dried to ‘oven dry’ before testing could begin. Oven drying soils provided a consistent reference point from which the required gravimetric water content of the soil could be achieved. The GENLAB OV/50 (GENLAB 2013) is a general purpose laboratory oven with an internal volume of 50 litres, a temperature range of 40 to 250°C, and a specified fluctuation of ±0.75°C. Soils were dried in the oven for longer than 24 hours at 100°C in order to achieve a consistent state of dryness.

Environmental Chamber

The environmental chamber used for all testing was a Weiss Gallenkamp Fitotron SGC 120 plant growth chamber (Fitotron, 2012). In its test configuration there were no internal shelves, and the chamber has a growth area of approximately 0.9m², but can be increased up to 3.4m² with additional shelving, but at the expense of losing vertical height for plant growth. With no internal shelving the chamber has a maximum growth height of almost
1.3m and a nominal volume of 1200 litres. The chamber ceiling is fitted with a lamp bank of
12 x 36W fluorescent tubes, with a specified colour output of ‘cool white’ and a colour
temperature of 4000 Kelvin. It is said that higher colour rating is more suited to seedlings
and early growth, which is ideal for the tests performed in this work (Alberta Agriculture
and Rural Development, 2011). The chamber does offer humidity control, but during these
tests was not configured, or required, to do so.

The chamber can be set to run at a constant temperature for an indefinite time period with
or without illumination from the lamp bank, or programmed for diurnal cycles in which the
user can program the day and night duration and temperature. In the daylight hours the
intensity of the light output is set prior to the test start with a small potentiometer, and is
not dynamically controlled during the test. The diurnal cycle program was primarily used
for rhizotron plant growth tests with 18 hours of sunlight at 25°C, and 6 hours of night at
10°C. A third mode of operation provides the ability to create set programs in which the
temperature can be ramped at user defined intervals. The program can be set to have a
maximum of 100 program cycles. Each program cycle can be used to ramp the temperature
at a maximum rate or over a set time period. This mode of operation was primarily used for
parallel-plate temperature testing.

**Bench Balance**

The balance used for this research was a KERN PCB 8000-1 precision lab balance (Kern,
2009). The device has a plate size of 150x170 mm and a maximum capacity of 8kg mass.
The balance was used to weigh all soil samples for parallel-plate measurements. The
balance accuracy is not provided on the product datasheet, but has a reproducibility of
0.1g.
Soil Penetrometer

A soil penetrometer is typically used to determine the pressure required to break the soil surface, and therefore estimate the level of compaction of the soil. A well compacted soil will require a much greater force to penetrate, and in terms of plant growth will be more difficult for roots to penetrate through the soil to those areas where moisture is present. The process and consequences of soil compaction were discussed in chapter 2. The device used is an E-280 Pocket Penetrometer (Geotest, 2013), and features a foot/piston of known area, and a spring located within the main shaft of the body which allows for measurement of the pressure required to break the soil surface. As the device is pressed into the soil a marker on the piston is used to determine the point at which a measurement should be taken. The measurement should be taken when the marker line is level with the soil surface, and therefore the piston has extended 5mm into the soil. A scale along the outer edge of the device notifies the user of the pressure exerted to penetrate the soil. The scale provided is kg/cm², and this device can measure a compaction level of 0 - 4.5 kg/cm². In these tests the penetrometer was not used to determine the soil compaction, but rather to compact the soil to a known pressure. This was to ensure that tests had good repeatability as the soil compaction levels could be made consistent.

Since soil was added to and removed from the test cell for each test, high levels of soil compaction were unachievable since field soils are typically compacted by gravity and water penetration over long periods of time. This low level of soil compaction caused the piston to penetrate the soil surface before a measurement of pressure was obtainable. Therefore an adapter plate was required to increase the surface area of the piston, which subsequently increases pressure required to penetrate the soil. The standard piston size of the penetrometer was 31.7 mm², compared to the adapter plate surface area of 600 mm². The adapter foot is approximately 19 times larger than the standard piston size, and measured values of pressure should be therefore divided by 19 in order to determine pressure applied. With an adapter foot in place the soil could be compacted to four ‘compaction levels’ corresponding to the scale on the penetrometer of 1-4. Table 4.2 shows the four compaction levels, and the scaled pressure exerted for each. For all soil compaction tests the scale of 1-4 levels of compaction is used, instead of referring to the actual pressure.
### Table 4.2: Four pressure levels used to compact the soil.

<table>
<thead>
<tr>
<th>Penetrometer Scale</th>
<th>31.7mm$^2$ standard plate</th>
<th>600mm$^2$ adapter plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.053</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.105</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>0.158</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>0.211</td>
</tr>
</tbody>
</table>

#### Parallel-Plate Test Cell

The parallel-plate test cells were constructed from 3mm thick Perspex, which was cut using a laser-cutter in the University of Manchester machine shop. The cell has a tessellated edge for increased strength, and was glued using an epoxy resin to ensure it was water tight. No lid was used on the test cells to allow easy placement and removal of soil and water samples. In order to reduce evaporation of water from the soil, plastic film was placed across the surface of the test cell. Their inner dimensions were 4 x 4 x 5cm, but with the PCB electrodes placed inside the length of the cell was reduced to 4.6 cm.

#### Rhizotron Test Cell

The rhizotron test cells are a standard issue test cell used within laboratory testing for Syngenta. They were designed and constructed by Syngenta based on their internal specifications and requirements for optimised plant growth whilst enabling analysis. As such, they were modified by the University of Manchester to include the necessary electronics to enable measurements to ensure no detrimental effect to plant growth. Three vessels were loaned to the University of Manchester for this research. They are predominantly constructed from plastic, with a clear plastic being used for the ‘front’ of the vessel as the viewing side. The internal dimensions of the rhizotrons are; 31 x 48.5 x 3cm. However, when the electrode array is placed within the test cell the internal depth reduces to 2.7cm. An example of the rhizotron test cell can be seen in Figure 4.1. The rhizotron
Electrodes were 3x3 cm, and had 2 cm spacing between electrodes, allowing for 60 electrodes to be placed along the back plane.

This concludes the overview of standard equipment used. The next section discusses the complete rhizotron measurement system, including the modifications to the standard vessels, additional equipment used, block diagram of the complete system, configuration files used to interface between the desktop PC and impedance analyser and an overview of the saved data file format.

4.2: Rhizotron Measurement System

A rhizotron is typically an underground viewing area, used to study soil and roots. In this research the rhizotron is a relatively small piece of equipment used in the laboratory with a purpose to study soil and roots. Laboratory based rhizotrons typically allow only visual observation of roots and soil through a Perspex window placed along one side of the vessel. Since the rhizotron has a shallow depth, any plant roots will be confined within the almost 2D volume, and while not replicating true root growth it will still allow roots to freely grow. The rhizotron used in this research is a modified version of a ‘typical’ laboratory rhizotron. Along the back plane, opposite the clear Perspex viewing window, is placed an array of 60 electrodes behind a dielectric coating which provides the insulating layer. Electrical impedance measurements are taken between pairs of adjacent electrodes to determine the impedance distribution of the soil volume, from which the aim is to determine the localised soil moisture relative to the placement of roots.

Rhizotron Measurement System Overview

The rhizotron measurement system comprises of four major components; the rhizotron vessel, an impedance analyser, bespoke switching electronics to perform multiple measurements and a desktop PC to control the switching electronics and log impedance
measurement data. The switching electronics were designed by Dr. Frank Podd of the SISP group, UoM, and the rhizotrons were provided by Syngenta. They are typical of those used in their laboratory based tests for visual observation of plant root growth. The complete rhizotron measurement system can be seen in Figure 4.1. Measurements are taken only between adjacent electrodes, and this is achieved through switching electronics which are controlled by a desktop computer and the TabUMS program. Measured electrical impedance data is processed in MATLAB, and a relative measurement of impedance over time at all adjacent electrode pairings is mapped and displayed in both a video format and as plots of impedance vs. time.

![Complete rhizotron measurement system](image)

**Figure 4.1: Complete rhizotron measurement system**

### System Block Diagram

The block diagram for the rhizotron measurement system can be found in Figure 4.2. The block diagram shows how the individual components of the measurement system connect together while a detailed operation of the system is found in the following sections.
Figure 4.2: Rhizotron system block diagram

**PC**
- Run TabUMS Software for data acquisition
- Send commands for switching pattern

**PIC USB**
- Convert to PC
- Send commands for switching pattern

**Demux/ Power x 2**
- Power Supply/Regulator
- IO Expander
- Status LED’s
- Power supply LED’s

**Switch x 4**
- Multiplexer 16ch
- Connects to 15 electrodes
- Power supply LED’s
- Daisy-chained via co-axial

**Imp. Analyzer**
- HP 4152a Impedance Analyser

**Rhizotron**
- Rectangular Array of 60 insulated electrodes
- Clear viewing window
Detailed System Operation

The rhizotron measurement system creates an image of soil moisture distribution by measuring conductance and susceptance between pairs of adjacent electrodes placed along the back plane of the vessel. Unlike tomography which utilises multiple electrode excitation strategies to improve spatial resistivity distribution, this work considers only point-to-point measurements between single pairs of electrodes. While this may reduce spatial resolution, it provides a simple and rapid method of obtaining resistivity distribution of the soil. As was discussed in section 3.15, further work may include additional excitation strategies and tomography techniques to improve knowledge of the medium under test and better estimate soil moisture distribution.

Measurements are taken between all horizontally and vertically adjacent electrodes except the right most column. This column was not measured as the current method for reconstructing data requires the number of horizontal and vertical measurements to be equal. If vertical measurements on the right most column were included the results would include 5 horizontal measurements and 6 vertical. An example of how the measurement data is saved into an array is seen in Figure 4.3. The complete measurement pattern can be seen in Figure 4.4, with the right column electrodes unused for vertical measurements.

The number in each cell of Figure 4.3 corresponds to the measurement number shown in Figure 4.4. Due to the nature of the electrode arrangement, horizontal measurements are spatially aligned between vertical measurements, rather than directly above them. However, the measurement data plotted in this research does not compensate for this, but instead aligns horizontal data points above vertical. This significantly reduces complexity in plotting measurement data, but also does reduce accuracy of spatial impedance plots. While this method is a less accurate representation of measurement placement, it still provides an impedance measurement at a high spatial resolution.
With the above measurement protocol it can be seen that the total number of measurements for a rhizotron system is 95, and is termed as a Frame. Multiple frames are taken over time and are combined to create a movie providing a temporal representation of soil moisture distribution.

The next section discusses the individual elements of the rhizotron measurement system, the interfacing between multiple PCBs and the outputted saved files.
Figure 4.4: Measurement protocol for rhizotron system.
Impedance Analyser / Desktop Computer

Control of the impedance analyser is achieved through the Prologix GPIB-USB converter, connecting the impedance analyser to a standard desktop computer USB port. The configuration and operation of the impedance analyser is performed via the same file used to configure the electrode switching pattern.

The following sections provide a detailed outline of the individual components of the switching electronics. Circuit schematics can also be seen in appendix B1.1. Photographs of the individual elements of the rhizotron measurement system are found in appendix B1.2.

Switch PCB

Along the internal face of the back plane of each rhizotron is located an array of 6 horizontal x 10 vertical electrodes. Each electrode is directly in contact with the soil under test through an insulating layer. The impedance analyser requires the use of switching electronics and multiplexers to automate measurements on all 60 electrodes. Each electrode is connected to one output of a 16 channel Analog Devices ADG1206 multiplexer (Analog Devices, 2009) on the Switch PCB, therefore four multiplexers are needed for the 60 electrodes. Switching is required to ‘activate’ pairs of adjacent electrodes to allow measurements for all adjacent pairs. Despite each multiplexer including 16 channels, only 15 channels from each are used. The remaining channel is left unconnected and used to pseudo-deactivate the multiplexer when required.

The Enable pin of the ADG1206 is active high, and is permanently held high by setting the PIC microcontroller pin (B11) as an output, see section GPIO/ PIC32 PCB for details on the PIC microcontroller device. Therefore, all multiplexers are permanently enabled. 4-bit binary address lines are used to determine which channel of the multiplexer is active and connected to the common output (pin 28) of the multiplexer. The common output of all multiplexers is daisy-chain connected to the impedance analyser to allow an impedance measurement to be taken. For a single measurement between two electrodes, two of the four multiplexers are used. The unused multiplexers must be deactivated, despite being
permanently enabled. This ‘deactivation’ is achieved using the unused 16\textsuperscript{th} channel of the two multiplexers not in use. Since the 16\textsuperscript{th} channel is left floating there will be no connection between unused electrodes and the impedance analyser resulting in a measured value only determined by the two ‘active’ electrodes. The multiplexers are each placed on their own circuit board, called the Switch PCB, and therefore each rhizotron requires four switch PCBs.

Other components on the switch PCB include two notification LEDs for ±15V and a 10-way connector to interface with the power/ demux PCB. Finally, the common output of the ADG1206 is split and connects to two SMB sockets; one is connected to the impedance analyser and the other allows daisy-chain connections to other rhizotrons for parallel measurements. Parallel rhizotrons can be connected together and work with the same principle as individual rhizotron measurements. For a single rhizotron the two multiplexers not required for the measurement are configured to be connected to the unused 16\textsuperscript{th} channel. When two rhizotrons are connected in parallel there will be eight multiplexer boards in the circuit. The user can configure the six unused multiplexers to be connected to the 16\textsuperscript{th} unused channel, leaving only two multiplexers connected to a pair of electrodes and the impedance analyser. In order for this to be achieved, each multiplexer must have a unique address.

**Power/ Demux PCB**

The 4-bit address lines of the ADG1206 multiplexers are controlled by a separate circuit board, the power/ demux PCB. It is thus named as it provides both the power to the switch PCBs and the 4-bit address lines to control the multiplexers. For all future references, the board will be referred to as the ‘demux PCB’. The board features a PCF8574 8-bit IO expander (Texas Instruments, 2008). One IO expander can only control two multiplexers, therefore two demux PCBs are required per rhizotron. The 8-bit operation of the IO expander is separated into two channels; 4 are used to control switch PCB 1 while the remaining 4 control switch PCB 2. The expander control commands are retrieved from the configuration file located on the desktop computer.
Alongside controlling the multiplexers, the demux PCBs also provide the necessary power to operate the multiplexer ICs. Included on the PCB is a TPS61041 Switch Boost Converter (Texas Instruments, 2010), which creates ±15V rails for the ADG1206, and various power supply notification LEDs to confirm proper operation. Each 4-bit channel has four status LEDs to provide a visual representation of the binary 4-bit address. Note: The LEDs are switched ON when the channel is logic 0 and vice versa.

The IO expander receives the control commands ultimately from the desktop computer as previously mentioned. However, there is a PIC32 starter kit which interfaces between the demux PCB and the computer. The IO expander communicates with the PIC32 via I²C.

### GPIO/ PIC32 PCB

The demux board is connected to a proprietary General Purpose Input/ Output (GPIO) PCB via a 5 way connector. The 5 connections are; +3.3V, GND, Serial Clock Line (SCL), and Serial Data Line (SDA) both required for I²C communication and Switch_Enable to permanently activate the ADG1206 ICs. The GPIO PCB shares outer dimensions with the PIC32 starter kit 2 PCB (Microchip, 2010). They are piggy-backed together via a 120+12 way connector, of which only the 5 previous stated connections are required. The GPIO board is used as a throughput board, where the 5 connections are routed from the two demux PCBs to the PIC32. The PIC32 is connected to the PC via ‘Micro B’ USB – USB Type A. Not only does this provide communications between the PC and the PIC32, but also power for the whole switching electronics.

The rhizotron electrode switching pattern is controlled by a configuration file created on a desktop computer, and implemented through the TabUMS software.
**Configuration File**

The basic functionality of the configuration file is to activate the first rhizotron, and deactivate the remaining two. Then a full frame of measurements is taken at five frequencies; 10, 50, 100, 500 and 1000 kHz. After the frame of measurements is achieved on the first rhizotron, it is deactivated and the second rhizotron only is activated and a full frame of measurements taken. The second rhizotron is then deactivated and the third is activated and a full frame of measurements taken. After this frame the whole measurement is complete and replicated again after a set time period decided by the user. For this particular configuration file each rhizotron frame takes approximately 1 minute, and since 5 frequencies are used a total of 5 minutes per rhizotron, leading to a total measurement time of approximately 15 minutes for three rhizotrons.

The first section of the configuration file defines a ‘device index’ to each of the USB-connected components. The device index is determined by the automatic USB port assignment of Microsoft Windows. The next section of code in the configuration file initialises the impedance analyser for measurements. Options such as measured values, measurement frequency, averaging and measurement mode are configured in this section. The following section is the code to provide the switching pattern. The switching occurs as the TabUMS program steps through the configuration file. In this section the lines of code alternate between the rhizotron switching and the impedance analyser. For example, the rhizotron switching code will ‘activate’ two adjacent electrodes for measurements. The subsequent line of code will then address the impedance analyser and measure the impedance between the two active electrodes. The configuration file will then activate the next pair of adjacent electrodes and the impedance analyser will record the measurement. This will continue until all electrode patterns defined in the configuration file have been performed. Once the configuration file is completed it repeats as many times as required by the user. The user defines the number of repeats in the TabUMS program.
Saved Data

Upon completion of measurements, data are saved into two documents with the *.csv file format. The saved measurement file contains an overview of chosen measurement parameters, such as frequency and start/stop time. The other file contains all the raw data for each electrode pairing and each test iteration. The test file can be split into three sections. The first three columns form the test header and provide the loop number, which is incremented each time a frame of measurements is taken, the Universal Time Convention (UTC) time in mS when the measurement commenced and a description column, typically not used. Following the header columns are the test data columns. The test data can be split into groups of four columns for each electrode pair. The first two detail the electrode number for the measurement. The remaining two columns store the measured conductance and susceptance value for the pair. The final column of the test data stores the measurement end time, and is used to determine the duration of each frame.

It is time consuming to manually extract data into a column array for each frame of measurements. In order to process raw data a MATLAB script is used which extracts all data into a series of workspace variables that can be used to plot data. The script used to read in test data is discussed in the following section.

Read Rhizotron Data into MATLAB

A function was created by Dr. Frank Podd of SISP, at the UoM, to read the rhizotron test data into MATLAB. The function is can be found in appendix B1.3.1. The basic function of the script is to import the test data from the TabUMS program.

The script determines the number of data columns and header columns, as previously discussed, followed by MATLAB code to determine the total number of measurements made. A for loop is then used to save the measurement data into specific arrays for each column, and frame of measurements. For example, all 95 measurements are saved into a one dimensional array with 95 elements. The for loop reads the conductance and
susceptance values for all measurements and converts the data to several parameters; complex impedance, absolute impedance, resistance and reactance. The final section of code determines the mean time for each frame of measurements. The function then requests a user definable filename for the workspace variables for future reference. Processing a dataset for three rhizotrons and eight iterations takes 1-2 seconds and is much faster than manually extracting data.

Creating a Movie from Temporal Rhizotron Data

The test data from the parallel rhizotron tests creates a very large amount of test data. As an approximation, it is calculated that a typical rhizotron plant growth test running for one month will produce over 300 000 data points. Since there are three rhizotrons, this equates to approximately one million for a typical test. Analysis of this number of data points is very time consuming, and prone to errors due to the likelihood of a mistake. Therefore a method of scripting is required to automate the process of data analysis, however, merely plotting the resistance change over the month period would be difficult to assess since there are 285 measurement pairs for all three rhizotrons and each would require its own data plot. One way to represent such a large volume of data is to produce image files for each data set based on colour representations for changing impedance. Image files are then joined and constructed into videos. A video file which shows the bulk impedance change for each measurement over time will show qualitative data, how localised areas change in relation to other areas of the soil.

MATLAB was used to create a movie file for test data. The code includes minor amendments made by the author and the script can be found in appendix B1.3.2. This section provides a brief overview of the script and the functions used to create a movie.

The script sets the size of an array based on the number of measurements taken with the rhizotron. The array is defined by the number of measurement rows and columns producing an array of size 19x5, a total of 95 elements. With only 95 unique measurements available for each measurement frame, the resolution of an image would be very low if a video was created based on this array. Since the movie files provide only a qualitative
analysis it was felt that a more visually appealing image representation would be beneficial. Therefore the MATLAB function `imresize` is used to interpolate vertical and horizontal resolution by a factor of 30, producing a much smoother transition between impedance measurement data from adjacent electrode pairings. This interpolation is achieved through a `for loop` for each measurement frame. As previously mentioned, further work would consider similar techniques to those from tomography, where multiple electrode excitation strategies are implemented. In such a scenario, a linear interpolation between measured data would not be required. Following this interpolation, the next section determines the maximum and minimum value of measured impedance in order to create a dynamic range for the colormap scaling. While the colormap range is dynamic, the code was also altered to allow the user to create a fixed range based on maximum and minimum values between multiple rhizotrons, to allow comparison between multiple rhizotrons. The final section is the compilation of the created images into a movie file. One key variable is the ability to change the number of frames per second (FPS). If the FPS are too high it will be difficult to observe the changes which occur, too low and the movie file will take too long to view.

4.3: Multiple Parallel-Plate Measurements

The switching electronics used for the rhizotron measurement system were modified to allow multiple parallel-plate test cells to be used for measurements pseudo-simultaneously. While only one measurement can be performed at a time, the switching system allows for automated switching between multiple cells, and therefore requires minimal user intervention. Multiple test cells were required for temperature testing when the soil was repeatedly heated and cooled to determine the temperature response of the soil, and the effect which temperature had on bulk material resistance.

Since parallel-plate measurements only use two electrodes, three test cells running in parallel required only six electrodes total. However, the system still requires two Switch PCBs as a measurement between two electrodes cannot be achieved with a single multiplexer. Therefore three electrodes were connected to Switch PCB 1, and three were connected to Switch PCB 2. All other connections were the same as the rhizotron.
measurement system. The configuration file was modified to switch between the three pairs of electrodes only. Through the use of the TabUMS program the impedance of three test cells could be determined throughout the entire temperature test with no manual intervention required.

### 4.4: Parallel-Plate Test Procedure

The overall aim of the parallel-plate tests was to determine the effect that soil compaction and temperature had on soil electrical resistance compared to soil moisture.

This section details the test procedures used for all parallel-plate measurements. Parallel-plate measurements can be separated into two main categories; measurements with a bulk material of water and measurements with a bulk material of soil. First, water measurements were performed to compare measurement data to simulated data discussed in chapter 3. Once completed, soil measurements were performed to determine whether the measurement of impedance could be used to monitor the conditions of the soil within the vessel. Within the soil based testing, a further two categories can be determined; soil compaction and temperature testing. For both compaction and temperature testing, soil moisture was also adjusted to determine the effects of soil moisture compared to a second variable. Combining two measurements together improves the speeds at which tests can be performed, and the ability to compare changes for multiple parameters, rather than just one.

**Water Based Parallel-Plate Measurements**

The first tests in the parallel-plate test cell were performed to determine whether simulated data was accurate compared to actual water measurements. The first tests used a bulk material of tap water. The tap water used was that from within the laboratory which was left to run for approximately 5 minutes prior to sampling to reduce any contamination.
from standing water within the mains water pipes. The tap water sample was left within the test laboratory for a period of 24 hours to acclimatize to the laboratory ambient temperature. If the temperature difference was too great between the tap water and ambient temperature of the laboratory, the water temperature could increase during testing at an unknown rate, making test results less repeatable or even void. All deionised water was also stored within the laboratory for 24 hours to acclimatise to the laboratory temperature, to avoid temperature difference between tests as with tap water. The deionised and tap water were stored in sealed glass jars to ensure no contamination.

The next tests used distilled/deionised water from the laboratory supply with increasing sodium chloride content to create a saline electrolyte. 500ml (500g) of deionised water was used, with sodium chloride added in 0.02% increments by weight, between 0% and 0.1%. While the test cell only holds approximately 74ml of water, a batch of 500ml of water was used to reduce effects of accidental water loss, changing the percentage of sodium chloride in the solution. Such a small amount of sodium chloride was required to ensure that bulk material resistance was still high enough to be measured, as a small increase in salinity will have a large effect on conductivity. By increasing the salinity too much the plateau region, in which the bulk material resistance could be estimated, would shift to a higher frequency and may become too high for the measurement equipment available. For each level of salinity the spectroscopic impedance was measured with the impedance analyser. A second measure of the conductivity of the water was provided by the Mettler Toledo SevenMulti conductivity meter, to allow comparison between the insulated electrode method and regular conductivity probe methods. A good level of accuracy between results would provide confidence that the insulated electrode method is capable of providing the bulk material resistance of soil, where a regular conductivity probe is unable to perform a measurement.

**Soil Based Parallel-Plate Measurements**

Since soil is so heterogeneous, it is unrealistic to assume that soil measurements from the 18-acre soil would be directly comparable to the simulations performed. The soil simulations previously discussed used a set of parameters to represent soil at three typical
moisture contents since the soil moisture was assumed to be the parameter which caused the biggest change to bulk resistance. The simulations provided confidence that the bulk material resistance could be used to determine properties of a typical soil. This section is split into two sub-sections in which the effect of compaction and temperature are compared to the change in bulk resistance from increasing moisture content.

For all tests a base level was required for soil moisture in order to create samples of soil of known and consistent moisture content. In order to determine the soil moisture increments the soil was first oven dried for a period of longer than 24hrs at 100°C. Once oven dry the only water remaining in the soil was deemed to be hygroscopic, and could not be removed by methods available. This oven dry soil presents a good base point for soil moisture measurements. The next step was to determine the saturation point, which was achieved by adding water until the soil reached saturation. At saturation the amount of water required to reach this stage was noted and a linear scale between dry and saturated was derived. For the 18-acre soil the saturation point was determined to be approximately 35% gravimetric water content. Therefore, for a 100g soil sample, saturation would occur when 35g water was added. If the soil was required to be wetted to the halfway point between oven-dry and saturation, 17.5g of water was required. In order to mix soil to the required moisture content, the appropriate quantity of water was added to the oven dry soil in a non-porous glass bowl. The soil sample was then agitated and stirred by hand until a uniform consistency was achieved. To avoid soil contamination from substances such as skin salts and oils a stainless steel mixing rod was used.

For all single cell parallel-plate tests a dry soil sample mass of 140g was used, therefore each 5% increment was achieved by adding 7g (7ml) of deionised water. Deionised water was used to remove variation from tap water. When multiple test cells were used in parallel the dry soil quantity and required water content were scaled to provide the correct quantities.
Soil Compaction Test Procedure

The aim of soil compaction tests was to determine by how much the electrical resistance was affected by soil compaction when compared to changes in resistance from increasing soil moisture content. Once known, the measured resistance of the bulk material could be attributed to a specific soil moisture with a specific error percentage to compensate for possible compaction levels. For soil compaction testing, soil moisture was incrementally increased, and for each moisture content the soil was compacted to increasing pressure. For each compaction level and moisture content the impedance at 58 frequencies between 10 Hz – 13 MHz was measured.

For all soil compaction tests, the soil moisture increments were 5% gravimetric. Therefore, tests were performed for eight moisture content levels; 0, 5, 10, 15, 20, 25, 30 and 35% gravimetric water content. However, it was found that it was impossible to perform soil compaction for 35% soil moisture since the wetness of the soil caused the soil to press out of the cell when pressure was applied. Therefore, only seven soil moisture levels were used between 0 - 30%. For each soil moisture content, electrical impedance measurements at four compaction levels were performed with the impedance analyser. Results were recorded with the TabUMS software program and inputted into MATLAB for analysis.

In order to achieve the required levels of compaction, soil was added to the test cell until full. The penetrometer and adapter foot were then used to compact the soil to a compaction level of ‘1’ on the penetrometer scale, equating to a pressure of 0.053 kg/cm² being exerted. This pressure would compact the soil significantly, causing the soil to no longer fill the test vessel. Therefore more soil was added until both the test cell were full and with a uniform compaction level of ‘1’.

Once the soil was compacted to level 1 the impedance analyser was used to measure the complex impedance at all 58 frequencies. For each compaction level of soil three repeat measurements were taken to ensure the sample had stabilised. The soil was not removed between repeat measurements due to the complexity and heterogeneity of soil which would alter the structure and reduce repeatability too much. Concluding the level 1 compaction testing, the soil was further compacted to level 2 and the spectroscopic impedance was again measured. This was repeated until a soil compaction of level 4 was achieved and measured.
When the spectroscopic impedance for level 4 compaction had been measured the soil sample was removed from the vessel and placed back into the mixing bowl with the unused soil. The next quantity of water was added to increase from 5% to 10% gravimetric water content and then the soil was reinserted into the test cell to a compaction level of ‘1’.

This procedure was repeated for all seven moisture contents at all compaction levels, providing 28 sets of measurements, each with three iterations. The test data were then inputted into MATLAB via a script file which slightly differs from that used to read the rhizotron data, but only in configuration, and therefore an explanation of the functionality is not required.

**Soil Temperature Test Procedure**

The aim of soil temperature testing was very similar to that of compaction testing, to determine the effect of changing temperature on soil electrical resistance compared to the effect from increasing soil moisture content. As with soil compaction testing this would determine an error margin, from which the soil temperature effects could be hoped to be negated.

For soil temperature testing an environmental chamber was used to incrementally increase the soil temperature while measuring the spectroscopic impedance for a set soil moisture content. The test was repeated for all seven soil moisture contents between 0-35% gravimetric water content. The chamber temperature was cycled through a range of temperatures from 10°C to 40°C. For each 5°C step the chamber held its temperature for 2 hours to allow the bulk mass of the soil to match that of the chamber. The chamber took approximately 10 minutes to reach the new temperature, but the soil sample had a delay of approximately 30 minutes to change temperature due to the thermal mass of the soil. This was determined with pre-testing in which an iButton thermometer was placed in a parallel-plate test cell filled with soil. Therefore, leaving the chamber at each temperature for 2 hours ensured the soil had reached temperature before it was changed.

During testing, soil temperature was logged with an iButton thermometer placed within a control test cell of exactly the same dimensions as the measurement test cell, with soil
mixed to the same moisture content. The thermometer was placed inside a control pot to minimise effects on measured impedance which would have occurred if placed in a measurement vessel from inserting a relatively large metallic into the test cell directly between electrodes. Again, soil samples were covered with plastic film to ensure minimal evaporation of water throughout the test. The test schedule for the temperature testing, including the temperature ramp program can be seen in appendix C1.2.

4.5: Rhizotron Measurement System Test Procedure

This section discusses the test procedures used to measure changes in the soil electrical properties using adjacent-plate measurements from the rhizotron test vessel. All rhizotron testing used three rhizotrons connected in parallel. Of the three rhizotrons, two included a maize plant, while one was kept as a control vessel. There are two primary reasons why plant growth tests were performed. First, plant growth tests can help to determine the effect of having a plant and root system in the soil, and how the insulated electrode system copes with the root system. Secondly, from growing plants the soil moisture will be removed far quicker from the plant filled vessels than the control vessel due to root water uptake. This will allow the determination of whether the measurement system can monitor soil moisture content local to the plant roots. The test duration was approximately 6–7 weeks, with the end being decided by observation of the plant health to see at what point they had exhausted all the water in the soil, and reached the wilting point.

To fill the rhizotrons with soil they were first laid flat, and a cap placed across the top. The Perspex wall was removed allowing soil to be placed in the vessel. Oven dry soil, sieved to 2mm, was added to the rhizotrons until completely full. Once full the Perspex wall was placed back on the vessel and they were stood upright. The filling cap was then removed from the top to allow them to be watered. Rather than filling the cells with a pre-mixed soil/water medium it was decided to water the soil in the rhizotrons to the point of saturation for all three test cells to attempt to achieve water uniformity. This was also chosen as the test required the soil to be as wet as possible, to allow for maximum plant growth throughout the test. Throughout the test all three rhizotrons were covered with plastic film to stop evaporation. Stopping evaporation from the top surface meant that the
only significant source of moisture movement was through plant roots. Since the control pot featured no plant system it was hypothesised that after the duration of the test the control pot would be close to field capacity.

In order to improve probability of plant germination, four seeds were planted within the middle 10cm of the rhizotron top surface. After 1 week, the seedling closest to the centre was kept and the others were carefully removed. This method caused minimal disruption to the soil core when compared to external propagation and re-planting seeds within the vessel. Once the plant seedling had emerged from the soil surface the plastic film was removed from the area immediately surrounding the plant stem, to allow growth to occur unhindered. The plastic film was placed carefully around the stem as close as possible to reduce evaporation.

Rhizotron tests operated on a diurnal cycle within the environmental chamber. The diurnal cycle was set to an 18/6hr split over the 24 hour period, with 18 hours of daylight at 25°C, and 6 hours of darkness at 10°C. This cycle was set to provide favourable conditions to encourage rapid plant growth, but not over stress plants. Electrical impedance was set to measure every 1 hour at the five frequencies previously mentioned; 10, 50, 100, 500 and 1000 kHz. Over a period of approximately 6 weeks this equated to a total of approximately 700 frames of measurements. The approximate total number of impedance measurements for a plant growth test is found by:

\[ \text{Total Measurements} = F \times r \times m \times f \]  

Where F is the number of frames, r is the quantity of rhizotrons, m is the number of measurements per rhizotron, and f is the number of frequencies. An approximate value for the total number of individual impedance measurements is 1 million. This very large number of measurements shows that the processing method must be simple and efficient, and why video representations are a good method of displaying and analysing the measurement data as they show changes in impedance over time, despite being only qualitative. With all test procedures detailed and explained, the following chapter provides the results and appropriate discussion of the results.
5: Results and Discussion

This chapter provides the results from all laboratory testing, based on the test procedures outlined in the preceding chapter. Alongside the presentation of test results, a discussion is given based on the findings of test results, and conclusions are drawn from these discussions.

The ultimate aim of the research programme was to improve rapid phenotyping in crop breeding programmes through selection of those strains which show strong genetic traits. This was to be achieved through measurement of soil moisture content around the root zone, to infer root water uptake. From the literature review it was proposed that electrical resistivity measurements be implemented in order to determine electrical properties of soil, from which the moisture content could be inferred. Limitations to the technique dictated research of alternative methods based on the use of electrical resistance measurements. This concluded that placing an insulating layer over the electrodes would inhibit electrode corrosion and reduce electrode polarisation effects whilst still allowing electrical resistivity measurements. A test vessel was proposed with parallel facing electrodes from which a relatively simple analytical solution could be derived. Simulated data confirmed that the insulated electrode method still allowed the bulk material impedance to be measured through spectroscopic measurements. Subject to positive laboratory results utilising the parallel-plate system, the insulated electrode method would be applied to a measurement system which featured a rectangular array of adjacent electrodes placed along the back plane of a rhizotron growth vessel.

Chapter 3 detailed the simulation of the parallel-plate test vessel through both analytical and FEM model simulations. Simulated results indicated that through spectroscopic measurements the bulk material impedance could be extracted from the total measured impedance within a plateau region, a bandwidth of frequencies within which the real part of the complex impedance of the solution was determined by only the bulk material, negating any effects of the insulating layer. The first aim of laboratory testing was to characterise the insulated electrode method. This would be achieved by determining whether through spectroscopic measurements a plateau region existed, and whether the bulk material electrical properties extracted at this frequency were relevant only to the bulk material. In order to determine the accuracy of the insulated electrode method a second measurement technique was required to measure the electrical properties of the
bulk material for comparison of data. For soil-based applications, it is challenging to find a suitable second method of determining soil conductivity, as a regular bench conductivity meter cannot measure conductivity within a solid material such as soil. Therefore, verification testing was performed with a water-based electrolyte of varying salinity, where a bench conductivity meter was able to measure the electrical conductivity of the electrolyte and be compared to the value achieved from the insulated electrode method. Once the validity of the insulated electrode system was confirmed, soil-based testing could be performed by the insulated electrode method.

For soil-based testing, three parameters were varied which were all expected to alter the electrical impedance of the soil. Soil moisture, compaction and temperature were chosen as the three parameters which were most likely to change during rapid phenotyping tests in controlled environmental chambers, and also have the largest effect on impedance. Therefore, knowing their effect on soil electrical properties was essential for estimating soil moisture content through electrical impedance measurements. Following the laboratory testing of soil in parallel-plate test vessels, plant growth tests were performed within the rhizotron test vessels which featured adjacent-plate electrodes. During each of these tests three rhizotron vessels were connected in parallel. Two of the test vessels included a maize plant growing in soil while the third was a control vessel filled only with soil. For all three vessels, soil was wetted to saturation and left to reach field capacity before tests started. Discussion will focus on the impedance measurements over time, and whether rhizotrons with an array of insulated electrodes, can be used to monitor temporal and spatial soil moisture content, and provide quantitative data relating to soil moisture variability within the soil core and measurement of root water uptake. The final sections in this chapter summarise all results and conclusions achieved from laboratory-based testing.

5.1: Characterisation of the Insulating Electrode Method in the Parallel-Plate Test Vessel

This section discusses the tests performed to determine whether the insulated electrode method could be used to measure the electrical resistance of a bulk material placed between two parallel facing electrodes as was suggested by simulated data. It represents
one of the most important sections of the research as all future test results are based on the ability and accuracy of the insulated electrode technique for measuring soil electrical properties and relating values of electrical impedance to moisture content. Simulation data previously acquired in chapter 3 suggested that at lower frequencies the measured impedance would be the sum of both the bulk material and the insulating layer. However, as frequency increased the reactance of the insulating layer decreases until it provides only minimal impedance. At this point a plateau region emerges, during which the total measured impedance was frequency independent. Within this plateau region the total measured real impedance was relative to the bulk material electrical impedance. Through the use of a saline electrolyte the spectroscopic impedance of the parallel-plate measurements were assessed.

Characterisation of the insulating electrode technique was required to ensure that during laboratory based testing the bulk material electrical properties extracted from the spectroscopic impedance were indeed representative of the actual electrical properties. In order to achieve this, an independent measurement technique was required to compare data acquired from the insulated electrode method. A bench conductivity meter was chosen as the secondary measurement technique, and the use of a saline electrolyte of varying NaCl levels was used as the bulk material. The technique and bulk material were chosen as a calibrated bench conductivity meter can measure the absolute values of electrical conductivity of an electrolyte with confidence. This will allow comparison of data between measurement methods to inform whether the use of insulated electrodes can be used to measure soil electrical properties, with the aim to determine moisture content.

5.1.1: Measurement of Electrical Conductivity for Water Based Electrolytes with Bench Conductivity Meters

This section presents the results obtained for the measurement of electrical conductivity of saline electrolytes using a bench conductivity meter. The aim of this section was to determine both relationships and absolute values of electrical conductivity for electrolytes of varying salinity with calibrated equipment of known operating limits and specifications. In the following section, section 5.1.2, the absolute values obtained here will be compared to those achieved through the insulated electrode method and impedance analyser, which
will enable the determination of the accuracy with which the insulated electrode method can measure electrical conductivity of water based mediums. Variation within the saline electrolyte was created by increasing the NaCl content within deionised water samples. For each salinity level the electrolyte was placed in the parallel plate test vessel for measurement, where the electrical conductivity of the electrolyte was measured with both methods. However, the values obtained for the insulated electrode method are discussed in section 5.1.2. This section discusses only the measurement data obtained with the bench conductivity meter.

The analysis of test data in this section can be separated into two sections. First is the consideration of the repeatability of measurements using bench conductivity meters. The second section discusses the increase in electrical conductivity relative to the quantity of NaCl added to the deionised water sample, and whether this relationship is linear. Knowledge of the repeatability provides confidence in measurement equipment, while knowledge of the relationship between NaCl content and electrical conductivity is essential when comparing with measured data from the insulated electrode method as the values obtained in this section will be deemed as the reference point to which insulated electrode measurement values are compared.

**Repeatability of Bench Conductivity Meter Methods**

In order to determine repeatability of the bench conductivity meter, two repeat tests were performed, and for each test six levels of salinity. Levels of salinity were achieved by the addition of predetermined quantities of NaCl. For both tests, a 500 ml sample of deionised water was used, and salinity increased between 0g and 0.5g, at intervals of 0.1g. Table 5.1 shows the measured electrical conductivity for both test iterations, obtained through the SevenMulti conductivity meter. The table also shows both the proposed and measured NaCl quantity for each test step. It is essential to know the exact quantity of NaCl when attempting to determine both repeatability and relationships between NaCl content and electrical conductivity.
The measured value of conductivity for deionised water, with no extra NaCl added, shows the largest relative difference between test iterations with the conductivity of test 1 being approximately three times greater than that of test 2, however, both values of electrical conductivity are very low. Section 4.1 presented the measured conductivity range of the laboratory deionised water supply, where it was found that a range of 0.586 to 0.891 μS/cm was found in multiple repeat tests with the same SevenMulti conductivity meter. The electrical conductivity values presented in Table 5.1, for no additional NaCl content, should be within this range also, which they are not. Since measured values of conductivity lie well within the operating limits of the SevenMulti conductivity meter, which has a quoted range of 0.001 μS/cm to 1000 mS/cm, it can be assumed that a slight contamination had occurred during the transition from mixing vessel to measurement vessel. Measured values of electrical conductivity suggest that the contamination is not significant, as the conductivity for both samples is still very low. If the contamination was caused by NaCl, the electrical conductivity would vastly increase due to the salts being dissolved into ions which conduct electricity.

<table>
<thead>
<tr>
<th>Sodium Chloride (g)</th>
<th>Measured Conductivity (μS/cm)</th>
<th>Sodium Chloride (g)</th>
<th>Measured Conductivity (μS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proposed</td>
<td>Measured</td>
<td>Proposed</td>
<td>Measured</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.1</td>
<td>0.107</td>
<td>0.1</td>
<td>0.102</td>
</tr>
<tr>
<td>0.2</td>
<td>0.213</td>
<td>0.2</td>
<td>0.203</td>
</tr>
<tr>
<td>0.3</td>
<td>0.314</td>
<td>0.3</td>
<td>0.302</td>
</tr>
<tr>
<td>0.4</td>
<td>0.414</td>
<td>0.4</td>
<td>0.407</td>
</tr>
<tr>
<td>0.5</td>
<td>0.513</td>
<td>0.5</td>
<td>0.510</td>
</tr>
</tbody>
</table>

Table 5.1: Sodium Chloride test quantities and measured values of electrical conductivity acquired with the SevenMulti Conductivity Meter.

Table 5.1 also shows that once NaCl is added to the deionised water the relative difference between test iterations is much smaller for all salinity levels. Results show that for all salinity levels above deionised water, the difference between measurements is less than 5%, giving confidence that the test procedure was satisfactory and repeatable.
The columns measured and proposed from Table 5.1 show that the measured quantity of NaCl differed between tests due to the difficulty in placing exactly 0.1g of NaCl within the electrolyte sample. For test 1, each salinity level has a marginally higher quantity of NaCl than test 2, and therefore was expected to have a higher conductivity. If simple linear scaling is applied to the conductivity values from test 1 and 2 based on the measured quantity of NaCl in the electrolyte, it can be determined whether an identical quantity of NaCl would provide a more repeatable data set. Table 5.2 shows the measured values of electrical conductivity for test 1 and 2, the scaled value of electrical conductivity and the percentage difference between test iterations for all salinity levels when scaling has been applied.

Scaling was achieved by linear approximation to calculate a value of conductivity based on exact step sizes of 0.1g, rather than those measured. With no scaling, the error margin between tests 1 and 2 was less than 5% for all salinity levels, excluding deionised water. With scaling applied, the error margin for all salinity levels, again excluding that for deionised water, was reduced to less than 1%, suggesting excellent repeatability between test iterations and giving confidence to the precision of the SevenMulti conductivity meter. While this scaling has suggested that repeatability can be improved, care must be taken when using scaled values for analysis as multiple uses of scaled values, which are estimates, can lead to compound errors being created and inappropriate conclusions.

<table>
<thead>
<tr>
<th>NaCl (g)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>% Diff. Imped.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meas. Cond. (μS/cm)</td>
<td>Scaled Cond. (μS/cm)</td>
<td>Meas. Cond. (μS/cm)</td>
</tr>
<tr>
<td>0</td>
<td>3.32</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>0.107</td>
<td>446</td>
<td>417</td>
<td>0.102</td>
</tr>
<tr>
<td>0.213</td>
<td>870</td>
<td>817</td>
<td>0.203</td>
</tr>
<tr>
<td>0.314</td>
<td>1273</td>
<td>1216</td>
<td>0.302</td>
</tr>
<tr>
<td>0.414</td>
<td>1678</td>
<td>1621</td>
<td>0.407</td>
</tr>
<tr>
<td>0.513</td>
<td>2050</td>
<td>1998</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 5.2: Scaled electrical conductivity and % difference between test iterations 1 and 2, for the bench conductivity meter method.
Relationship between NaCl Content and Electrical Conductivity from Bench Conductivity Meter Measurements

This section considers the relationship between the measured values of electrical conductivity relative to the quantity of NaCl placed within the electrolyte. Values of electrical conductivity, observed in Table 5.2, show that the electrical conductivity increases with increasing salinity, expected due to the higher concentration of ions within the electrolyte as NaCl is increased. Observation of the measured values of electrical conductivity with the SevenMulti conductivity meter show good linearity for increasing salinity, with an increase of approximately 400 μS/cm experienced for each change in salinity level, for both test iterations. Within the range of NaCl levels used for these tests the relationship was found to show good linearity.

The relationship between electrical conductivity and NaCl content is important because the insulated electrode method may not be capable of determining accurate absolute values of electrical conductivity, but produce a measured value of conductivity which has a consistent percentage difference between absolute values, but is still linear. However, if the value of conductivity acquired through the insulated electrode method is not linear for increasing salinity it may indicate that the measured value of impedance is not solely determined by the bulk material, but is also a function of multiple parameters, such as the impedance of the insulating layer.

This section has determined that the SevenMulti conductivity meter has excellent precision, with measured values of electrical conductivity being within 1% for repeat tests at multiple salinity levels, when a scaling factor was applied to negate the effects of varying salinity between test iterations. The final observation from this section is that the relationship between electrical conductivity and NaCl content shows good linearity between 0.1 – 0.5g of NaCl per 500 ml deionised water. This linearity will be used when analysing data from the insulated electrode method, to determine whether the value of electrical conductivity extracted from the plateau region is determined only by the bulk material electrical properties with insignificant influence of the insulating layer.

The following section discusses test data acquired with the insulated electrode method in the parallel-plate test vessel for an electrolyte of increasing salinity, to determine how
accurate the insulated electrode method is compared to a calibrated bench conductivity meter.

5.1.2: Measurement of Electrical Conductivity for Water Based Electrolytes through the Insulated Electrode Method

The previous section discussed those tests performed to determine the accuracy and repeatability of bench conductivity meters, in relation to an electrolyte of increasing salinity. For each test performed with the bench conductivity meter, a second test was performed immediately afterwards with the impedance analyser and insulated electrode method. This allows a direct comparison between test data as exactly the same batch of electrolyte was tested. The aim of this section is to determine whether the insulated electrode method is capable of measuring the electrical impedance of a bulk material placed between two parallel facing electrodes. Measured values will be compared to those achieved with the bench conductivity meter.

The results and discussion in this section are again separated into multiple smaller sections for ease of analysis. In the first section the discussion relates to the selection of the plateau frequency for each level of salinity, and the extraction of electrical impedance at the selected plateau frequency. The extracted values of electrical impedance are converted to electrical conductivity to allow easier comparison with bench conductivity meter data. The next section then considers the repeatability of the insulated electrode method based on the values of electrical conductivity for both test iterations, and all salinity levels. Following this, the discussion considers whether the electrical conductivity measured through the insulated electrode method is linear, and also presents the comparison of data between the two measurement methods to determine whether the insulated electrode method may be used to measure the electrical properties of a bulk material placed between two parallel facing electrodes.
Extraction of Electrical Impedance Data from Insulated Electrode Methods

Insulated electrode methods require a frequency sweep in order to determine the spectroscopic response of the measurement. This spectroscopic response can be used to extract data relative to the bulk material, the insulating layer or a combination of both, dependent on the frequency at which the real impedance is taken. Since the aim is to determine the bulk material properties only, careful selection of the frequency at which the total measured impedance is influenced by only the bulk material is essential. In chapter 3 it was determined that the low frequency impedance would be attributed to the electrical impedance of the insulating layer, but that as frequency was increased a plateau region would emerge, for which bandwidth the total real impedance of the solution could be used to estimate the bulk material impedance. The location of the plateau region in relation to frequency was dependent on the conductivity of the bulk material. For materials of a low conductivity the plateau region occurred at low frequencies, but as conductivity increased, so also did the plateau frequency. Therefore, the frequency used to extract bulk material impedance was dependent on the conductivity of the solution. If multiple materials were compared where the bulk material had a significantly different electrical conductivity, it may be the case that multiple plateau frequencies would be required. If a value of impedance is extracted when not at the plateau frequency the value of impedance may be the function of both the insulating layer and the bulk material, giving a false result.

Figures 5.1 and 5.2 show the measured spectroscopic impedance for each salinity level for tests 1 and 2 respectively. For all tests a distinct plateau region emerges, however, for tests where no NaCl was present and the electrolyte was deionised water only, the plateau region is significantly different to all other levels of salinity. This leads to the requirement of multiple plateau frequencies. For deionised water a plateau frequency of 5 kHz was selected, as seen by the vertical marker placed on both figures. For all samples where NaCl was present in the electrolyte, a unique plateau frequency was required, which highlights the importance of spectroscopic measurements for each test. For electrolyte of salinity 0.1 g a plateau frequency of 2 MHz was used. However, if a single value of 2 MHz was used for all tests, including the deionised water, the value of real impedance for the deionised water at 2 MHz is less than that for all salinity levels, which would be incorrect. It can be seen that as NaCl content increases the plateau region magnitude decreases, and the lower
frequency cut-off of the plateau region increases also. The plateau frequency used for each salinity level can be found in Table 5.3.

**Figure 5.1**: Measured spectroscopic impedance for an electrolyte of increasing salinity, test iteration 1.

**Figure 5.2**: Measured spectroscopic impedance for an electrolyte of increasing salinity, test iteration 2.
<table>
<thead>
<tr>
<th>NaCl (g)</th>
<th>Plateau Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5 kHz</td>
</tr>
<tr>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>0.2</td>
<td>4</td>
</tr>
<tr>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>0.4</td>
<td>6</td>
</tr>
<tr>
<td>0.5</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 5.3: Selected plateau frequency for each level of salinity, based on visual observation of the spectroscopic impedance for test iterations 1 and 2.

With the plateau frequencies decided, the electrical impedance of the bulk material for each test could be extracted at the selected plateau frequency. This value of impedance was then converted to electrical conductivity based on the known internal cell dimensions of the parallel-plate test vessel. Conversion to electrical conductivity was performed to allow easier comparison between measurement methods. The value of electrical impedance at each plateau frequency, and the converted electrical conductivity values can be found in Table 5.4.

<table>
<thead>
<tr>
<th>Sodium Chloride (g)</th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meas. Imped. (Ω)</td>
<td>Converted Cond. (μS/cm)</td>
</tr>
<tr>
<td>Proposed</td>
<td>Measured</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>232k</td>
</tr>
<tr>
<td>0.1</td>
<td>0.107</td>
<td>710</td>
</tr>
<tr>
<td>0.2</td>
<td>0.213</td>
<td>368</td>
</tr>
<tr>
<td>0.3</td>
<td>0.314</td>
<td>251</td>
</tr>
<tr>
<td>0.4</td>
<td>0.414</td>
<td>190</td>
</tr>
<tr>
<td>0.5</td>
<td>0.513</td>
<td>154</td>
</tr>
</tbody>
</table>

Table 5.4: Proposed and measured sodium chloride test quantities, electrical impedance measured with the insulated electrode method and converted values of electrical conductivity.
Repeatability of Insulated Electrode Methods

This section discusses the repeatability of the insulated electrode method. The bench conductivity meter produced a difference between measurements of less than 5% for all salinity levels, excluding deionised water. However, this was improved to less than 1% when linear normalisation was applied based on the measured quantity of NaCl in the electrolyte, rather than the proposed value. The same procedures used to compare the repeatability of the bench conductivity meter will be used here. Since the electrical impedance was converted to conductivity, only the values of conductivity are considered during the remainder of this section.

From Table 5.4 it was seen that values of electrical conductivity between test iterations 1 and 2 are similar for all salinity levels. Analysis of the numerical values shows that as with the bench conductivity meter all values are less than 5% difference between test iterations, excluding deionised water, for all salinity levels. The same scaling method applied to the bench conductivity meter results was also applied to the results obtained from the insulated electrode method. The scaling results are found in Table 5.5, where it can be seen that scaling has again improved difference between measurements, here to less than 2.5%, based on linear scaling relative to the step size of 0.1g increments in salinity. This improved repeatability demonstrates that the insulated electrode method was capable of measuring with precision.

<table>
<thead>
<tr>
<th>NaCl (g)</th>
<th>Test 1</th>
<th>Test 2</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meas. Cond. (μS/cm)</td>
<td>Scaled Cond. (μS/cm)</td>
<td>Meas. Cond. (μS/cm)</td>
</tr>
<tr>
<td>0</td>
<td>1.24</td>
<td>n/a</td>
<td>0</td>
</tr>
<tr>
<td>0.107</td>
<td>405</td>
<td>379</td>
<td>0.102</td>
</tr>
<tr>
<td>0.213</td>
<td>781</td>
<td>733</td>
<td>0.203</td>
</tr>
<tr>
<td>0.314</td>
<td>1145</td>
<td>1094</td>
<td>0.302</td>
</tr>
<tr>
<td>0.414</td>
<td>1521</td>
<td>1470</td>
<td>0.407</td>
</tr>
<tr>
<td>0.513</td>
<td>1866</td>
<td>1819</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Table 5.5: Scaled electrical conductivity and % difference between test 1 and 2 for the insulated electrode method.
The measured conductivity obtained with the bench conductivity meter showed good linearity for all salinity levels tested, with an increase of approximately 400 μS/cm for each step increase in electrolyte salinity. This section aims to determine whether the measured value of electrical conductivity extracted from the insulated electrode method is also linear. Since the insulated electrode method demonstrated good repeatability between test iterations, only the values of electrical conductivity obtained from test iteration 1 are analysed in this section.

Analysis of the results shows good linearity between increasing salinity and electrical conductivity, but that each step increase in salinity results in an increase of approximately 360 μS/cm, compared to 400 μS/cm for the bench conductivity meter. This suggests that the value of electrical impedance initially extracted at the plateau frequency is not completely independent of other properties such as the impedance of the insulating layer. However, the values of impedance are consistent, as the difference between measurement methods is consistent for all salinity levels.

Figure 5.3 shows the electrical conductivity for increasing salinity level for both measurement methods; the bench conductivity meter and the insulated electrode method. Both techniques appear to show good linearity, but assuming the bench conductivity data to be most accurate, the plotted data appear to show that as salinity increases the insulated electrode method becomes more inaccurate. However, calculation of the percentage difference between both methods determines that the value of conductivity obtained from the insulated electrode method is approximately 10% less than that of the bench conductivity meter for all salinity levels, excluding deionised water. Being able to measure the electrical conductivity of a bulk material to within 10% of a calibrated instrument is a reasonable result, and one which gives confidence in the insulated electrode measurement technique, suggesting that it is possible to measure the electrical properties of the bulk material properties through capacitively coupled measurements.
5.2: Measuring Change in Electrical Impedance for Varying Soil Moisture, Compaction and Temperature

This section considers the change in electrical impedance resulting from the variation of three soil properties: moisture content, compaction level and temperature. Other factors will affect the electrical impedance of the soil, which are not tested in this research. Factors such as organic matter, salinity of the soil fertiliser levels etc. These parameters are not considered here as all tests performed within this research utilise soil from the same batch, which was characterised prior to testing and use of the same soil will reduce variation of these parameters.

It was anticipated that of the three parameters tested, soil moisture would provide the largest change in electrical impedance, with increasing moisture content resulting in decreasing electrical impedance. It was also expected that both increasing soil compaction and temperature would decrease electrical impedance. For compaction, this reduction in electrical impedance would be caused by the reduced porosity and subsequent increase of ionic pathways in compacted soils. As temperature increases the electrical conductivity of the water will also increase, which will lead to a reduction in electrical impedance for increasing soil temperature.
Three sets of tests were performed in order to determine the change resulting from adjustment of each parameter. In the first set, soil moisture was varied by wetting soil to six moisture levels between 5-30% gravimetric water content, in steps of 5%. For each level of moisture content the spectroscopic impedance was measured. In the second set the level of compaction was varied between four levels at each of the six moisture levels previously tested. This allowed a comparison between change in electrical impedance resulting from moisture content and change resulting from compaction. In the final set of tests the soil temperature was varied between 5-40°C in steps of 5°C, for each of the six moisture levels. Again, this allowed comparison between changes in electrical impedance due to soil moisture compared to that experienced from temperature. For all sets of tests three repeat iterations were performed for each change in parameter to determine repeatability.

5.2.1: Change in Electrical Impedance due to Variation of Moisture Content

For soil moisture testing, three test iterations were performed. For each test the soil moisture was increased from 5-30% gravimetric moisture content. For each level of moisture content, the soil was compressed to a pressure of 0.05 kg/cm² for consistency. This is the same pressure as exerted on the loosest compacted soil in section 5.3.2. Care was taken to ensure that the soil remained at ambient temperature. This was achieved by placing test vessels within a controlled environmental chamber during testing and ensuring that both the soil and deionised water used to wet the soil was normalised to ambient temperature. For all tests a plateau region is desired from which a single frequency can be selected, at which the complex impedance is most relative to the bulk material resistance. As with the characterisation tests previously discussed, section 5.1, the plateau frequency was chosen through visual observation of the plotted spectroscopic impedance of each test.

The aim of this section was to determine whether there is a repeatable change in electrical impedance for varying soil moisture content. A secondary aim was to determine a typical rate of change to electrical impedance for increments of 5% gravimetric water content in
the soil, and establish whether a linear relationship existed between soil impedance and increasing water content.

Figures 5.4 to 5.6 show the measured spectroscopic real impedance for all six soil moisture contents, for test repeat iterations 1-3 respectively. For soils less than 15% moisture content visual observation suggests that a plateau region is distinguishable and will allow the selection of a plateau frequency. For soils greater than 20% moisture content the decrease in impedance causes difficulty in analysis of test data as the plateau shifts towards the upper frequency limits of the impedance analyser, 13 MHz, and is also not horizontal. Since no clear plateau region can be estimated based on visual observation alone, a method of estimating the plateau frequency based on tests performed on drier soils was implemented. Therefore, the discussion and analysis of estimating the plateau frequencies has been split into two sections; first the analysis of samples less than 15% soil moisture from which a visual estimation of a plateau frequency could be achieved. The second the analysis was of those samples greater than 20% moisture content and utilised a method of numerically estimating the plateau frequency. Following this the discussion focuses on the values of impedance extracted for each level of moisture content, their magnitude and whether any linearity exists between increasing moisture content and electrical impedance.
Figure 5.5: Measured real impedance for test 2; 5-30% soil moisture.

Figure 5.6: Measured real impedance for test 3; 5-30% soil moisture.
Estimating the Plateau Frequency for Soil with Gravimetric Water Content ≤15%

For tests 1 - 3, Figures 5.4 to 5.6 respectively, the real impedance plots for 5% - 15% soil moisture contents in test 1 show that a plateau region is visible, which enables estimation of a plateau frequency and subsequent estimation of impedance of the soil. However, for both tests 2 - 3, the plateau region is more difficult to estimate and the plateau regions are estimated with less confidence. It can also be seen that for all tests the plateau region is not horizontal, unlike that suggested by simulation, but has decreasing impedance with increasing frequency. However, for soils with less than 15% moisture a plateau like area can still be estimated in which the resistance change is relatively small. This decreasing impedance in the plateau region confirms that the simple electrical model used in simulations is not perfect, which was expected and previously mentioned. However, the electrical model is still adequate for providing an estimation of expected spectroscopic impedance with an insulated electrode measurement in a parallel-plate test cell.

Consideration of test data also reveals that the measured impedance at low frequency changes with varying soil moisture content, which should not occur as simulation results suggested that low frequency impedance is dependent only on the electrical properties of the insulating layer and not the bulk material. As was implemented previously, the use of the SMP GUI suggested that low frequency impedance should be independent of the bulk material if the model is correct. It was found that no combination of simulation parameter values for resistance and capacitance of the bulk material had an effect on the impedance of the insulating layer, except when a very high bulk material resistance was simulated, as the impedance of the bulk material is greater than that of the insulating layer. Therefore, it was concluded that the changes in measured impedance at low frequency were due to the impedance analyser performing measurements out of range. It was previously discussed that the high impedance measurement operating limit of the impedance analyser was 1.5 MΩ and that the impedance of the insulating layer far exceeded that, which may be the cause of erratic measurement data at low frequencies. Despite this low frequency variation, the main area of interest is at much higher frequencies, where the total measured impedance is dominated by the impedance of the bulk material, which is typically much lower than 1 MΩ and therefore within the operating specification of the impedance analyser.
Table 5.6 shows the estimated plateau region for 5-15% soil moisture content for test 1-3, based on the spectroscopic impedance data from Figures 5.4 to 5.6. For all three values of moisture content, test 1 has a significantly lower plateau region than tests 2 and 3. It is suggested that this is due to the heterogeneity of the soil as well-defined test procedures were followed. Tests 2 - 3 show an improved repeatability for 5 - 15% moisture content, with the estimated plateau region bandwidth being very similar, and having a common ‘overlapping’ plateau frequency which could be used for both tests.

<table>
<thead>
<tr>
<th>Soil Moisture %</th>
<th>Estimated Plateau Region (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 01</td>
</tr>
<tr>
<td>5</td>
<td>700 – 5k</td>
</tr>
<tr>
<td>10</td>
<td>40k – 700k</td>
</tr>
<tr>
<td>15</td>
<td>300k – 4M</td>
</tr>
</tbody>
</table>

Table 5.6: Plateau region estimates based on spectroscopic real impedance plots found in Figures 5.4 to 5.6.

For future analysis of bulk material impedance relative to soil moisture content, the plateau regions presented in Table 5.6 are used to estimate a plateau frequency at the mid-range value from the bandwidth, from which the total electrical impedance will be estimated for soils of 5-15% moisture content, Table 5.7. The following section discusses the use of data trend fitting of data, from soils with 5-15% moisture content, to estimate the plateau frequency for soils of 20-30% moisture content.

**Estimating the Plateau Frequency for Soil with Gravimetric Water Content ≥20%**

Consideration of Figures 5.4 to 5.6 indicates that for soils of higher moisture content it was not possible to estimate a plateau region or frequency through visual observation alone with any degree of confidence. A data fitting technique was therefore implemented to allow estimation of a plateau frequency based on the trend experienced in soils of lower moisture content.
The value of plateau frequency for soils of 5 - 15% moisture content was used to calculate the ratio of change in electrical impedance at the transition between 5 - 10% and 10 - 15% soil moisture contents. The ratio of change between these transitions was used to estimate the plateau frequency of soils greater than 20% moisture content. Figure 5.7 shows the estimated plateau frequency for all levels of soil moisture content. Those estimated for soils less than 15%, achieved through visual observation of the spectroscopic impedance alone are seen in section (a), while those estimated through data fitting are seen in section (b). The second plot in Figure 5.7 shows the corresponding electrical impedance for each plateau frequency. From this impedance plot it can be seen that the decrease in measured impedance between 5-10% moisture content is very large, approximately 50 times less, whereas the difference for 10-15% is only 4 times less. Estimation of the 20% soil moisture plateau frequency was based on curve fitting, and the difference in impedance between 15-20% was estimated to be approximately 1 - 1.5 times. This technique was continued until a plateau frequency was achieved for all six soil moisture contents. This decreasing gradient of impedance for increasing moisture content was expected due to soils of high moisture content tending towards a point of saturation where the increase in water content has a much smaller effect than an increase of water in very dry soils. The plateau frequencies derived for soil moisture levels 5 – 30% are seen in Table 5.7.

Figure 5.7: Estimated plateau frequencies for 20-30% soil moisture content based on measured values for 5-15%, test 01.
<table>
<thead>
<tr>
<th>Soil Moisture %</th>
<th>Plateau Frequency (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.004</td>
</tr>
<tr>
<td>10</td>
<td>0.2</td>
</tr>
<tr>
<td>15</td>
<td>0.8</td>
</tr>
<tr>
<td>20</td>
<td>1.3</td>
</tr>
<tr>
<td>25</td>
<td>1.4</td>
</tr>
<tr>
<td>30</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Table 5.7: Estimated plateau frequencies for 5-30% soil moisture content.

One difficulty encountered with this method of estimating a plateau frequency was that no impedance measurements were performed at those plateau frequencies obtained through data fitting. For example, the estimated plateau frequency for test 1; 20% soil moisture was 1.3 MHz. Of the frequency sweeps performed only measurement data for 1 or 2 MHz were acquired. Therefore, a linear approximation was applied to estimate the impedance at 1.3 MHz based on the value of impedance at 1 and 2 MHz. While the technique provides a relatively crude estimation of the plateau frequencies and corresponding impedances, it does allow the derivation of a value for plateau frequency which can be used to estimate the impedance of the soil at higher moisture contents.

**Analysis of Impedance for Varying Soil Moisture Content Based on Estimated Plateau Frequencies**

This section discusses the change in electrical impedance for increasing soil moisture content. Figure 5.8 shows the real impedance at all six moisture contents for all three tests performed. It can be seen that despite variation in absolute values of measured impedance the plots follow a similar trend, that for low moisture content the impedance is very high and as a small amount of water is added, 5-10% increase, the impedance reduces significantly. However, as more water is added to the soil the magnitude of impedance change decreases, confirming that the soil reaches a point of saturation in which the addition of water has less effect on electrical impedance than in drier soils.
The numerical values of electrical impedance for all three tests can be found in Table 5.8. For 5% soil moisture content the difference in electrical impedance between test iterations is as large as 1 MΩ. It is suggested that this is due to differences in the soil structure between tests. Taking the smallest and largest values of impedance for soil with 5% moisture content, the largest value of impedance is approximately 6 times greater than the smallest, despite the well-defined test procedures followed for each test. For soil of 30% moisture content the variation between lowest and highest values of impedance between test repeats was approximately 0.15 times greater, a significantly smaller variation for wetter soils. It is suggested that this variation in drier soils is caused by the reduced number of ionic pathways through the soil due to lack of water. This will lead to the impedance being much more dependent on soil structure and porosity, which will both vary for each test iteration. As water is added to the soil the air gaps will be filled with water, creating multiple pathways for the electrical current. Once these pathways have been created the variation due to porosity was expected to reduce. Despite the variation at low levels of moisture content, the values of impedance show that the measurement technique shows good repeatability for greater than 10% moisture content. This repeatability confirms both the adequacy of the measurement procedures and that despite the difference in absolute values, the addition of water has a repeatable effect on electrical impedance.
Table 5.8 also shows percentage change between each 5% gravimetric step of soil moisture content relative to the electrical impedance of the previous sample. These percentage values show whether the change is linear. For all three test iterations it can be seen that the difference in impedance between 5% and 30% soil moisture is very large, with the 30% moisture content having a value of impedance approximately 1000 times smaller than that for 5% soil. The analysis also shows that the difference in impedance between moisture contents is non-linear. As was confirmed in Figure 5.8, as moisture content increases the magnitude of the change in electrical impedance between moisture levels reduces.

### Determining Parameter Values Based on Empirical Modelling

The previously discussed method of estimating the plateau frequency was based on visual observations of spectroscopic data alone. This allowed a rapid method of estimating the bulk material resistance, but does not allow for estimation of the bulk material capacitance. Empirical data fitting with the SMP GUI can be used to fit the analytical solution to measurement data to determine a value of both resistance and capacitance since the impedance roll-off which occurs at the highest frequencies is determined by the capacitance of the bulk material. For water based measurements this value is not essential to know, since water typically has a relative permittivity of 80. For soil, however, the relative permittivity of the soil will be largely dependent on the moisture content, and will
vary from approximately 3-5 for dry soil to greater than 50 for saturated soils. This section aims to determine whether the estimated value of capacitance of the soil, and subsequent converted relative permittivity value, will reflect the level of soil moisture content.

Figure 5.9 shows an example of empirically fitted data in soil of 5% moisture content, where the differences between simulated and measured data are apparent. At low frequency the simulation data can be fitted to measurement data with good agreement, despite ambiguity between absolute values of both theoretical and measured impedance of the insulating layer. Fluctuations occur in measurement data at approximately 1 – 100 Hz. It is suggested that this is due to the impedance analyser being unable to accurately measure such a high value of impedance. The most significant discrepancy between simulation and measurement data occurs at frequencies greater than 10 kHz. The analytical solution suggests that in this region the decreasing impedance is determined by the capacitance of the bulk material. It was found to be impossible to fit simulation data to measurement data within this region with the analytical solution proposed. However, through trial and error it was determined that the best fit of data was achieved by the use of a value of bulk material capacitance of 1.5pF, which correlates to a relative permittivity value of 4.87. Despite the lack of confidence in the fitting of data within this region, this value of relative permittivity is within the typical range of that experienced for drier soils. The value of relative permittivity used for dry soil in simulations was 4, which is in good agreement with this value. However, this value was expected to be slightly higher since it was not dry soil measured, but instead soil wetted to 5% gravimetric moisture content.

Empirical data fitting also enables the estimation of complex impedance values for the insulating layer to confirm accuracy of simulation parameters. Theoretically calculated values of $R_w$ and $C_w$ were 1.5 MΩ and 178 pF respectively, based on the measured electrical properties of the insulating layer with tap water as the bulk material. These do not correlate well with values derived from empirical modelling where $C_w$ was found to be 70 pF and $R_w$ 45 MΩ. This highlights limitations due to the simplicity of the electrical model and the possible errors caused by the impedance analyser being used outside its operating specification.
Figure 5.9: Empirical data fitting to determine parameter values soil wetted to 5% moisture content. Where; 
\[ CW = 70\text{pF}, \; RW = 45\text{M}\Omega, \; CB = 1.5\text{pF}, \; RB = 1.4\text{ M}\Omega. \]
Test 01; 5% Moisture Content.

Figure 5.10 shows the empirical fitting of data for test 1 at 15% moisture content to demonstrate another example of empirically fitted data, and the drawbacks experienced from the simple model which was used to create the analytical solution. It can be seen that for this example uncertainty exists at lower frequencies of less than 100 kHz where simulation data cannot be fitted to measurement data, despite variation of parameters \( R_W \) and \( C_W \). At higher frequencies, greater than 100 kHz, the simulation data can be fitted to measurement data with greater confidence.

Figure 5.10: Empirical data fitting to determine parameter values soil wetted to 15% moisture content. Where; 
\[ C_W = 70\text{pF}, \; R_W = 15\text{M}\Omega, \; C_B = 3.5\text{pF}, \; R_B = 4.6\text{ k}\Omega. \]
Test 01; 15% Moisture Content.
Table 5.9 shows the values of capacitance, determined through empirical fitting, for test 1 at each level of soil moisture content. The values of capacitance were converted to electrical permittivity based on the internal cell dimensions of the parallel-plate test vessel. It can be seen that the capacitance, and relative permittivity, significantly increase for increasing soil moisture content as was proposed. The values of permittivity are in good agreement with those to be expected based on values used in chapter 3. In chapter 3, soils of three moisture contents were simulated; dry, moderate and saturated. The relative permittivity values were 4, 25 and 30 respectively. The value of relative permittivity derived from measurement data was higher than the simulated values, but is still within an acceptable margin of error, due to high water content in saturated soil. With water having a relative permittivity of 80 the relative permittivity of the soil would be expected to tend towards this value.

It can therefore be seen how analysis of both the bulk material resistance and capacitance can be advantageous as knowledge of the capacitance can assist in determining the moisture content of the soil, due to the soil permittivity being primarily dependent on its water content. The same process will be applied for soil compaction and temperature testing to determine whether altering these parameters will affect the capacitance.

<table>
<thead>
<tr>
<th>Soil Moisture Content</th>
<th>Empirically Derived Values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capacitance (pF)</td>
<td>Relative Permittivity</td>
</tr>
<tr>
<td>5%</td>
<td>1.5</td>
<td>4.9</td>
</tr>
<tr>
<td>10%</td>
<td>2.5</td>
<td>8.1</td>
</tr>
<tr>
<td>15%</td>
<td>3.5</td>
<td>11.4</td>
</tr>
<tr>
<td>20%</td>
<td>5</td>
<td>16.2</td>
</tr>
<tr>
<td>25%</td>
<td>8</td>
<td>26.0</td>
</tr>
<tr>
<td>30%</td>
<td>17</td>
<td>55.2</td>
</tr>
</tbody>
</table>

Table 5.9: Empirically determined values of Capacitance, and calculated relative permittivity values for test 01.
Conclusions for Testing of Soil Moisture Content

Plotting the impedance, extracted from the plateau frequencies, for increasing moisture content has shown that reliable measurements of the moisture content in soil can be obtained using the parallel-plate test cell. As expected, when the moisture content increases the soil impedance decreases. However, this relationship is not linear, and the rate of change between drier soil samples is far greater than when the soil tends towards saturation. It was also found that large variability existed in soil of 5% moisture content, attributed to the lack of water and large variation in porosity despite the controlled level of compaction in the soil. As moisture content in the soil increased, the variation between test iterations improved. Empirical modelling also confirmed that the capacitance of the soil significantly increases with increasing moisture content. The value of capacitance was converted to relative permittivity, where it was found that measured values were similar to those used for simulations, suggesting they are accurate. Being able to determine the permittivity of the soil can improve the confidence with which moisture content can be predicted, since its value is very dependent on water content of the soil.

If soil moisture content was the only parameter which affected electrical impedance, the moisture level could be estimated with confidence based on the data presented. However, the soil impedance is a function of many parameters. Two other parameters which will significantly affect the impedance of the soil are compaction and temperature. The next section discusses the change in impedance relating to increasing compaction of the soil. It was expected that as the soil was compacted to a greater physical pressure the impedance would decrease, due to decreasing air porosity in the soil. However, it was unknown whether the change in impedance from compaction would be comparable in magnitude to the change resulting from moisture content change. If increasing compaction had a small effect compared to that of increasing moisture content it could be either disregarded or an error factor be applied to soil moisture measurements.
5.2.2: Change in Electrical Impedance due to Variation of Soil Compaction

When a soil is compacted, large pore spaces between soil particles are reduced, restricting air and water movement through the soil. The physical restrictions caused by compaction will limit the growth of plants in the soil as roots struggle to push through compacted soil due to its increased strength. This limited movement of roots may lead to water and air starvation, and ultimately death of the plant if compaction becomes too severe. In field based applications detrimental effects caused by soil compaction are difficult to correct, often requiring destructive procedures to physically break up the soil and recreate good structure. Therefore it is advisable to avoid the use of heavy machinery on wet soils, those most susceptible to compaction due to the moisture content enabling changes to soil structure. However, heavy machinery is not the sole blame for soil compaction. Over time, soil will naturally compact due to rain fall and the weight of the soil pushing down on itself. While heavy machinery, rain fall and gravity may not affect soil compaction in laboratory based testing, the pressure exerted during placement of soil within the test vessel can vary significantly unless controlled test procedures are followed.

With regard to electrical properties, an increase in soil compaction will subsequently increase the number of ionic pathways as porosity is reduced. This will lead to an increase in electrical current flow through the soil, which will cause a reduction in the electrical impedance. In saturated soils, however, it was expected that compaction would have little to no effect on impedance due to the soil pores being full of water. It is also suggested that increasing compaction will have no significant effect on the permittivity of the soil per unit volume, unlike varying moisture content, as compressing the soil does not change its moisture content, which is the predominant factor in the value of permittivity. If this is confirmed it will highlight the importance of measuring the capacitance of the soil to determine moisture content.

This section aims to determine the typical change in bulk impedance for varying levels of compaction which will ultimately be compared to the change of electrical impedance associated with increasing soil moisture content. The aim is to also determine whether a well-defined test procedure can provide repeatable results, giving confidence in future test procedures. Since the overall aim of the research is to determine the movement of soil moisture as a result of root water uptake, knowledge of the effects of compaction on electrical impedance will assist in estimating soil moisture content. If a consistent rate of
change is found for varying soil compaction, the overall soil moisture can be better
determined within a certain error margin, relating to possible variation from compaction.

The complete test procedure for compaction testing can be found in chapter 4. In
summary, the soil is wetted to each of the six levels of moisture content previously
discussed, and for each level of moisture content the soil is compacted to four levels of
increasing pressure; 0.05, 0.11, 0.16 and 0.21 kg/cm². The electrical impedance is measured
at each level of compaction. As with soil moisture testing, three repeat test iterations were
performed to determine repeatability.

**Determining Repeatability of Measurements through
Comparison of Multiple Test Iterations**

The following paragraphs discuss the measurement data acquired for soils of increasing
compaction in order to determine the repeatability of test procedures and the
measurement system. Where possible a single plateau frequency was chosen for each level
of moisture content, which was common between all levels of compaction. If required, the
data fitting technique discussed in section 5.3.1 was utilised to acquire a value of
impedance at a non-measured frequency.

Figure 5.11 shows the spectroscopic real impedance at 5% soil moisture content acquired
in test iteration 1. The figure shows four plots representing the four compaction levels 1-4.
It can be seen that for increasing soil compaction the magnitude of impedance within the
plateau region decreases with increasing compaction as was anticipated. The spectroscopic
impedance for all four levels of compaction show good repeatability when considering the
anticipated spectroscopic impedance at low and high frequency regions outside of the
plateau, which should be unchanging and independent of bulk material properties. While
not completely horizontal, a clear plateau region occurs between approximately 500Hz
and 6 kHz. It is within this bandwidth that the largest change of electrical impedance for
each level of compaction occurs, suggesting that the plateau region represents the
bandwidth where the total measured impedance is relative to the bulk material only. It can
also be seen that the spectroscopic impedance follows the typical shape expected from the
simulated measurement data, which is that of high impedance at low frequency decreasing down to the plateau region as frequency increases. Figure 5.12 shows a zoom of the plateau region for test 1 and 5% soil moisture content to clearly show the decrease in impedance for increasing compaction. The selected plateau frequency can be observed by the vertical marker placed on both Figures 5.11 and 5.12. The plateau frequency of 4 kHz was selected by visually observing the plotted impedance and choosing a frequency which was common among all levels of compaction.

Other plots of electrical impedance for changing compaction level and moisture content display similar behaviour and therefore are not presented in this report. Table 5.10 shows the values of impedance extracted from each test, relative to the appropriate plateau frequency, to allow an analysis of repeatability.

![Figure 5.11: Impedance for increasing compaction pressure of 5% gravimetric soil moisture content.](image)
From Table 5.10 it can be seen that the greatest difference in absolute values of electrical impedance between test iterations occurs in tests performed at 5% soil moisture content. This was expected as drier soils show more variability due to the very limited number of ionic pathways through the soil and therefore soil structure determines the impedance. Once sufficient moisture is added to the soil, greater than 10% moisture content, the repeatability of absolute values significantly improves.
Tables 5.11 to 5.13 show the percentage change for increasing compaction level, at each soil moisture content, for tests 1-3 respectively. The percentage change provides a relative method of comparing data to determine the magnitude of change for both soil moisture content and compaction change independent of the absolute values. For all tests it can be seen that increasing the compaction significantly decreases the impedance from the original reference value of level 1 compaction, but that the decrease is largest in drier soils. When the 5% soil moisture is compacted between levels 1 to 4, the impedance decreases by a very repeatable percentage of 43-47% over all three tests, giving confidence in the measurement procedure used. It was previously discussed how the absolute values of measured impedance for test 1 were significantly higher than tests 2 and 3, highlighting the difficulties in analysis of absolute values alone. However, relative measurements of impedance change show that increasing the compaction has a similar rate of change on impedance despite the magnitude of measured impedance.
### Table 5.11: Percentage change in measured impedance from compaction level 1 for each soil moisture content – test 1.

<table>
<thead>
<tr>
<th>Compaction</th>
<th>Soil Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>-21</td>
</tr>
<tr>
<td>3</td>
<td>-29</td>
</tr>
<tr>
<td>4</td>
<td>-43</td>
</tr>
</tbody>
</table>

### Table 5.12: Percentage change in measured impedance from compaction level 1 for each soil moisture level – test 2.

<table>
<thead>
<tr>
<th>Compaction</th>
<th>Soil Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>-29</td>
</tr>
<tr>
<td>4</td>
<td>-46</td>
</tr>
</tbody>
</table>

### Table 5.13: Percentage change in measured impedance from compaction level 1 for each soil moisture level – test 3.

<table>
<thead>
<tr>
<th>Compaction</th>
<th>Soil Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>-25</td>
</tr>
<tr>
<td>3</td>
<td>-38</td>
</tr>
<tr>
<td>4</td>
<td>-47</td>
</tr>
</tbody>
</table>

Table 5.14 shows the percentage change in measured impedance from compaction level 1 - 4, the loosest to most compressed, to provide a summary of whether the change due to compaction is similar relative to the measured impedance. The largest variation in repeatability between test iterations occurs when the soil is wettest, at 30% moisture content, where the effect of compaction varies from 22% to 34%. One reason for this could be due to the data fitting used to estimate a plateau frequency. It could also be caused by the increased difficulty in compaction within the wettest soils. As soil moisture content increases its structure changes, and tends towards a more liquid state, which can present difficulties in consistent pressure exerted despite the use of a penetrometer. The effect of this was particularly evident in test iteration 2, where it can be seen that the percentage
difference is significantly more than tests 1 and 3. It was anticipated that the cause of the variation was primarily due to the difficulty in repeatable levels of compression in soils at saturation. However, since the aim of the research was to determine soil moisture content, particularly in drier soils where water stress can have a destructive effect on crop performance, it was decided that the larger variability in wetter soils was not an area of significant concern, but something that should be considered in future work.

Despite the variation, which was expected due to the heterogeneity of the soil, the levels of repeatability experienced further provided confidence that the experimental procedure and technique were consistent, and that despite differences in absolute values, the effect on magnitude of change for compressing soil is repeatable.

The following section discusses the derivation of the complex impedance of the bulk material, determined by the bulk material resistance and capacitance. It is achieved through visual observation of the plateau region, and through empirical modelling with the SMP GUI.

<table>
<thead>
<tr>
<th>Test</th>
<th>Soil Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>-43</td>
</tr>
<tr>
<td>2</td>
<td>-46</td>
</tr>
<tr>
<td>3</td>
<td>-47</td>
</tr>
</tbody>
</table>

Table 5.14: Percentage change in measured impedance from level 1 to 4 compaction for tests 1-3.

**Determining Parameter Values Based on Empirical Modelling**

This section discusses the use of empirical modelling to determine the parameter values of $R_b$ and $C_b$ and determine whether increasing the compaction of the soil affects the capacitance of the bulk material. It was previously discussed how the capacitance of the soil sample is predominantly determined by its water content, due to the high permittivity of water. It was therefore postulated that if only the level of compaction was increased, the value of capacitance should remain constant, but the value of resistance will still decrease.
One limitation, however, is that the bulk material capacitance defines the high frequency roll-off and as soils become wetter the frequency at which this roll-off occurs increases. This increase in frequency approaches the operating limits of the impedance analyser and can therefore be difficult to accurately determine. A single-frequency measurement is not adequate to determine a relationship for the roll-off and measurements at multiple frequencies are required. Where possible, with the equipment available, the capacitance of the soil will be measured to assist with estimating soil moisture content.

Table 5.15 shows the measured values of real impedance for increasing compaction for soil wetted to 5% moisture content from test 1, and the empirically determined values of \( R_W, \) \( C_W, \) \( R_B \) and \( C_B \). It can be seen that only the value of bulk impedance, \( R_B \), decreases with increasing compaction, whereas \( C_B \) remains constant, at 1.5pF, despite changes in compaction level. The same findings were achieved for tests 2-3 and for all levels of moisture content, confirming that compaction has no effect on capacitance with the measurement techniques used. Since the overall aim of the research is to determine the soil moisture content, observation of the capacitance of the soil is important.

<table>
<thead>
<tr>
<th>Soil Compaction Level</th>
<th>Measured real impedance (MΩ)</th>
<th>Empirical Simulation values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_W ) (pF)</td>
<td>( R_W ) (MΩ)</td>
</tr>
<tr>
<td>1</td>
<td>1.443</td>
<td>70</td>
</tr>
<tr>
<td>2</td>
<td>1.140</td>
<td>70</td>
</tr>
<tr>
<td>3</td>
<td>1.022</td>
<td>70</td>
</tr>
<tr>
<td>4</td>
<td>0.824</td>
<td>70</td>
</tr>
</tbody>
</table>

Table 5.15: Measured real impedance for each level of compaction for 5% gravimetric soil moisture content from test 1, based on the plateau frequency of 5 kHz. Empirical simulation values were obtained through SMP GUI.

The following section discusses the magnitude of change in impedance due to compaction compared to the change due to increasing moisture content.
The aim was to compare the effects due to compaction and soil moisture. Figure 5.13 shows a plot of variation in impedance value for increasing moisture content. The solid colour line in each plot shows the decreasing impedance with increasing soil moisture. The impedance value for each moisture level was calculated by taking the mean of the measured impedance for all four compaction levels. The error bars placed at each moisture content show the total difference in impedance between the lowest and highest compaction levels. The plot offers a visual representation of the variation seen from compaction for each soil moisture level. For soils wetted to 5% moisture content, it can be seen that the change in impedance due to compaction is very small compared to that arising from a step increase in gravimetric soil moisture content from 5 to 10%. However, as soil moisture increases the percentage change due to compaction becomes similar to that for increasing moisture, making it more difficult to determine soil moisture content independent of compaction level. If soils less than 15% moisture content only are considered, the effect due to compaction can be considered to be small compared to any changes arising from fluctuations in soil moisture content. The data for tests 2 and 3 was not presented in this work as it follows a very similar trend to that seen in Figure 5.13.
Soil Compaction Testing Conclusions

The analysis of soil compaction testing has shown that in drier soils the effect of compaction has a negligible effect on electrical impedance when compared to that arising from the addition of extra moisture to the soil. However, as the soil moisture content increases the effects of compaction become comparable to a 5% increase in moisture content, making it difficult to factor out compaction through the use of a scaling factor. It was also found that the repeatability between tests suffered most in drier soils.

Empirical modelling confirmed that for increasing compaction level the soil resistance decreased, but the capacitance stayed constant, suggesting that the capacitance of the soil was dominated by the water content. The values of capacitance derived from empirical modelling were converted to relative permittivity and found to be in agreement with simulation values, providing confidence in the measurement technique and ability to measure soil moisture through both resistance and capacitance measurements. Since this research only considers laboratory based testing with careful preparation of samples, the effects of compaction are expected to be insignificant.

5.2.3: Change in Electrical Impedance due to Variation of Soil Temperature

This section discusses the change in electrical impedance for soils due to varying temperature. As with compaction and moisture content, the temperature of the soil is expected to have an effect on the electrical impedance of the bulk material. Since the soil impedance is predominantly dependent on its water content a positive correlation was anticipated between temperature and electrical conductivity. The soil temperature is likely to change at a rapid rate when compared to that of gravity induced compaction change In field based measurements a typical diurnal cycle will adjust the temperature of the soil as the sun radiates down onto the soil surface. The heat from the sunlight will penetrate down into the soil warming the upper-most soil first. However, due to the thermal mass of the soil it is only the upper-most regions which will experience significant, rapid diurnal temperature fluctuations. At deeper depths the soil temperature will remain more constant. Therefore, over the typical root size of a plant, localised temperature changes
may occur near the surface and root-stem interface, but the temperature may remain stable at the root tips. Therefore temperature measurement and correction is of paramount importance in order to provide accurate data. For testing performed in the plant growth tests reported here, the temperature inside an environmental chamber is arranged to simulate a typical diurnal cycle. By logging the temperature the change in impedance caused by temperature variation can be characterised.

The aim of this section was to determine the change in electrical impedance due to the change in soil temperature. In order to achieve this, the soil temperature was cycled between 40-5°C, in 5°C steps, over a 16 hour test period within the laboratory environmental chamber, for six soil moisture contents between 5-30% gravimetric moisture content. The purpose was to define whether the rate of change in electrical impedance due to temperature change was the same for each soil moisture percentage. For each temperature step, the temperature was held constant for 2 hours to allow the bulk mass of the soil to reach the desired temperature. Chamber and soil temperatures were logged throughout the test through the use of iButton (Maxim Integrated, 2003) thermometers to ensure both the soil and chamber reached the desired temperatures. Due to the time required for each test, three tests were performed in parallel through the use of three test multiplexed cells. The full test procedure can be found in chapter 4.

The discussions presented in this section follow a similar outline to that utilised for compaction testing. First the discussion considers the repeatability achieved through the three repeat test iterations. This is followed by a discussion of the estimation of impedance values for increasing temperature based on visual observation of a plateau frequency. As with moisture and compaction testing, where no plateau frequency was observed data fitting was used to estimate its value. Following this is a discussion relating to the use of empirical data fitting to estimate both the resistance and capacitance of the bulk material for each temperature tested. The final section relates the change in electrical impedance experienced from temperature testing to the change from soil moisture.
Determining Repeatability of Measurements through Comparison of Multiple Repeat Tests

The following paragraphs discuss the measurement data acquired for soils of decreasing temperature in order to determine the repeatability of test procedures and the measurement system. They detail the procedure used for an arbitrary test, from which all other temperature tests are analysed in the same way. Where possible a single plateau frequency was chosen for each level of moisture content, which was common between all levels of compaction. If required, the data fitting technique discussed in section 5.3.1 was utilised to acquire a value of impedance at a non-measured frequency.

Figure 5.14 shows an example plot of the spectroscopic impedance for varying temperature within a soil wetted to 20% moisture content. The general shape of the impedance plots is similar to that previously experienced, where again the low frequency impedance is dominated by the insulating layer. As frequency increases the total impedance becomes dependent on the properties of the bulk material. At low frequencies, where the impedance is dominated by the insulating layer, again the limitations of the impedance analyser become apparent with significant variation between tests. At 2 kHz, identified by marker A, the impedance begins to decrease due to the reactive element of the insulating layer reducing to a value of impedance lower than its resistance. At this point the plot shows much better repeatability, with all measurements been in agreement. This was attributed to the impedance analyser not operating outside specifications within this region.

At approximately 100 kHz, marker B, the impedance begins to flatten suggesting that total impedance is becoming dominated by the bulk material. While not completely horizontal, a clear plateau region occurs between approximately 1 – 6 MHz. It is within this bandwidth that the largest change of electrical impedance for each temperature occurs, suggesting that the plateau region represents the bandwidth where the total measured impedance is relative to the bulk material only. Within this region it can be seen that as temperature decreases from 40°C to 5°C the impedance increases as was anticipated. Due to the relatively small change in impedance within the plateau region a zoom is provided in Figure 5.15 between 100 kHz – 6 MHz. In this figure the change in impedance within the plateau region is easier to determine. The marker placed on Figure 5.15 represents the visual estimation of the plateau frequency, which was 2 MHz. The plateau frequency was selected
by visually observing the plotted impedance and choosing a frequency which was common among all temperatures.

Figure 5.14: Measured real impedance for decreasing temperature between 5-40°C in soil wetted to 20% moisture content; Test 3.

Figure 5.15: Measured real impedance for decreasing temperature between 5-40°C in soil wetted to 20% moisture content; Test 3. Zoom on plateau region.

Once the plateau frequency was identified, the measured impedance at this frequency could be extracted and plotted to observe the change in impedance over time, relative to change in temperature. Figure 5.16 shows the plotted impedance relative to time, where it can be seen that the impedance increases over the duration of the test. It is known from
the test schedule that the temperature at test start is 40°C, decreasing in 5°C intervals over a 12-14hr period down to 5°C. The plot of impedance shows how the temperature affects the value of impedance, and that the mass of the soil causes a slow response of the soil to changes in temperature. For verification the measured temperature within the soil is also plotted in Figure 5.16, where the temperature and impedance change over time are in good agreement. It can be seen that the slow response of measured impedance to change in temperature is reflected in the measured temperature of the soil. In order to measure the impedance relative to the set point temperatures, 40-5°C in 5°C intervals, the plotted impedance at intermediate temperature values must be filtered to provide only eight values of impedance at each set point temperature.

The previously discussed plots in this section have detailed the process of extracting data from temperature based measurements. All other plots of electrical impedance for changing temperature and moisture content are not shown due to the repetitive nature of data extraction. However, the same process was followed for all tests to achieve a value of impedance at each temperature and for all levels of moisture content tested. Table 5.16 shows the values of impedance extracted from each test to allow an analysis of repeatability. One immediate observation of the data presented is the ‘n/a’ achieved in test cell 1 for both 5 and 30% moisture content at all tested temperatures. In these tests the measurement equipment failed, producing random values of impedance. It was unknown why the measurement system failed in these tests, however, it demonstrates the requirement of multiple measurements to ensure integrity of data and the reason why data for test 2 and 3 are also shown.
<table>
<thead>
<tr>
<th>Test Iteration</th>
<th>Temperature (°C)</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
<th>25%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 1</td>
<td>5</td>
<td>n/a</td>
<td>23.2</td>
<td>8.1</td>
<td>3.8</td>
<td>2.4</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>n/a</td>
<td>20.3</td>
<td>7.1</td>
<td>3.4</td>
<td>2.1</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>n/a</td>
<td>17.6</td>
<td>6.2</td>
<td>3.0</td>
<td>1.9</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>n/a</td>
<td>15.3</td>
<td>5.5</td>
<td>2.7</td>
<td>1.7</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>n/a</td>
<td>13.6</td>
<td>5.0</td>
<td>2.5</td>
<td>1.6</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>n/a</td>
<td>11.9</td>
<td>4.5</td>
<td>2.3</td>
<td>1.5</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>n/a</td>
<td>10.4</td>
<td>4.0</td>
<td>2.2</td>
<td>1.4</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>n/a</td>
<td>9.2</td>
<td>3.7</td>
<td>1.9</td>
<td>1.4</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Test 2</strong></td>
<td>5</td>
<td>490</td>
<td>26.9</td>
<td>7.7</td>
<td>3.7</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>421</td>
<td>23.6</td>
<td>6.7</td>
<td>3.3</td>
<td>2.1</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>366</td>
<td>20.7</td>
<td>5.9</td>
<td>2.9</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>313</td>
<td>18.2</td>
<td>5.2</td>
<td>2.7</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>270</td>
<td>16.2</td>
<td>4.7</td>
<td>2.4</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>235</td>
<td>14.3</td>
<td>4.3</td>
<td>2.3</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>199</td>
<td>12.6</td>
<td>3.9</td>
<td>2.1</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>167</td>
<td>11.2</td>
<td>3.5</td>
<td>1.9</td>
<td>1.4</td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Test 3</strong></td>
<td>5</td>
<td>422</td>
<td>28.6</td>
<td>8.1</td>
<td>3.7</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>364</td>
<td>25.3</td>
<td>7.1</td>
<td>3.3</td>
<td>2.2</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>312</td>
<td>22.3</td>
<td>6.3</td>
<td>2.9</td>
<td>1.9</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>271</td>
<td>19.7</td>
<td>5.7</td>
<td>2.7</td>
<td>1.7</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>237</td>
<td>17.5</td>
<td>5.1</td>
<td>2.5</td>
<td>1.6</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>206</td>
<td>15.4</td>
<td>4.6</td>
<td>2.3</td>
<td>1.5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>179</td>
<td>13.5</td>
<td>4.2</td>
<td>2.1</td>
<td>1.4</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>152</td>
<td>11.7</td>
<td>3.8</td>
<td>1.9</td>
<td>1.4</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Table 5.16: Measured values of electrical impedance (kΩ) for each temperature at each level of soil moisture content, and for all 3 test iterations.

Table 5.17 shows the percentage change for increasing temperature with respect to the value of impedance at 5°C, at each soil moisture content and for tests 1, with both tests 2 and 3 showing very similar results, and therefore not shown. As with acquired data for
compaction testing, this percentage change provides a relative method which is used to
determine the magnitude of change for both soil moisture content and temperature
change independent of the absolute values. For all three tests it was found that increasing
the temperature significantly decreases the impedance from the original reference value at
5°C, and that the decrease is largest in drier soils. Because of the erroneous data in test 1,
the analysis in this section focuses on those tests where three repeat iterations were
achieved.

When the temperature of soil at 10% moisture content changes from 5 - 40°C, the
impedance decreases by a value of approximately 140 – 152% over all three tests, giving
confidence in the validity of the measurement procedure used. This change in value of
impedance is much larger than the change experienced at the maximum level of
compaction testing, which was approximately 40%. Observation of all tests shows that the
measurement procedure and subsequent results are repeatable for the three tests
performed.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Soil Moisture %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>n/a</td>
</tr>
<tr>
<td>15</td>
<td>n/a</td>
</tr>
<tr>
<td>20</td>
<td>n/a</td>
</tr>
<tr>
<td>25</td>
<td>n/a</td>
</tr>
<tr>
<td>30</td>
<td>n/a</td>
</tr>
<tr>
<td>35</td>
<td>n/a</td>
</tr>
<tr>
<td>40</td>
<td>n/a</td>
</tr>
</tbody>
</table>

Table 5.17: Percentage change in measured impedance from value at 5°C, for each soil moisture content – test 1.

The following section discusses the derivation of the complex impedance of the bulk
material, determined by the bulk material resistance and capacitance. It is achieved
through visual observation of the plateau region, and through empirical modelling with the
SMP GUI.
Determining Parameter Values Based on Empirical Modelling

Empirical modelling of data for increasing compaction of the soil showed that no measurable effect on the value of relative permittivity was attained. Empirical modelling was again used here to determine whether there was a change in the capacitance of the bulk material, here soil, for varying temperature. The relative permittivity of the soil is predominantly dependent on its water content with dry soils having a very low relative permittivity of approximately 3-5, while saturated soils tend towards that of water at ≈ 50. The relative permittivity of water is approximately 80 at 20°C, but is negatively correlated with temperature (Fernandez, 1994). Until this point all tests have been performed at the ambient temperature of the laboratory, which was between 20 - 25°C, so changes in the relative permittivity of water would be small, and as such the relative permittivity change in the soil would be even smaller. Fernandez quotes that at 40°C the relative permittivity of water will have decreased from 80 to a value of approximately 73. For a parallel-plate test cell filled with water only, a relative permittivity value of 80 would equate to a capacitance of 24pF. If the relative permittivity was reduced to 73, due to an increase in temperature, the value of capacitance would change to approximately 22.5pF, a change of only 1.5pF. Again, since the relative permittivity of the soil is a function of multiple parameters, the effect of temperature change will be less than that of water only. Therefore, if the system is incapable of a resolution high enough to measure this, it is anticipated that the relatively small temperature used in these tests will have no measurable effect on the value of relative permittivity of the soil.

As with compaction testing, an example data set was chosen to demonstrate the values achieved for one test iteration. All sets of test data were empirically modelled, but are not presented here in the interests of space constraints. Figure 5.17 shows the attempted data fitting for a soil of 15% moisture content, at 5°C. It can be seen that at higher frequencies, those greater than 4 MHz, the impedance begins to increase with increasing frequency where it should decrease due to the reactance of the sample also decreasing. It can also be seen that some higher frequency values of impedance are not plotted, 8-10 MHz, due to measurement data having negative values. The impedance at 11-13 MHz returned to a positive value, but again shows an erroneous increase in impedance for increasing frequency. These high frequency anomalies occurred for all test values, and for all iterations of temperature testing suggesting limitations of the measurement system. The
only explanation suggested is due to operating close to the limits of the impedance analyser, which has an upper frequency limit of 13 MHz, however, previous tests showed that the impedance analyser was capable of measuring at these frequencies. Because of these anomalies, it was difficult to empirically fit data at higher frequencies for all temperature based test data and therefore estimate relative permittivity change with temperature. Despite the difficulties, estimations were made for all tests based on any trends experienced in spectroscopic data, but only limited confidence was achieved.

Table 5.18 shows the measured values of real impedance based on visual estimation of the plateau frequency and the parameter values derived from empirical modelling. As has been expressed previously, the parameter values for the insulating layer, \(C_W\) and \(R_W\), should not vary despite changes in the bulk material conditions. Empirically fitted data shows, however, that the value of \(R_W\) decreases with increasing temperature, suggesting that temperature also has a positive correlation with the electrical conductivity of the insulating layer. While the measured value of impedance returned from the impedance analyser is well within specification of the equipment, the actual impedance of the insulating layer significantly exceeds that of the measured value, and again these inaccuracies are attributed to the impedance analyser. The value of capacitance associated with the
insulating layer was 70 pF, the same as empirically modelled for compaction testing, so shows consistency.

Empirically fitted data for the bulk material resistance is in good agreement with that achieved from extraction of the resistance based on visual determination of plateau frequencies. However, observation of the capacitance of the bulk material, $C_b$, shows that there was no measurable change in the value of capacitance for increasing temperature. This was attributed to two reasons. First was the difficulty in data fitting, due to the irregular spectroscopic impedance achieved at higher frequencies for all tests previously discussed and secondly was due to the coarse resolution of the SMP GUI method, and difficulty in being able to observe small changes in the spectroscopic impedance and fit data to these small changes. With the inability to accurately determine the capacitance of the soil, conclusions cannot be drawn as to whether the temperature has a measurable effect on the measured relative permittivity. In order to achieve this, it is proposed that future work be performed with measurement equipment which has operating limits significantly higher than 13 MHz in order to ensure that the equipment was not the cause of data anomalies.

<table>
<thead>
<tr>
<th>Soil Temperature (°C)</th>
<th>Measured real impedance (kΩ)</th>
<th>Empirical Simulation values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_w$ (pF)</td>
<td>$R_w$ (MΩ)</td>
<td>$C_b$ (pF)</td>
</tr>
<tr>
<td>5</td>
<td>70</td>
<td>1.1</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>1.1</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>70</td>
<td>0.9</td>
<td>5</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
<td>0.7</td>
<td>5</td>
</tr>
<tr>
<td>25</td>
<td>70</td>
<td>0.6</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
<td>0.6</td>
<td>5</td>
</tr>
<tr>
<td>35</td>
<td>70</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>40</td>
<td>70</td>
<td>0.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 5.18: Measured real impedance for each temperature for 15% gravimetric soil moisture content from test 3, based on the plateau frequency of 5 kHz. Empirical simulation values were obtained through SMP GUI.
Estimation of Impedance for Set-Point Temperatures Based on Linear Data Fitting

Figure 5.18 shows a typical change in measured real impedance for one temperature cycle, between 40-5°C in 5°C step sizes, of a soil sample wetted to 5% gravimetric water content. The plateau frequency for each moisture content level was chosen by means of the same methods previously described. In this example, the range of electrical impedance is 270 kΩ over the 35°C range which, assuming a linear relationship, equates to a change of approximately 9 kΩ/°C. The effect on water conductivity for increasing temperature is approximately 2-3%/°C from the value at 25°C (Lenntech, 2013). Since the impedance is considered here and not conductivity, it was expected that an inverse relationship would exist, where it was expected that increasing temperature would decrease electrical impedance, but by the same approximation of 2-3%/°C from the 25°C value. Therefore, the value of measured impedance at 25°C is used as the reference point, and used to calculate the value of impedance at each temperature set-point. These calculated values are then compared to measured values.

Table 5.19 shows the measured impedance for all eight temperatures tested, for soil with 5% moisture content, and the theoretical values of electrical impedance from the

![Figure 5.18: Measured real impedance for varying temperature. Data taken from Test 3.](image-url)
measured impedance at 25°C, based on the calculation of both 2%/ °C and 3%/ °C for comparison. Figure 5.19 shows the values from Table 5.19 plotted to visualise the accuracy of the linear approximations compared to measurement data. It can be seen that, assuming the measurement system is correctly measuring the bulk material impedance, the value of measured impedance for increasing temperature is not a linear relationship, but one which has a decreasing gradient for increasing temperature.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Measured Impedance (Ω)</th>
<th>Impedance estimation for 2%/ °C (Ω)</th>
<th>Impedance estimation for 3%/ °C (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>422000</td>
<td>331380</td>
<td>378720</td>
</tr>
<tr>
<td>10</td>
<td>363800</td>
<td>307710</td>
<td>343215</td>
</tr>
<tr>
<td>15</td>
<td>312400</td>
<td>284040</td>
<td>307710</td>
</tr>
<tr>
<td>20</td>
<td>271300</td>
<td>260370</td>
<td>272205</td>
</tr>
<tr>
<td>25</td>
<td>236700</td>
<td>236700</td>
<td>236700</td>
</tr>
<tr>
<td>30</td>
<td>206300</td>
<td>213030</td>
<td>201195</td>
</tr>
<tr>
<td>35</td>
<td>179400</td>
<td>189360</td>
<td>165690</td>
</tr>
<tr>
<td>40</td>
<td>152300</td>
<td>165690</td>
<td>130185</td>
</tr>
</tbody>
</table>

Table 5.19: Measured electrical impedance of 5% gravimetric soil moisture between 5-40°C, and theoretical values calculated on measured value at 25°C. Data taken from Test 3.

Due to the linear approximation of impedance it can be seen that for temperatures below 25°C, the 3%/ °C scaling is the most accurate with respect to measured values while for temperatures above 25°C, the 2%/ °C is the most accurate with respect to the measured values. While the linear approximations do not completely match that of the measured impedance, they do suggest that a simple linear approximation can be used to estimate the soil impedance for varying temperature, and that scaling of impedance values could be performed, dependent on knowledge of soil temperature.

This common relationship between soil and water temperature dependence is most likely due to the soil impedance being predominantly dependent on its water content and therefore it is to be expected that the electrical properties will be subject to the same relationships that exist for water alone.
Electrical Impedance Change due to Temperature for all Tests

The previous section provided three areas of analysis for soil wetted to 5% gravimetric water content; first a plot of electrical impedance for decreasing temperature, confirming that the impedance is both temperature dependent and the resulting change is measurable. Second, a table was provided to show how measured values of impedance compared to theoretical values, calculated from the measured impedance at 25°C and scaled according to a linear approximation. Finally, the tabulated values were plotted to provide a visual representation of the temperature dependence, and shows the plausibility of using a linear scaling factor to provide temperature correction.

In this section, only the final plot of measured and approximated impedance for varying soil temperature is provided, for the five remaining soil moisture levels of Test 3. The plot of temperature change and tabulated values are not provided as the final plot summarises these values and reduces the presentation of unnecessary data. At the end of the section a set of conclusions are provided, relating the typical change in measured impedance due to temperature to that of the change from soil moisture content variation.
Figure 5.20: Measured and theoretical real impedance for increasing temperature of soil at 10% gravimetric moisture content.

Figure 5.21: Measured and theoretical real impedance for increasing temperature of soil at 15% gravimetric moisture content.
Figure 5.22: Measured and theoretical real impedance for increasing temperature of soil at 20% gravimetric moisture content.

Figure 5.23: Measured and theoretical real impedance for increasing temperature of soil at 25% gravimetric moisture content.
Figures 5.20 to 5.24 show the plots of measured impedance, and the accuracy of the linear approximations for temperature compensation. All plots show a decrease in impedance for increasing temperature, as expected, and that the linear approximations are suggestive of the measured values. For soils less than 10% moisture content, the 2% scaling factor is most accurate above 25°C, but the 3% scaling factor is more accurate below 25°C. It is suggested that this is due to the limited water content within drier soils, and the temperature effects of the soil being a product of both the dependency of the bulk material and water. For soils greater than 15% gravimetric water content, the 2% scaling is ‘most accurate’ when compared to measured values. It can also be noted that a typical diurnal cycle will not cause such a large fluctuation of temperature. Over the duration of the daylight hours the soil temperature will increase at a slower rate than air temperature, and over the night period will also cool much slower than the air temperature. Therefore, an example fluctuation of 10°C may be considered, between 15-25°C, for a typical summer growing season. Brevik (2004) measured the daily soil temperature within a local field in the Netherlands, where at a depth of 10cm the soil temperature was found to fluctuate by approximately 10°C, between 20-30°C, while at 30cm depth the temperature variation reduced to less than 5°C, between 20-25°C, over a 12 hour day time period. For a fluctuation of this magnitude the error percentage between the scaling factor and measured values are provided in Table 5.20. The largest error percentage between measured and scaled is -9.1% for the driest soil sample, 5% gravimetric water content.
Other large values of error are produced for 10 and 30% moisture contents. However, for mid-range moisture levels in the soil, 15-25% gravimetric, the linear scaling produces values of temperature corrected impedance that were less than 2% difference. Since the soil temperature will change very little during a diurnal cycle, and the soil will typically be within the middle region, the effect of temperature on measured conductivity can be scaled with confidence, according to the results analysed.

<table>
<thead>
<tr>
<th>Soil Temperature (°C)</th>
<th>Soil Gravimetric Moisture Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>-21.5</td>
</tr>
<tr>
<td>10</td>
<td>-15.4</td>
</tr>
<tr>
<td>15</td>
<td>-9.1</td>
</tr>
<tr>
<td>20</td>
<td>-4.0</td>
</tr>
<tr>
<td>25</td>
<td>0.0</td>
</tr>
<tr>
<td>30</td>
<td>3.3</td>
</tr>
<tr>
<td>35</td>
<td>5.6</td>
</tr>
<tr>
<td>40</td>
<td>8.8</td>
</tr>
</tbody>
</table>

Table 5.20: Percentage difference between measured impedance and 2%/°C linear scaling temperature correction, for all soil moisture contents. Highlighted region denotes an example diurnal temperature range.

Change in Impedance due to Temperature vs. Soil Moisture Content

Until this point the effect of temperature relative to soil moisture content on measured impedance has not been considered. The data presented here show the variation in electrical impedance for both temperature and moisture within one plot. Figure 5.25 shows the measured impedance for increasing soil moisture level compared to the change in impedance for increasing temperature. The plot ‘5-30% Soil Moisture’ is the measured impedance for soil at 5°C and compaction level 1, and is therefore the maximum value of impedance for each level of soil moisture tested. The six steep lines are the measured impedance for each soil moisture level for temperature between 5 and 40°C. The gradient
of the lines displays the change in impedance relative to temperature change, and as such can be compared to the change due to increasing moisture content. The steeper the gradient, the smaller the effect temperature has on measured impedance. From Figure 5.25 it can be seen that for low moisture content the change in impedance with temperature is less significant than the change when considering higher moisture content. However, as previously suggested within the envelope of expected soil moisture and temperature, typical of that for plant growth, the linear scaling of impedance for changing temperature was found to be within 2% of the measured impedance for varying temperatures.

![Figure 5.25: Real impedance change for increasing temperature compared to soil moisture content.](image)

**Soil Temperature Testing Conclusions**

Perhaps the most important conclusion is that the insulated electrode measurement system shows changes in soil impedance with temperature. It was found that for all moisture contents the approximate linear scaling of 2%/°C provides a temperature correlated value of impedance to within 20% across all moisture and temperature levels. Since the rate of impedance change for temperature is non-linear this error margin becomes greater above 25°C. However, when a smaller range, applicable to typical plant-
growing soil is considered, the error percentage between measured and simulated reduces to less than 2%.

As with compaction testing, the data shows that the temperature effects are largest on drier soils and that as the soil moisture level increases, differentiating between soil moisture and temperature becomes more difficult. However, unlike soil compaction, the linear scaling factor of 2%/ °C is much simpler to apply than any relationship found for soil compaction. Due to this simple approximation from a scaling factor, the use of thermometers within the test core are recommended.

As previously mentioned, in the field the soil temperature will change most near the surface due to heating from sunlight. Therefore, it would also be advised that multiple thermometers are required to monitor soil temperature throughout the depth of measurement in order to correct for temperature effects.

The following section utilises the rhizotron vessel which features an adjacent arrangement of electrodes. Tests using the rhizotron aim to utilise the basic principles determined from parallel-plate testing.

5.3 Tests of Maize Growth within Rhizotron Vessels

This section presents and discusses the results obtained from growth tests performed within rhizotrons. As with previous tests performed in parallel-plate vessels, repeat iterations were performed to check repeatability of soil tests within the rhizotron vessels. Two growth tests were studied over a 6-9 week period, in which three rhizotrons were connected in parallel. The electrical impedance at each adjacent electrode pair in each rhizotron was measured independently by the use of the switching electronics discussed in chapter 4. This parallel-connection of multiple rhizotrons allowed for six independent sets of test data to be acquired over the two growth periods.

Data acquired from parallel-plate methods has shown that the insulated electrode method can be used to measure changes in the bulk resistance of the soil relating to soil moisture,
compaction and temperature. Unlike the parallel-plate formation, the electrodes in the rhizotrons are arranged in an adjacent configuration and this does not lend itself to a simple analytical solution. However, the measured impedance will still be dependent on soil moisture conditions. For example, as moisture content of soil increases, it was expected that the measured impedance would decrease as experienced with parallel-plate test data. As such, the same relationships that exist between soil impedance and temperature or compaction should also exist. Challenges were anticipated since there was no analytical solution that could be used to provide an estimation of impedance. However, results achieved from parallel-plate testing will be used as to inform conclusions relating to the measurements using rhizotrons.

The aim of the growth tests within rhizotrons was to determine whether the use of an array of adjacent-formation electrodes, as found in the rhizotron test vessels, was capable of measuring a change in electrical impedance for drying soil over a large time period. In order to achieve this, the soil in one test vessel must be dried while the soil moisture content should remain as close to constant as possible in a control vessel, to allow comparison of the change between them. One way of achieving rapid drying of soil was to grow a plant in each of the non-control vessels. The plant root system would be expected to remove water from the soil in order to grow and thus achieving differential soil moisture content between control and measurement vessels. However, the use of a plant root system in the measurement vessel has other advantages. First, it allows for a more ‘real-world’ test, in which a plant is grown in the rhizotron to determine whether the measurement system is affected by the presence of a plant root in the soil core. It was unknown how the system would respond to a plant root system, which is both an electrical insulator and conductor depending on the measurement frequency (Aubrecht, 2006). Secondly, the placement of a plant system within the soil core also offers the possibility of localised soil drying relative to the growth pattern of the plant roots. It was expected that as the plant begins to grow most change in moisture will occur at the surface. Over time, as the roots extend down into the soil core, the drying will reflect this root growth. Since the rhizotron system features a large number of electrode excitation options, the aim was to determine the spatial resistivity distribution throughout the soil core over a temporal period of growth. From this it may be possible to infer root growth and location. This ability to measure spatial resistivity distribution also lends itself to observation of changes in measured impedance for localised temperature changes as previously discussed. In field-based applications these localised temperature fluctuations typically occur at, or close to,
the soil surface due to heating of the soil from sunlight. The ability to present spatial soil resistivity distribution, correlated with temperature correction, will allow for more accurate results that are representative of moisture in the soil core.

For both growth tests, all three rhizotrons contained 18-Acre soil wetted to saturation and left to drain pre-test for a period of approximately 24 hours to reach field capacity. For each test two of the rhizotrons had four maize seeds placed in the centre of the top surface between the middle-most electrodes. After 24-48 hours, once seedlings had emerged, the central most plant which had emerged was kept while the others were removed, leaving only one plant per rhizotron. The open surface of each rhizotron was covered to reduce evaporation, leaving a small opening for the plant stem to grow. For growth test 1 the control vessel soil surface was completely covered since no opening was required for plant growth. However, for growth test 2 it was decided that the control vessel surface should be exposed in a similar method to measurement vessels, leaving a small central region uncovered to replicate that of the measurement vessels, and provide a fairer test.

Measurements were taken between all vertical and horizontal adjacent electrode pairs, providing a data set of 95 measurements per rhizotron. Five measurement frequencies were used in the testing; 10, 50, 100, 500 and 1000 kHz. For each excitation frequency, each dataset of 95 measurements takes approximately 1 minute to be performed. Therefore, a complete dataset for each rhizotron and for all five frequencies takes approximately 5 minutes. Since there are three rhizotrons a full measurement is achieved in approximately 15 minutes. Measurements were acquired every hour. As with previous soil based measurements, the electrical conductivity cannot be verified with traditional bench meters, and therefore the control test was of paramount importance. A valid control test would ensure that the change in impedance in the measurement vessels can be attributed to the changes from external factors, such as soil moisture changes due to the root system extracting water from the soil as these factors should not occur within the control vessel. Since two growth tests were performed, they are first discussed independently, followed by a comparison of the two sets of data to establish repeatability.

The three rhizotrons are identified as FNS 3, 4 and 5. The placement of vessels was kept consistent between tests, with the left-most vessel being FNS3, central FNS4, and right most FNS5. All connecting cables were marked with unique identifiers to ensure they were reconnected to the same ports between test iterations to minimise variability. While the vessel placement and connections were kept constant, the assignment of control and
measurement vessels were altered between plant growth tests 1 and 2. In test 1 the control was vessel FNS4, while in test 2 the control was vessel FNS3. This was performed to ensure that the response of the control vessel was caused by the soil impedance, and not the operation of that specific vessel. As an example of the naming convention for the tests, “T1-FNS3”, refers to test 1, FNS3.

5.3.1: Destructive and Qualitative Analysis

Test 1 was started on 06/02/2013, and concluded on 21/03/2013. Test 2 was started on 04/04/13 and ended on 03/06/2013. Both tests were terminated when the maize plants began to show signs of water stress, evidenced by leaf browning and slight wilting. Upon completion of the tests, all three rhizotron vessels were removed from the environmental chamber to be photographed and post-test analysed. Figures 5.26 and 5.27 show the three test vessels, FNS3-5, shortly after being removed from the environmental chamber for test 1 and 2 respectively. For both tests there are several points worthy of discussion relating to visual observation.

Test 1

Firstly, all three vessels show evidence of growth of other plants/weeds at the surface, due to the soil being a ‘living soil’, and not sterilised prior to testing. This was particularly evident in T1-FNS5 where a large weed can be seen at the upper left corner on the surface. The weed was strong enough to push the plastic film covering away from the surface, however, the plastic film still restricted some vertical growth, and once removed the weed extended to a more vertical position. This growth of weeds at the surface occurred in all three test vessels, and was expected due to the soil being un-purified when removed from a field, and the only pre-test preparation was sieving to 2mm particle size. While the weed growth is not ideal due to extra water uptake, it occurs in all three test cells and as such is a common factor.
The second visual observation is the distinct size difference in maize plants between T1-FNS3 and T1-FNS5. The plant size was measured as the distance from the soil surface to the tip of the longest leaf. T1-FNS3 had a length of 46cm, while T1-FNS5 had a length of 67cm. It would be expected that a larger plant will remove moisture from the soil at a faster rate than a smaller plant, and therefore the soil in T1-FNS5 should be drier than T1-FNS3.

Third is the visible difference in soil moisture between the three vessels. Since the control vessel, T1-FNS4, had no maize plant and subsequent root system the soil was expected to be wetter than both T1-FNS3 and T1-FNS5. This was evident in visual observation, where the soil in T1-FNS4 was clearly wetter, and suffered no visual cracking. T1-FNS3 and T1-FNS5 suffered significant cracking, which is a typical trait of drying soils as they shrink, as can be seen in Figure 5.26. A visual comparison of both growth vessels also showed that of the two, T1-FNS5 suffered from greater cracking, suggesting that the soil was even drier. It was determined that the most likely cause for this was due to the larger plant system, and therefore larger quantity of water removed to sustain the extra growth.

The final visual observation is the extent to which the root system has grown within the rhizotron vessels. Both T1-FNS3 and T1-FNS5 clearly show the root system has penetrated both vertically and horizontally through the vessel, and is well established. The presence of roots throughout the soil core will lead to drying of soil throughout the vessel over the duration of the test. The three regions with soil removed are for post-test gravimetric analysis of the soil moisture content, and are discussed in section 5.3.2.
Test 2

The test procedure for growth test 2 was improved based on post-test analysis of test 1. The first improvement was the use of a black tape to better seal the top surface, and also avoid light penetration, which had allowed weeds to grow under the plastic covering. It was decided to not completely seal the top surface of the control vessel, but instead replicate the opening found in measurement vessels. This would allow analysis of the moisture which was removed from the soil purely due to evaporation, rather than evapotranspiration as is experienced in measurement vessels. The second improvement was to take more photographs of the plants during the growth period, and post-test. At the completion of the measurement phase the plants were also immediately removed from the soil while roots were fresh and therefore stronger which allowed the soil to be carefully removed exposing the root mass.
The growth of weeds on the top surface in test 1 was caused by the clear plastic covering used. In test 2 the covering was changed to a black tape, which allowed no light to penetrate, and therefore no weed growth. However, it can be seen in Figure 5.27 that for T2-FNS5 a small weed grew directly next to the stem, which was unavoidable due to the opening required to allow plant growth. Since little or no weed growth was present, and a tape was used rather than a film, the surface remained better sealed in test 2 than test 1, which would significantly reduce evapotranspiration from the surface.

Measurement of the plant size determined that both plants in test 2 were significantly bigger than test 1, with T2-FNS4 being 79cm, while T2-FNS5 was 71cm. It can also be seen that the plants from test 2 were more similar in size compared to those from test 1. This highlights the variability which can be experienced from plant growth tests, where well-defined test procedures create a matching start point, yet the plant growth is dependent on other factors which are difficult to control. As was assumed with test 1, the larger plant found in T2-FNS4 should remove more moisture from the soil than T2-FNS5. Analysis of the gravimetric moisture content and impedance measurement data in section 5.3.2 will determine whether this occurred.

As with test 1, the control vessel suffered minimal cracking due to moisture content remaining high. Two significant cracks appeared at the top of the vessel where the surface was exposed, due to drying of the soil through evaporation. A third, smaller, crack can be seen travelling vertically down the centre of the vessel from the top surface. This crack was caused when the front plate was removed due to flex in the measurement vessel, and is not attributed to soil drying. In vessels T2-FNS4 and 5 the root system can be seen to have penetrated the full vessel. For vessel T2-FNS4 the root system tends towards the left of the vessel. This may be due to the potential of localised compaction, highlighted in Figure 5.29, where the structure of the soil appears different to that where the plant roots grew. If the highlighted region is indeed compacted soil it may explain the preference of the plants roots away from this region due to the difficulty in penetrating through compacted soil.

It was previously mentioned how the test procedure from test 1 was improved for test 2. The final method of improvement was to analyse the plant mass, achieved through destructive sampling. Immediately prior to analysis the root structure was removed from the vessel and soil was removed exposing the bulk root mass. While some root mass was lost due to the fragility of roots, the majority was kept complete. The aim of this test was to observe whether the complete plant mass correlates well with the size of the plant above
the surface and the remaining moisture content of the soil. Table 5.21 shows the mass of the complete system, root and stem, after the soil was removed. It can be seen that the percentage difference between both plants is similar for both plant height and total mass. However, it should be noted that the root bundle alone was not measured, which will only represent a small mass due to the fine roots. However, the total mass and plant height correlate well.

![Figure 5.27: Rhizotron vessels plant growth test 2; Post-test visual observations.](image)

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Plant Height (cm)</th>
<th>Plant Mass (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2-FNS4</td>
<td>78.5</td>
<td>47.3</td>
</tr>
<tr>
<td>T2-FNS5</td>
<td>71.1</td>
<td>43.3</td>
</tr>
<tr>
<td>Difference</td>
<td>9.4</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 5.21: Comparison of plant height and total mass for growth test 2.
Figure 5.28 shows the destructively sampled plants T2-FNS4 and 5. A 30cm rule is used for scale, and demonstrates the significant root length which occurred in the soil. As an approximation, the root length was found to be similar to the plant height above the surface. The weed structure also found in T2-FNS5 is also presented for comparison.

In summary, despite the differences experienced between growth tests, they show similarities suggesting that test procedures created a well-controlled test. Both control vessels suggest a much higher value of residual moisture within the soil, expected since a plant root system was not present to remove moisture. All growth vessels featured significant cracking attributed to soil drying from root water uptake. It should be noted that such cracking compromises the measurement of impedance due to the discontinuities that arise. The final observation is the variability of crop sizes which occurred for both tests, despite well-defined test procedures.
Figure 5.28: Destructively sampled root bundles for growth test 2. A) T2-FNS4, B) T2-FNS5.
Figure 5.29: Post-test photographs of soil cores from growth test 2. A) T2-FNS3, B) T2-FNS4, C) T2-FNS5. Highlighted region of T2-FNS4 denotes possible area of localised compaction based on visual observation.
5.3.2: Quantitative Analysis of Post-Test Gravimetric Moisture Content

This section provides the quantitative analysis of test data derived from both rhizotron growth tests. The first area to be discussed is the procurement of gravimetric soil moisture levels post-test, to determine the remaining moisture content of the soil. Due to the method used to saturate soil samples pre-test, it was impossible to remove a small quantity for analysis of soil moisture content. However, the pre-test procedure was controlled and consistent for all tests, and all vessels were therefore assumed to have similar water content, at close to the field capacity. Since the same soil was used this was expected to be very close to the same value, at approximately 30-35% gravimetric water content. Post-test, three small soil samples were removed from each rhizotron vessel providing a total of 9 independent samples. They were removed in order to determine the gravimetric soil moisture content through weighing, drying and re-weighing the soil samples. In Figure 5.26 the three locations of soil removal for each vessel can be seen. Three locations were chosen as the soil was not expected to dry in a uniform manner, but instead dry from the surface downwards, and also relative to the location of roots. Measurement of soil moisture content in only one location would be imprudent based on these assumptions of how soil will dry over time. Knowledge of soil moisture content at three locations can also be a method of verifying the electrical impedance data since the soil moisture is the largest factor that influences electrical impedance of soil. As an additional test, the soil at the top centre of the control vessel in test 2, T2-FNS3, was sampled to determine the effects of evaporation.

Tables 5.22 to 5.23 show the gravimetric moisture content for all 9 soil samples from tests 1 and 2 respectively. Soil in rhizotron T1-FNS4 and T2-FNS3, the control vessels, clearly have a much greater quantity of residual water than measurement vessels. For growth vessels in test 1 the moisture content towards the top of each vessel is significantly lower than that at the bottom. Three possible explanations are suggested. First is that gravity will have an effect on the water content of the soil, and as such will pull the water downwards in the vessel. However, this will only occur in very wet soils typically above field capacity. The test was not started until the soil had reached field capacity, the point at which the soil can hold the water with more force than gravity can exert. Therefore, the effect of gravity causing this is unlikely. The second explanation is that the soil at the top of the vessel will be driest due to water use from vegetation growth, either from the maize seed in early growth or that experienced in all vessels through weed coverage across the top surface.
The final explanation is that the top surface features sections of soil exposed to the air, due to the inability to completely seal around the plant stem and weeds lifting the plastic covering. This will cause the soil to evaporate starting at the surface and penetrating down into the soil core.

It was felt that the main cause of the soil drying non-uniformly was due to the plastic covering not sealing the soil caused by the growth of weeds across the top surface. This had a compound effect, which caused evaporation at the top surface and plant transpiration from both the maize plants and the weeds. For this reason the test procedure was adjusted as previously detailed, to implement another method of covering the top surface, which could not be removed from plant growth, and was also opaque in order to discourage weed growth. With the improved test procedure, test 2 shows that the soil dried in a more uniform manner, suggesting that evapotranspiration was the cause of the non-uniform drying in test 1.

<table>
<thead>
<tr>
<th>Soil Sample Location</th>
<th>T1-FNS3</th>
<th>T1-FNS4</th>
<th>T1-FNS5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>1.9</td>
<td>13.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Middle</td>
<td>8.4</td>
<td>14.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Bottom</td>
<td>13.2</td>
<td>17.2</td>
<td>5.5</td>
</tr>
</tbody>
</table>

Table 5.22: Post-test gravimetric soil moisture content for rhizotron growth test 1. Highlighted column denotes control vessel.

<table>
<thead>
<tr>
<th>Soil Sample Location</th>
<th>T2-FNS3</th>
<th>T2-FNS4</th>
<th>T2-FNS5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>9.0</td>
<td>4.3</td>
<td>4.0</td>
</tr>
<tr>
<td>Middle</td>
<td>11.5</td>
<td>3.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Bottom</td>
<td>12.4</td>
<td>4.0</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Table 5.23: Post-test gravimetric soil moisture content for rhizotron growth test 2. Highlighted column denotes control vessel.

The measured gravimetric soil moisture content also indicates that while the control vessel is much wetter than the measurement vessels, of the two measurement vessels T1-FNS5 is noticeably drier than T1-FNS3. This difference in soil moisture content correlates to the
larger plant in cell T1-FNS5. While lower soil moisture content does not provide sufficient proof alone that the plant will be bigger, it is a further positive correlation that the water content within the soil was used primarily by the plants, and that a larger plant required more water. Comparison of the two measurement vessels in test 2 show that the residual moisture content is very similar which can be attributed to the similar size of both plants, when compared to plants from test 1.

The 18-Acre soil used in all tests was classified as a sandy loam. Brady, Figure 5.30, provided a scale which shows the estimated field capacity and wilting point of soils for varying texture. For a sandy loam soil the wilting point is estimated at being approximately 7-9% gravimetric, and field capacity was approximately 17%.

In test 1, comparison of these values with Table 5.22 shows that for the control vessel, T1-FNS4, the gravimetric water content is very close to the theoretical value of field capacity, as would be expected for a soil in which no moisture is removed. Measurement vessel T1-FNS3 features a very dry soil at the surface, below the wilting point, suggesting that the top-most soil has reduced in water content due to factors other than root water uptake. However, the middle of the vessel shows residual moisture content slightly above the theoretical wilting point, suggesting there was still some moisture available to the plant, and the lowest sample lays approximately midway between wilting point and field capacity suggesting there was still an adequate supply of water left in the soil available for the plant. For measurement vessel T1-FNS5, there is a much lower content of soil moisture throughout the vessel. Again, at the top of the vessel there is very low moisture content, suggesting that water is removed from the soil most likely due to evaporation as well as root water uptake. For the mid and lower soil moisture test the gravimetric water content is the same as the approximate estimation of wilting point, suggesting that the visual wilting which had occurred, and signalled the end of the test, was indeed correct as the plant had used all the water available from the soil.

In test 2 all three vessels were drier than their equivalent vessels in test 1. The control vessel moisture varied between 9-12%, tending towards the wilting point rather than field capacity. This was attributed to the exposed top surface, and subsequent evaporation of moisture initiated from the top surface. Measurement vessels T2-FNS4-5 showed that residual moisture content was significantly below wilting point, which was expected due to the wilting that had started to occur on maize plants.
Figure 5.30: Available Water for Different Soil Textures (Brady, 1974).

Analysis of post-test soil moisture levels has shown that the control vessel had significantly higher moisture content than all measurement vessels. In test 1 the soil moisture reflects the growth of the larger plant, T1-FNSS, which has drier soil than that of the smaller plant. This suggests that the plant size is indeed correlated to root water uptake. The correlation between estimated wilting point and field capacity and post-test moisture content are all an excellent confirmation of the validity of test results.

5.3.3: Extraction of Electrical Impedance Measurement Data for Quantitative Analysis

Before quantitative analysis of the rhizotron measurement data could begin, acquired data were extracted from raw measurement data. This section discusses the extraction of the relevant data. Within this section the analysis is separated into multiple sub-sections; the use of conditional formatting test data to quickly observe hardware operation, the temperature correction from linear approximations, the filtering of data to remove all temperature effects and reduce the dataset size, the analysis of data at only a few arbitrary electrode pairings relating to the five excitation frequencies used, and how the measured
impedance changes for these frequencies. The data utilised and documented within this section are all extracted from growth test 1. The same principles and procedures were applied to data from test 2, and the subsequent data are used in the following sections, but the repeated process is not discussed.

Conditional Formatting to Confirm Hardware Operation

The operation of the hardware was verified through the implementation of conditional formatted images in the Microsoft Excel software package. Conditionally formatted images provide a rapid method of determining whether all electrodes were working as required by simply assigning a colour from a linear scale based on the measured value of impedance at each location, compared to the range of values from each frame of measurement data. Values of impedance which are significantly different to typical values may indicate malfunctioning electrodes, which will skew visual interpretation of data, as the colour range used to create movie files is based on the minimum and maximum range of values for each vessel. A value of impedance which is larger than the majority by an order of magnitude will significantly skew colour ranges used.

The impedance test data for each rhizotron and frequency was imported into MATLAB and stored as multiple column arrays, with a column per measurement iteration. Each column was 95 elements long, determined by the total number of measurements. Therefore, each measurement set was stored in a 1x95 array. To observe the hardware operation, the 1-dimensional arrays were extracted and reshaped in MATLAB to represent the measurement location of the appropriate electrode pairings, with all 95 measurements reshaped into a 19x5 array. Figure 5.31 shows the measurement numbers and correlating electrode pair, to aid analysis of conditionally formatted data.
Figure 5.31: Measurement number, and assigned electrode pairings based on measurement protocol for rhizotron testing. View from soil side of rhizotron.

<table>
<thead>
<tr>
<th>Meas #</th>
<th>95</th>
<th>94</th>
<th>93</th>
<th>92</th>
<th>91</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>89</td>
<td>88</td>
<td>87</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>84</td>
<td>83</td>
<td>82</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>79</td>
<td>78</td>
<td>77</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>74</td>
<td>73</td>
<td>72</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>69</td>
<td>68</td>
<td>67</td>
<td>66</td>
<td></td>
</tr>
<tr>
<td>65</td>
<td>64</td>
<td>63</td>
<td>62</td>
<td>61</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>59</td>
<td>58</td>
<td>57</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>54</td>
<td>53</td>
<td>52</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>49</td>
<td>48</td>
<td>47</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>44</td>
<td>43</td>
<td>42</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>39</td>
<td>38</td>
<td>37</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>29</td>
<td>28</td>
<td>27</td>
<td>26</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>24</td>
<td>23</td>
<td>22</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>19</td>
<td>18</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrode Pairs</th>
<th>59-60</th>
<th>58-59</th>
<th>57-58</th>
<th>56-57</th>
<th>55-56</th>
</tr>
</thead>
<tbody>
<tr>
<td>53-59</td>
<td>52-58</td>
<td>51-57</td>
<td>50-56</td>
<td>49-55</td>
<td></td>
</tr>
<tr>
<td>53-54</td>
<td>52-53</td>
<td>51-52</td>
<td>50-51</td>
<td>49-50</td>
<td></td>
</tr>
<tr>
<td>47-53</td>
<td>46-52</td>
<td>45-51</td>
<td>44-50</td>
<td>43-49</td>
<td></td>
</tr>
<tr>
<td>47-48</td>
<td>46-47</td>
<td>45-46</td>
<td>44-45</td>
<td>43-44</td>
<td></td>
</tr>
<tr>
<td>41-47</td>
<td>40-46</td>
<td>39-45</td>
<td>38-44</td>
<td>37-43</td>
<td></td>
</tr>
<tr>
<td>41-42</td>
<td>40-41</td>
<td>39-40</td>
<td>38-39</td>
<td>37-38</td>
<td></td>
</tr>
<tr>
<td>35-41</td>
<td>34-40</td>
<td>33-39</td>
<td>32-38</td>
<td>31-37</td>
<td></td>
</tr>
<tr>
<td>35-36</td>
<td>34-35</td>
<td>33-34</td>
<td>32-33</td>
<td>31-32</td>
<td></td>
</tr>
<tr>
<td>29-35</td>
<td>28-34</td>
<td>27-33</td>
<td>26-32</td>
<td>25-31</td>
<td></td>
</tr>
<tr>
<td>23-29</td>
<td>22-28</td>
<td>21-27</td>
<td>20-26</td>
<td>19-25</td>
<td></td>
</tr>
<tr>
<td>23-24</td>
<td>22-23</td>
<td>21-22</td>
<td>20-21</td>
<td>19-20</td>
<td></td>
</tr>
<tr>
<td>17-23</td>
<td>16-22</td>
<td>15-21</td>
<td>14-20</td>
<td>13-19</td>
<td></td>
</tr>
<tr>
<td>17-18</td>
<td>16-17</td>
<td>15-16</td>
<td>14-15</td>
<td>13-14</td>
<td></td>
</tr>
<tr>
<td>11-17</td>
<td>10-16</td>
<td>9-15</td>
<td>8-14</td>
<td>7-13</td>
<td></td>
</tr>
<tr>
<td>11-12</td>
<td>10-11</td>
<td>9-10</td>
<td>8-9</td>
<td>7-8</td>
<td></td>
</tr>
<tr>
<td>5-11</td>
<td>4-10</td>
<td>3-9</td>
<td>2-8</td>
<td>1-7</td>
<td></td>
</tr>
<tr>
<td>5-6</td>
<td>4-5</td>
<td>3-4</td>
<td>2-3</td>
<td>1-2</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.32 shows the conditionally formatted measured real impedance for vessels T1-FNS3 and 5. Conditional formatting was applied with a linear red-blue colour bar, where red represented higher values of impedance, and blue lower. The specific numerical values of impedance are not important in this analysis as observation of the colour indicates the magnitude of the values. For vessel T1-FNS3, measurement number 1; electrode 1-2 shows a significantly larger impedance value than the rest of the measurements, indicating a possible error in measurement. To reduce erroneous colour scaling the test data from the adjacent measurement; electrodes 2-3 were copied for all measurement iterations.
Figure 5.32: Conditional Formatting of measured real impedance in all three rhizotrons, for first measurement after test start. Blue = low impedance, Red = high impedance. View from soil side of rhizotron.

Measured impedance for vessel T1-FNS4 shows that measurements 59, 63, 64 and 69 return a measured value of impedance that is approximately 2 orders of magnitude greater than all other values. This impedance change is of such magnitude that it would distort test data, particularly visualisation techniques, as any variation in electrical impedance due to soil drying would be insignificant in magnitude. Observation of these measurements show a common electrode between all electrode pairs failed; electrode 40. Therefore, test data were again copied from adjacent neighbouring measurements to remove erroneous data.

Due to the copying of test data between adjacent measurement pairs, the spatial resolution within this region will again be reduced, however, this still highlights the flexibility and advantage of utilising a 60 electrode measurement system, where failure of one electrode does not completely compromise test data. Figure 5.33 shows the amended data for T1-FNS4, where data were copied from cells to remove the effects of the malfunctioning electrode. Whilst Figure 5.33 shows only the measurement data for a single iteration, the complete dataset was amended to remove all effects of the malfunctioning electrode. Finally, test vessel T1-FNS5 appears to show a region of high impedance towards the centre of the vessel. As with vessel T1-FNS3 the impedance is of the same order of magnitude as the other measurements. However, there are no common electrodes that appear to have failed, and therefore the data was not edited as with T1-FNS 3-4.
The use of conditional formatting has highlighted two key features. First, that it can be used as a rapid method of electrode failure detection. Secondly, it highlights the flexibility and advantage of a system with a high spatial resolution, that data can be copied from adjacent measurements, if required, with no significant loss of resolution.

**Temperature Correction of Impedance Measurements based on Linear Scaling Methods**

With data corrected for erroneous measurements due to failed hardware, the next section discusses the effects on electrical impedance for temperature variation. Analysis of data from the parallel-plate cell previously determined that a linear approximation of 2%/ °C, from measured impedance at 25°C, was a suitable scaling factor for soil based measurements. The aim here was to determine whether the temperature effects on measured impedance in an adjacent-electrode formation can be approximated with the same linear approximation previously determined in parallel-plate testing. This is required as in field based measurements temperature fluctuations will not be predictable like that

<table>
<thead>
<tr>
<th>FNS4</th>
<th>FNS4 Corrected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>2255</td>
</tr>
<tr>
<td>2077</td>
<td>2370</td>
</tr>
<tr>
<td>2457</td>
<td>2480</td>
</tr>
<tr>
<td>3201</td>
<td>3360</td>
</tr>
<tr>
<td>3941</td>
<td>3721</td>
</tr>
<tr>
<td>3572</td>
<td>451887</td>
</tr>
<tr>
<td>3631</td>
<td>451071</td>
</tr>
<tr>
<td>3476</td>
<td>372747</td>
</tr>
<tr>
<td>3398</td>
<td>3190</td>
</tr>
<tr>
<td>3333</td>
<td>2902</td>
</tr>
<tr>
<td>3537</td>
<td>3412</td>
</tr>
<tr>
<td>3206</td>
<td>2824</td>
</tr>
<tr>
<td>2942</td>
<td>2892</td>
</tr>
<tr>
<td>2576</td>
<td>2627</td>
</tr>
<tr>
<td>2183</td>
<td>2299</td>
</tr>
<tr>
<td>1744</td>
<td>2106</td>
</tr>
<tr>
<td>1253</td>
<td>1671</td>
</tr>
<tr>
<td>1185</td>
<td>1590</td>
</tr>
<tr>
<td>1064</td>
<td>1350</td>
</tr>
</tbody>
</table>

Figure 5.33: Conditional formatted data for non- and corrected real impedance in vessel T1-FNS4.
experienced within the test vessel, and simple time based filtering of data may not be possible. Figure 5.34 shows the measured impedance for the first 350 measurement iterations, which correlates to a period of 15 days. This can be confirmed by the 15 peaks and troughs seen in the plot. The impedance at each peak and trough, 10°C and 25°C respectively, was acquired and tabulated in order to calculate the theoretical impedance.

![Figure 5.34: Measured Impedance for First 15 Days (350 Test Iterations) in Vessel T1-FNS4. Non-Filtered.](image)

Table 5.24 shows the measured electrical impedance for the first fifteen days of measurements at both 25°C and 10°C, taken from T1-FNS4. The table also shows the theoretical impedance based on both a 2%/°C and 3%/°C linear approximation from the measured value at 25°C, followed by the error percentage between theoretical and measured impedance for each scaling factor. The 2%/°C is the most accurate with respect to the error margin between measured and theoretical impedance at 10°C. For the first 15 days of test data the error between theoretical and measured is less than 2%. This is an excellent result, and provides confidence that with temperature logging the impedance can be correlated to remove temperature effects. However, in this example the vessel T1-FNS4 was used, which shows a relatively small change in impedance due to other effects such as soil drying, since it was used as the control vessel. Therefore a second analysis was performed on an electrode pair and vessel which exhibited a greater change in impedance not solely related to temperature effects.
<table>
<thead>
<tr>
<th>Day</th>
<th>Measured Impedance</th>
<th>Theoretical Impedance at 10°C based on 25°C value.</th>
<th>Error Between Measured and Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25°C</td>
<td>10°C</td>
<td>2%</td>
</tr>
<tr>
<td>1</td>
<td>3498</td>
<td>4513</td>
<td>4547</td>
</tr>
<tr>
<td>2</td>
<td>3481</td>
<td>4511</td>
<td>4525</td>
</tr>
<tr>
<td>3</td>
<td>3462</td>
<td>4478</td>
<td>4501</td>
</tr>
<tr>
<td>4</td>
<td>3432</td>
<td>4435</td>
<td>4462</td>
</tr>
<tr>
<td>5</td>
<td>3414</td>
<td>4389</td>
<td>4438</td>
</tr>
<tr>
<td>6</td>
<td>3394</td>
<td>4363</td>
<td>4412</td>
</tr>
<tr>
<td>7</td>
<td>3355</td>
<td>4330</td>
<td>4362</td>
</tr>
<tr>
<td>8</td>
<td>3327</td>
<td>4284</td>
<td>4325</td>
</tr>
<tr>
<td>9</td>
<td>3298</td>
<td>4250</td>
<td>4287</td>
</tr>
<tr>
<td>10</td>
<td>3280</td>
<td>4204</td>
<td>4264</td>
</tr>
<tr>
<td>11</td>
<td>3251</td>
<td>4171</td>
<td>4226</td>
</tr>
<tr>
<td>12</td>
<td>3225</td>
<td>4145</td>
<td>4193</td>
</tr>
<tr>
<td>13</td>
<td>3225</td>
<td>4122</td>
<td>4193</td>
</tr>
<tr>
<td>14</td>
<td>3207</td>
<td>4099</td>
<td>4169</td>
</tr>
<tr>
<td>15</td>
<td>3189</td>
<td>4096</td>
<td>4146</td>
</tr>
</tbody>
</table>

Table 5.24: Measured and theoretical values of impedance (Ω) and error margins for temperature variations in T1-FNS4, first 15 days of test data.

Figure 5.35 shows the impedance for the same electrode pair as discussed, but for vessel T1-FNS5, a measurement vessel featuring a maize plant. Therefore, the soil moisture content was expected to fluctuate more due to the plant root system extracting water from the soil. There is a clear temperature effect as the temperature fluctuates in correlation with the diurnal cycle of the chamber, however, at approximately measurement 400 a significant increase in impedance begins, which was attributed to the plant root system extracting water from the soil. In early measurements the difference in impedance for temperature is much smaller than the change towards the end of the test. However, since the linear approximation is a percentage scaling, it was required to check whether the linear approximation was still appropriate for soils with a significantly higher value of impedance. The impedance for six day/night temperature cycles was extracted and tabulated for analysis. The first two values were taken from Figure; point A, which is
approximately measurement 100, correlating to days 5-6. The second set of impedances were extracted at point B, days 23-24 and finally two sets of impedances were extracted at point C, correlating to days 34-35. This method was chosen as analysis of all data points is not required.

The extracted data can be found in Table 5.25. The linear approximation with the smallest error percentage between measured and theoretical was again 2%/°C. For the impedance extracted at days 5 and 6 the error is less than 1%. However, for all other tests the error does increase, but is still well correlated. For days 23-24 the impedance in the test cell had its steepest increase, indicating that the soil in that region was not only varying in temperature, but drying at a rapid rate. The error percentage between theory and measurement data is approximately 5%, which is still relatively accurate. However, this can be attributed to not only a change in impedance from temperature but also to the soil drying between temperature fluctuations, therefore the linear approximation was expected to be less accurate here. For days 34 and 35 the general trend of impedance is still increasing, but not as rapidly as was experienced for days 23 and 24. Here the error was approximately 3.5% between measured and theoretical values of impedance, suggesting that the previous hypothesis was indeed correct, that the soil drying was
causing an associated increase in impedance which was skewing the accuracy of the linear temperature scaling.

<table>
<thead>
<tr>
<th>Day</th>
<th>Measured Impedance</th>
<th>Theoretical Impedance at 10°C based on 25°C value.</th>
<th>Error Between Measured and Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25°C</td>
<td>10°C</td>
<td>2%</td>
</tr>
<tr>
<td>5</td>
<td>3400</td>
<td>4445</td>
<td>4420</td>
</tr>
<tr>
<td>6</td>
<td>3439</td>
<td>4498</td>
<td>4471</td>
</tr>
<tr>
<td>23</td>
<td>5632</td>
<td>7674</td>
<td>7322</td>
</tr>
<tr>
<td>24</td>
<td>6505</td>
<td>8931</td>
<td>8457</td>
</tr>
<tr>
<td>34</td>
<td>12040</td>
<td>16230</td>
<td>15652</td>
</tr>
<tr>
<td>35</td>
<td>12240</td>
<td>16450</td>
<td>15912</td>
</tr>
</tbody>
</table>

Table 5.25: Measured, theoretical and error margins for temperature variations in T1-FN55, Impedance extracted at 6 days throughout test duration.

This section has provided confidence that the linear approximation of 2%/ °C is appropriate for temperature correction. However, caution must be applied when other factors such as soil drying are also present. In this application it is simple to remove unwanted temperature fluctuations through time based filtering of data as the temperature is consistent in magnitude and frequency due to the diurnal cycle of the environmental chamber. However, in field based measurements the soil temperature will not be consistent, temperature correction becomes of significant importance.

**Removal of Temperature Fluctuations through Time-Based Data Filtering**

The following paragraphs consider the filtering of data to reduce both the number of measurements, and fluctuations in impedance from temperature effects caused by the temperature cycle of the environmental chamber. In order to ensure rapid and healthy
growth of plants, a diurnal cycle was applied in the environmental chamber. The cycle featured 18 hours of daylight at 25°C, and 6 hours of darkness at 10°C. It was decided to filter out excess data and that which fluctuated due to variation in temperature. Over the duration of the test there were 1033 test iterations over a 43 day period. A test iteration is termed as each time the impedance analyser takes a set of measurements, at approximately hour intervals. The slow nature of water movement in soil allows for a temporal resolution as low as 1 measurement per day. However, since these rhizotron growth tests were the first to be performed it was decided to measure impedance hourly, and filter out unwanted data post-test. Therefore, only 1 in every 24 measurements was required, where a MATLAB script was written to extract the filtered data.

Figure 5.36 shows the non-filtered measured impedance at an arbitrary electrode pair, 38-39, in vessel T1-FNS4 over the duration of the complete growth test. There are two main observations that can be drawn. Firstly, there is a distinct cycle of impedance dependent on temperature as previously discussed. When correlated with the temperature of the soil and chamber it was found that the high value of impedance was measured when the chamber was in the night cycle and therefore at its coldest. This can be verified by the longer duration that the impedance is at the minima as the diurnal was an 18/6 hour split and therefore daylight impedance should exist for longer than night. The second observation is
that there is a significant decrease in impedance until approximately measurement iteration 350, and then a gradual increase in impedance throughout the remaining duration of the test. The initial decrease in impedance may be attributed to the moisture content reaching a state of equilibrium within the soil, followed by the increase in impedance caused by the soil drying. However, it is only possible to provide suggestions as to why the impedance of the control vessel changed in this way.

Figure 5.37 shows data from the same measurement set as Figure, but filtered to remove all data except one daily measurement of impedance. While there are slight fluctuations which highlight possible hysteresis as moisture should not change in the control vessel. Since temperature was the variable with the largest and most rapid change, it was proposed that hysteresis may cause the slight fluctuations in impedance values. Also note that the x-axis has been adjusted to display ‘Days’, and represents the number of 24hr periods since the test began.

For all future tests analysed the data will be filtered to reduce the number of data points, and remove confusion which may arise from changes in impedance due to temperature fluctuations. Any references to ‘Day n’ are taken as the number of days since the test began. Filtering has provided a much smaller and more manageable dataset for the
impedance growth tests. Reducing the data set magnitude to a smaller level decreases the risk of incorrect analysis which can occur in such large data sets.

## Selecting the Excitation Frequency

The next section considers the excitation frequency used, and how varying the excitation frequency affects the measured impedance. Only five excitation frequencies were used for the rhizotron measurements; 10, 50, 100, 500 and 1000 kHz as it was not feasible to utilise a full sweep of 58 frequencies as was performed in parallel-plate testing due to the large number of electrode pairings in the rhizotron vessel. For each rhizotron the same arbitrary electrode pairing was chosen, and the impedance at this electrode pair, for each frequency, was plotted. Table 5.26 shows the measured real impedance for all rhizotrons, at the chosen electrode pair; measurement number 36; electrodes 19-25. The tabulated data show that the excitation frequency has a large effect on measured impedance for all three rhizotrons, with a large reduction in impedance between 10 kHz and 1 MHz.

<table>
<thead>
<tr>
<th>Measurement Vessel</th>
<th>Electrical Impedance (Ω) at Excitation Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>T1-FNS3</td>
<td>31317</td>
</tr>
<tr>
<td>T1-FNS4</td>
<td>36771</td>
</tr>
<tr>
<td>T1-FNS5</td>
<td>54524</td>
</tr>
</tbody>
</table>

*Table 5.26: Measured electrical impedance at five excitation frequencies, in an arbitrary electrode pair for all three test cells; Electrode pair; 19-25. Measurement data from day 07 after test start.*

In order to visualise the impedance change due to excitation frequency, Figure 5.38 shows the measured impedance at all five frequencies, for all three rhizotrons at electrode pair 19-25. The measured impedance follows a similar trend to that experienced in parallel-plate measurements, in that the impedance significantly reduces for increasing frequency. Indeed, it appears that a plateau region may be occurring as measurement frequency
approaches 1 MHz. The impedance plots of Figure also show the substantial variability that exists between different soil samples. Since the soil moisture content was not quantified pre-test, the difference could be predominantly due to a variance in moisture content. Only minimal losses should have occurred from plant extraction due to the early time of data presented, and assuming the soil moisture contents were similar prior to testing, the other explanation is the heterogeneity of the soil causing large changes in impedance. However, the main point for analysis here was to determine the measurement excitation frequency to use for analysis of rhizotron test data.

Figure 5.38: Measured real impedance between electrodes 19-25, on Day 07, for all Rhizotrons.

Figure 5.39 shows the measured impedance between electrode pair, 45-46, in the control vessel, T1-FNS4, over the duration of the rhizotron growth test, for all five excitation frequencies to demonstrate the change in impedance values for varying frequency. This electrode pair was chosen as it is in the centre of the vessel vertically, and towards the upper surface, so any changes in soil properties should be manifest earlier than a measurement towards the bottom. All five excitation frequencies show a relatively constant slight increase in impedance, which is consistent with a soil that is drying over time, with no external assistance, such as by plant roots. However, Figures 5.40 and 5.41 consider the same electrode pairings, but for measurement vessels in which a plant is growing. In both there is the same steady increase of impedance, again assumed to be due
to a naturally drying soil. However, in both vessels there is a stage where a large increase in impedance occurs, which is attributed to the presence of a root system and subsequent extraction of moisture, which will increase impedance. For test vessel T1-FNS5, Figure 5.40, this occurs at approximately day 20. And for test vessel T1-FNS3, Figure 5.41, it occurs at day 32. This also correlates with the size of the plants, with T1-FNS5 producing a larger plant, and would be expected that the root system would penetrate down into the soil faster, and subsequently remove moisture from the soil at a faster rate.

Figure 5.39: Measured Real Impedance between electrodes 45-46, for Rhizotron FNS4 at all Five Excitation Frequencies.
It was suggested that at 10 kHz there should be little or no change in impedance regardless of the soil since this impedance was dominated by the resistance of the insulating layer. The observation of impedance values for multiple excitation frequencies shows that for all measured frequencies, there is a change in impedance over time, which is attributed to the soil drying. From previous observations, it was determined that the plateau region in field capacity soils was typically in the region of 1 MHz. At frequencies lower than this the total impedance...
impedance will be influenced by both the insulating layer and bulk material. It was decided to use only the 1 MHz data, as it was felt that this was the frequency at which the bulk material was best represented by the total impedance.

5.3.4: Qualitative Analysis of Plant Growth Test Data

This next section utilises the numerical data extracted by the processes detailed in the previous section to create movie files. Movie files feature colour-band scaling, which is relative to the measured value of electrical impedance and allows visual analysis for identifying detection of soil moisture patterns over time. Further work would consider automated quantitative analysis of such movies. The process of creating movie files from the raw data was discussed in chapter 4. Multiple screenshots are provided of the resulting movie files to cover the duration of the test. The colour scaling uses red and blue to represent high and low values of impedance respectively. Therefore, at the beginning of the test when soil was at field capacity, the colour was expected to be blue and, as the test progresses, drying soil would be seen as a red front moving down through the soil. Since the test duration differed for both tests, screenshots for test 1 are presented at intervals of 10 days, whereas 15 day intervals are implemented for test 2.

Figures 5.42 to 5.47 shows screenshots of the created movie files for all three rhizotrons over the duration of the test, at 10 day intervals for test 1 and 15 day intervals for test 2. Within each growth test the minimum and maximum values used to create the colourmap range within MATLAB is kept the same for each rhizotron vessel to allow comparison. However, the current method of creating a colourmap is based on a linear range between minimum and maximum values of impedance measured throughout the entire test period. Since the impedance values vary by so much in growth tests, a linear range does not provide a sufficient resolution of colours. For example, the test vessel T1-FNS5 has a minimum value of approximately 1 kΩ, and a maximum value of 60 kΩ. Only one measurement pair in the vessel gets close to this value of 60 kΩ, and with such a large range the resolution is lost. Rhizotron vessel T1-FNS3 has a range from 1 kΩ - 26 kΩ, less than half that of T1-FNS5, despite both being measurement vessels. Vessel T1-FNS4, the control vessel has a very small range of approximately 3 kΩ, and any change in impedance...
is insignificant in the coarse resolution of the colourmap. This limitation from the linear scale is evident in Figures 5.42 and 5.43 where even measurement vessels show limited change in soil moisture over the test duration despite gravimetric soil analysis establishing that the soil approached or exceeded wilting point in measurement vessels. This occurs as only very few values of impedance are close to the maximum impedance value. This highlights the non-linear method of soil drying patterns, previously attributed to the non-sealed top surface due to weed growth and subsequent enhanced evapotranspiration.

Figure 5.43 shows the same scaling applied, where the maximum and minimum values of measured impedance are used as the limits of the colourmap range for all three vessels. The control vessel, T2-FNS3, shows only slight evidence of soil drying at day 60, where a small light blue area appears at the top surface. For measurement vessels significant drying occurs at day 45, which is much more uniform than that experienced in test 1, attributed to the improved method of sealing the top surface, and reduced evapotranspiration.

Since the full range of impedances was so large, it was decided to limit the colourmap range to a value of impedance which approximates the wilting point, Figures 5.44 and 5.45. This would provide a visual indication of when the soil exceeds wilting point, and could, for example, be used to advise watering requirements. The value chosen as the impedance representing the wilting point was based on the measured impedance at the end of the test, and the gravimetric soil moisture obtained post-test. It was previously determined, Table 5.22, that the soil in the middle location of vessel T1-FNS3 at test end was close to the wilting point, at 8% gravimetric, compared to the theoretical value of 7-9%. Since the same soil was used for each test it was assumed that all six vessels over both test iterations would have a similar wilting point. Therefore, the measured impedance correlating to the location of the sample used to determine gravimetric moisture content was acquired, and used as the value of wilting point for all vessels. Analysis of the data acquired at measurement #46, electrodes 25-31, showed that the electrical impedance at the wilting point was 9.3 kΩ. This value of impedance became the maximum value, and only when values exceeded this would the soil be deemed to have reached wilting point. In Figures 5.46 and 5.47, it can be seen that the reduced range can be used to alert users of those areas where electrical impedance increased to such a value that wilting point may have approached or been exceeded. This range still allows small changes in soil moisture to be observed, but loses the ability to observe change in very dry soils. Once they exceed the
maximum value of impedance, or the wilting point, they remain a red colour and it is impossible to determine by how much the soil has exceeded wilting point.
Figure 5.42: Movie representation of plant growth tests over complete growth test 1. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on maximum and minimum values for all three test vessels.
Figure 5.43: Movie representation of plant growth tests over complete growth test 2. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on maximum and minimum values for all three test vessels.
Figure 5.44: Movie representation of plant growth tests over complete growth test 1. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on values of impedance for the estimated wilting point.
Figure 5.45: Movie representation of plant growth tests over complete growth test 2. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set based on values of impedance for the estimated wilting point.
Figure 5.46: Movie representation of plant growth tests over complete growth test 1. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set to show variation of control vessel.
Figure 5.47: Movie representation of plant growth tests over complete growth test 2. Blue shows areas of low impedance, and red shows high impedance. Colour-band range set to show variation of control vessel.
It is clear from the screenshots of Figures 5.46 and 5.47 that for both measurement vessels, T1-FNS3 and 5, there is a distinct drying of the soil from the top downwards into the soil core, following the path expected of the roots. At the end of the test, the drying of the soil is much more advanced in test cell T1-FNS5, which again correlates to previous results, and visual observation of the plant size post-test. From visual observation of the movie screenshots it can be seen that this increased drying of the soil in vessel T1-FNS5 has caused the measured impedance to almost completely rise above the estimated threshold for wilting point, with only the bottom right corner showing any signs of significant water left in the soil. Control vessel T1-FNS4 shows a small patch towards the centre of the vessel, in which there is a significantly higher value of impedance than the rest of the vessel. This could easily be attributed to a localised dry patch in the soil, which appears to marginally increase in size over the duration of the test, as one would expect as the soil will slightly dry throughout the test. From Figure 5.47 it is evident that the majority of the measured impedance measurements in test cells T2-FNS4-5 have exceeded the wilting point by day 45, with only small localised areas towards the bottom of the test vessels. By day 60 both vessels have completely exceeded the wilting point. The control vessel shows significant drying at the top most surface, correlating with the exposed region of soil, but the rest of the soil does not approach the wilting point, suggesting that the exposed surface only allows so much evaporation.

The final set of movie screenshots is presented in Figure 5.46 and Figure 5.47, where a further reduced impedance range is used in an attempt to show more variation in the measured impedance of the control vessels. The colourmap used for both growth tests is based on the maximum and minimum values acquired from T1-FNS4, and uses a range of only 3 kΩ, demonstrating how little the measured impedance changes within the control vessel throughout the test duration. For test 1, the localised dry section of soil towards the centre can be seen more distinctly than in previous examples. Observation of the images also suggests that the soil moisture may actually be increasing over the test duration in certain locations within the rhizotron. Two circles have been placed over the screenshots for day 10 and day 40, for vessel T1-FNS4 to illustrate this. At day 10 several small patches of ‘drier’ soil are seen within the circle as seen by lighter blue areas. By day 40, however, these patches are a darker blue, suggesting that the soil has become wetter. This wetting of the soil could occur as the soil moisture reaches equilibrium, reducing the localised patch of drier soil. However, this highlights limitations of using movie files to analyse test data, they are qualitative and provide no numerical data. For test 2 the control vessel shows a
central region of drying extending beyond that experienced in previous examples, due to the limited range used in the colourmap. This drying is again attributed to the evaporation of moisture caused by an exposed area, and suggests the magnitude of the effect that an exposed area at the soil surface can have on the moisture distribution throughout the whole vessel.

Despite any conclusions drawn throughout this section, they are only qualitative and based on user interpretation of images. Therefore, the next section utilises numerical test for analysis to provide quantitative data.

5.3.5: Quantitative Analysis of Plant Growth Test Data

This section presents plots of impedance for multiple electrode pairings within all three rhizotron vessels to determine how the impedance changed over the duration of the test. Figures 5.48 and 5.49 each show fifteen plots of the measured impedance for each rhizotron, each for a different measurement pair of electrodes. Each plot is positioned relative to its location within the rhizotron to ease analysis. If the hypothesis was correct, that the root system will remove soil moisture and therefore increase its electrical impedance, the upper-most plots should see an increase in impedance quickest compared to measurements towards the bottom of the vessel due to the nature of root growth down through the soil.
Figure 5.48: Measured Impedance in Test 1 for FNS3, 4 and 5 for the duration of the test for selected measurement pairings.
Figure 5.49: Measured Impedance in Test 2 for FNS3, 4 and 5 for the duration of the test for selected measurement pairings.
Numerical analysis of the data plots presented in Figure 5.48 test 1 suggest that soil in the upper-most regions of the rhizotrons displayed increased impedance much earlier than soil in the lower regions, exhibited by a sharp increase of impedance for measurement vessels T1-FNS3 and 5 at approximately day 15, compared to the lower measurements which did not significantly change impedance until at least day 40. This was initially attributed to the growth location of roots which caused the soil to dry as they penetrated further into the soil to extract more moisture. This was assumed to be confirmed by the relatively unchanging impedance of the control vessel, in which no root system was present.

However, test 2, Figure 5.49, demonstrate a much more uniform drying pattern of the soil, where upper and lower measurements both show a significant increase of impedance at the same time, day 30-35, suggesting that while moisture extraction from the soil via the root system was occurring, another factor also caused the non-uniform drying of soil in test 1.

Analysis of the test procedure after test 1 had highlighted the weakness of the plastic layer covering the surface, which allowed growth of weeds and provided a lack of sealing from evaporation. The weakness of the plastic layer was amended for test 2, and aimed to improve the procedure by removing both the majority of evaporation at the surface, and transpiration through weed growth by better sealing the top surface, and denying any weed growth through blocking light available. Therefore it is concluded that in test 1 evapotranspiration from weeds and the top surface was the main cause of the non-uniform drying pattern of soil, highlighting the importance of well-defined test procedures.

Despite the weakness of the method used to cover the soil surface in test 1, the control vessel still remained better sealed than measurement vessels. This improved sealing was confirmed with analysis of T1-FNS4 which shows minimal change in impedance throughout the complete rhizotron vessel over the test duration, suggesting a low amount of soil moisture loss throughout the test. Although the method used to seal the top surface was improved for growth test 2, it was also decided to leave a small central area of the soil surface exposed to air, to replicate the exposed area also experienced in measurement vessels. This exposure would encourage more evaporation to occur in the control vessel of test 2, than test 1, and was expected to be manifest as an increase in impedance in the top central measurements. This was confirmed by analysis of T2-FNS3, where it can be seen that the impedance in the top most measurements increases at approximately day 30, while the lowest measurements show no significant increase in impedance over the
complete test duration. The measured value of impedance for measurement 93 exceeds that of the proposed wilting point, 9.3 kΩ, while measurements either side of this point tend towards the wilting point, but do not exceed it. Measurements 71, 73 and 75 also show a measurable change in impedance, again attributed to evaporation. For all other measurements, evaporation had no significant, measurable effect. This suggests that soil drying caused by evaporation can extend as far as 10cm into the rhizotron vessel, below the soil surface. This non-uniformity experienced within the control vessel of test 2 demonstrates the magnitude of the soil drying caused by evapotranspiration alone when a small area on the soil surface was left exposed.

The enhanced test procedure implemented in growth test 2 provided greater confidence that the measured change in impedance was related to root growth, and root water uptake since weed growth was almost completely eradicated. Monitoring values of electrical impedance over time indicates potential drying patterns of the soil. Analysis of the impedance values extracted from both measurement vessels suggests a more uniform drying of soil throughout the vessel, different to what was experienced in test 1. For both measurement vessels, at approximately day 30, there is a large increase in impedance, attributed to a reduction in moisture content of the soil. This sudden use of water correlates with both the plant growth and the previously discussed evaporation experienced in the control vessel. Qualitative analysis of the plant growth through photographs, Figure 5.50, showed that in the early section, day 5, of the test only 1-2 major roots penetrated down into the soil. The longest root was approximately 15-20cm long, so moisture extraction would be minimal. By day 27 the two significant roots were still clearly visible against the Perspex viewing window of the rhizotron and had grown the full length of the rhizotron, 60cm, and from which a significant number of smaller shoots had grown which would be responsible for moisture extraction. It would only be when a large set of roots has established in the soil that significant moisture began to be extracted, which gives confidence that the large increase at day 30 is attributed to the root water uptake primarily, especially lower in the rhizotron where evaporation had no measurable effect. The difficulty in analysing data, and determining root water uptake, is in quantifying the moisture loss from evaporation. Further test improvements would focus on attempting to reduce or remove completely any moisture loss through evaporation. Figure 5.50 also highlights a limitation of typical rhizotrons, the reflections caused by the Perspex viewing window causes difficulty in achieving adequate photographic images. However, in this
application the photographs are used to correlate with quantitative data acquired from the array of insulated electrodes on the rear plane of the vessel.

For both plant growth tests, the measurement vessels, T1-FNS3, 5 and T2-FNS4-5 provide a much higher value of maximum impedance than control vessels, due primarily to the extraction of moisture from the soil in addition to any evaporation. In growth test 1, plant T1-FNS3 was much smaller than T1-FNS5, and measured values of impedance reflect this with acquired maximum values of approximately 60 kΩ compared to only 25 kΩ, respectively. In test 2 both plants were much closer in height, and the maximum values of impedance again reflect this similarity. For T2-FNS4 maximum impedance was measured to be 41 kΩ compared to 42 kΩ for T2-FNS5.
Figure 5.50: Photograph of plant growth in Rhizotron T2-FN55 at: A) Day 05, B) Day 27.
Tables 5.28 and 5.28 show the numerical value of measured impedance at the start and end of the both tests, for the same measurement locations as provided in Figures 5.48 and 5.49 respectively. The tabulated values allow a purely numerical observation of the impedance change over the duration of the test for 15 measurement locations. Analysis of the data shows that for all three rhizotrons in test 1, the impedance measured at the start lies within the range of 1.2 – 4.2 kΩ, but that the impedance at the end lies between 1.6 - 50.6 kΩ. For test 2, the initial impedance again lies within a similar range of 1 – 6.4 kΩ, whereas the impedance at the end of the test was 1.9 – 40 kΩ.

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. #95</td>
<td>FNS3</td>
<td>1223</td>
<td>9612</td>
<td>FNS4</td>
<td>2007</td>
<td>2125</td>
</tr>
<tr>
<td></td>
<td>FNS5</td>
<td>2458</td>
<td>47907</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meas. #93</td>
<td>FNS3</td>
<td>1335</td>
<td>25938</td>
<td>FNS4</td>
<td>2367</td>
<td>2329</td>
</tr>
<tr>
<td></td>
<td>FNS5</td>
<td>3834</td>
<td>50642</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meas. #91</td>
<td>FNS3</td>
<td>1159</td>
<td>20961</td>
<td>FNS4</td>
<td>2011</td>
<td>2260</td>
</tr>
<tr>
<td></td>
<td>FNS5</td>
<td>2359</td>
<td>44988</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meas. #75</th>
<th>Meas. #73</th>
<th>Meas. #71</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNS3</td>
<td>1351</td>
<td>1449</td>
</tr>
<tr>
<td>FNS4</td>
<td>3818</td>
<td>4136</td>
</tr>
<tr>
<td>FNS5</td>
<td>3314</td>
<td>3033</td>
</tr>
<tr>
<td></td>
<td>5987</td>
<td>9101</td>
</tr>
<tr>
<td></td>
<td>2997</td>
<td>4253</td>
</tr>
<tr>
<td></td>
<td>19916</td>
<td>13073</td>
</tr>
<tr>
<td></td>
<td>8213</td>
<td>3103</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2486</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11414</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meas. #55</th>
<th>Meas. #53</th>
<th>Meas. #51</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNS3</td>
<td>1501</td>
<td>1543</td>
</tr>
<tr>
<td>FNS4</td>
<td>3311</td>
<td>2790</td>
</tr>
<tr>
<td>FNS5</td>
<td>4053</td>
<td>3221</td>
</tr>
<tr>
<td></td>
<td>3468</td>
<td>4441</td>
</tr>
<tr>
<td></td>
<td>2580</td>
<td>2542</td>
</tr>
<tr>
<td></td>
<td>11157</td>
<td>12207</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5192</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2662</td>
</tr>
<tr>
<td></td>
<td></td>
<td>13981</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meas. #35</th>
<th>Meas. #33</th>
<th>Meas. #31</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNS3</td>
<td>1418</td>
<td>1429</td>
</tr>
<tr>
<td>FNS4</td>
<td>2926</td>
<td>2752</td>
</tr>
<tr>
<td>FNS5</td>
<td>3886</td>
<td>3546</td>
</tr>
<tr>
<td></td>
<td>2830</td>
<td>2980</td>
</tr>
<tr>
<td></td>
<td>2805</td>
<td>2533</td>
</tr>
<tr>
<td></td>
<td>8317</td>
<td>4167</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3264</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2678</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14360</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meas. #15</th>
<th>Meas. #13</th>
<th>Meas. #11</th>
</tr>
</thead>
<tbody>
<tr>
<td>FNS3</td>
<td>1157</td>
<td>1330</td>
</tr>
<tr>
<td>FNS4</td>
<td>1305</td>
<td>1809</td>
</tr>
<tr>
<td>FNS5</td>
<td>2660</td>
<td>3153</td>
</tr>
<tr>
<td></td>
<td>2684</td>
<td>2649</td>
</tr>
<tr>
<td></td>
<td>1612</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>12480</td>
<td>25120</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2635</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1696</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9193</td>
</tr>
</tbody>
</table>

Table 5.27: Start and end impedance for multiple measurement locations. Table position relative to actual measurement position. Test 1. Test data for FNS3-5. Highlighted cells denote control vessel.
<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. #95</td>
<td>Meas. #93</td>
<td>Meas. #91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNS3</td>
<td>1641</td>
<td>7522</td>
<td>2029</td>
<td>15819</td>
<td>1592</td>
<td>7776</td>
</tr>
<tr>
<td>FNS4</td>
<td>2683</td>
<td>39778</td>
<td>4516</td>
<td>34174</td>
<td>2193</td>
<td>19297</td>
</tr>
<tr>
<td>FNS5</td>
<td>2700</td>
<td>21726</td>
<td>2814</td>
<td>33909</td>
<td>3906</td>
<td>39787</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. #75</td>
<td>Meas. #73</td>
<td>Meas. #71</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNS3</td>
<td>1587</td>
<td>3242</td>
<td>1640</td>
<td>3249</td>
<td>1533</td>
<td>2895</td>
</tr>
<tr>
<td>FNS4</td>
<td>3096</td>
<td>19920</td>
<td>3218</td>
<td>17065</td>
<td>3612</td>
<td>23559</td>
</tr>
<tr>
<td>FNS5</td>
<td>3682</td>
<td>19539</td>
<td>6390</td>
<td>26819</td>
<td>5369</td>
<td>19661</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. #55</td>
<td>Meas. #53</td>
<td>Meas. #51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNS3</td>
<td>1253</td>
<td>2007</td>
<td>1539</td>
<td>2796</td>
<td>1370</td>
<td>2269</td>
</tr>
<tr>
<td>FNS4</td>
<td>2789</td>
<td>21979</td>
<td>3717</td>
<td>17142</td>
<td>3023</td>
<td>17823</td>
</tr>
<tr>
<td>FNS5</td>
<td>2623</td>
<td>13428</td>
<td>3169</td>
<td>17525</td>
<td>4246</td>
<td>18768</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. #35</td>
<td>Meas. #33</td>
<td>Meas. #31</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNS3</td>
<td>1166</td>
<td>1928</td>
<td>1341</td>
<td>2453</td>
<td>1306</td>
<td>2075</td>
</tr>
<tr>
<td>FNS4</td>
<td>2562</td>
<td>24562</td>
<td>3333</td>
<td>14845</td>
<td>2484</td>
<td>22572</td>
</tr>
<tr>
<td>FNS5</td>
<td>2178</td>
<td>12486</td>
<td>2839</td>
<td>15866</td>
<td>2903</td>
<td>18918</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
<th>Start</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meas. #15</td>
<td>Meas. #13</td>
<td>Meas. #11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FNS3</td>
<td>1091</td>
<td>2093</td>
<td>980</td>
<td>2075</td>
<td>1257</td>
<td>2031</td>
</tr>
<tr>
<td>FNS4</td>
<td>1887</td>
<td>18210</td>
<td>1981</td>
<td>18260</td>
<td>1808</td>
<td>22123</td>
</tr>
<tr>
<td>FNS5</td>
<td>1458</td>
<td>20709</td>
<td>2826</td>
<td>20188</td>
<td>2361</td>
<td>17925</td>
</tr>
</tbody>
</table>

Table 5.28: Start and end impedance for multiple measurement locations. Table position relative to actual measurement position. Test 2. Test data for FNS3-5. Highlighted cells denote control vessel.

For tests T1-FNS 3, 5 and T2-FNS 4-5, the measurement vessels, the measured values of electrical impedance typically show a significant increase in the value of measured impedance over the duration of the test, and particularly towards the upper section of the rhizotron where the plant root systems will be most established and evaporation occurs. The significant increase in electrical impedance at various electrode pairings correlates with the placement of the main root system through photographic images taken throughout the test duration, which was closest to the middle pair of electrodes at the top surface. Since temperature effects were removed, and the soil was deemed to have no significant compaction over the test duration due to no interference from at the soil surface, the main factor which could change the soil impedance was the moisture content. Therefore, the
change is believed to be predominantly due to changes in moisture content, which are brought about by the placement of a root system, as proved by the relatively unchanging moisture content in control vessel T1-FNS4, and evaporation, proved by control vessel T2-FNS3.

5.4: Summary of Results

This section provides a summary of the most significant findings from the analysed test data.

Chapter 3 considered the use of a saline electrolyte to determine the accuracy of the insulated electrode method compared to a calibrated bench conductivity meter. First, the precision of the bench conductivity meter was addressed, which was found to be within 1%. For the insulated electrode method the precision was found to be within 2.5%. In terms of accuracy, the bench conductivity meter results were deemed as ‘accurate’ since the meter was calibrated as per specification with the use of calibration fluids. Therefore, the results acquired through the insulated electrode method were compared to those of the bench conductivity meter. It was found that for all levels of salinity tested, the insulated electrode method was within a constant value of 10% error from the value measured from the bench conductivity meter.

For soil moisture testing, results suggested that the change in impedance relative to moisture content is not linear, but one with a decreasing gradient with respect to the reduction in impedance for increasing moisture content. In drier soils, the addition of water had a significant effect on the electrical impedance, but as soils tended towards saturation the change in impedance was smaller.

It was found that for both temperature and compaction testing, the effect on impedance is lower in drier soils. At 5% moisture content the change in impedance resulting from compaction or temperature change was insignificant when compared to the change experienced from additional moisture in the soil. However, as residual soil moisture tended towards saturation, the change from compaction and temperature became comparable with moisture change. For temperature testing a linear approximation was found to fit the
data well, which allows for temperature correction, but only if the soil temperature is known. A linear scale of 2%/ °C provides a good fit to the data. This linear approximation is typical of water conductivity and temperature. For compaction, no such approximation was made, however, it was determined that for change in compaction the relative permittivity of the soil remained unchanged. This was expected due to no additional moisture content within the soil for increasing compaction, and the relative permittivity being predominantly determined by the moisture content of the soil.

It was previously discussed how compaction change is unlikely to occur in laboratory based testing, but that controlled test procedures can ensure consistent levels of compaction in the soil which will improve test data repeatability. For temperature testing, either the linear approximation can be applied, or if a cyclic temperature sequence is performed in controlled environmental chambers the use of time based filtering of data can remove temperature effects.

Empirical modelling was performed for all moisture, compaction and temperature tests to determine parameter values of the insulating layer and bulk material to check whether they correlate well with expected values. For changes in moisture content, empirical modelling confirmed that increased moisture content of the soil will increase the relative permittivity value, which can assist with estimating moisture content from impedance measurements. Empirical modelling performed on compaction testing demonstrated that when only the compaction level was increased, the relative permittivity was unchanged. This was attributed to no additional moisture present in the sample, and therefore an unchanging permittivity. For temperature testing it had been proposed that while the temperature of the sample will affect the relative permittivity, the change will be very small and possibly immeasurable. However, erroneous data led to an inability to empirically fit data with any confidence, which was suspected due to the high frequency limitations of the impedance analyser.

Rhizotron growth tests were performed to determine the ability to measure soil impedance change over a 6-8 week growing period, and conclude whether the C4D technique in an adjacent-plate formation could be used to infer moisture content movement in the soil. One control and two measurement vessels were used for each test. In growth test 1 the control vessel showed very little change in electrical impedance, which was expected as little water was lost through evapotranspiration. For the measurement vessels, significant moisture was lost over the test duration. This was observed as a “front” which moved
down the soil. Gravimetric testing determined that the control vessel remained at field capacity for the duration of the test while the measurement vessels reached, or even exceeded the wilting point. This moving front of drying soil was attributed to both root water uptake, and evaporation from the poorly sealed top surface around the plant stem.

For test 2 an enhanced test procedure was applied, which improved the seal at the top soil surface, reducing weed growth and evaporation. The control vessel showed that significant and measurable evaporation, which was capable of drying the soil to beyond wilting point, occurred within approximately the top 10cm of the soil. This was caused by an opening in the top covering left to replicate that found in measurement vessels to allow the stem to grow. Measurement vessels again showed that the placement of a root system within the vessels increased the removal of moisture throughout the whole vessels. Post-test residual moisture content levels were found to confirm the measured values of impedance and the assumed drying of the soil based on these values.

The results obtained in this research have shown that the insulated electrode method is capable of determining a relative value of soil moisture content within rhizotron vessels. The results show excellent correlation with post-test destructive analysis.

6: Conclusion
This section presents the conclusions based on results and observations obtained throughout this research programme. It is separated into two sections. In the first section is provided a summary of all findings throughout the research with a brief overview of results, and the implications of obtained results. The second section presents any limitations which were experienced within the research, both expected and unexpected, and if overcome, how this was achieved. This section also provides a discussion relating to future work, detailing those limitations which were not overcome, suggestions of how that may be possible. It also covers future work which may not have been considered within this research, but which would be beneficial to improving the work already performed.

### 6.1: Summary of Main Findings

The summary of main findings is further split into three sections for ease of reading. First is a discussion relating to conclusions drawn from the simulations performed. Second is conclusions based on parallel-plate measurement data. The last section relates to the conclusions derived from rhizotron testing and the plant growth tests performed.

### 6.1.1: Simulation Conclusions

One of the initial aims of the research was to replicate typical methods of determining soil moisture content by means of electrical impedance measurements, but with modification to the implementation of the technique to reduce effects such as electrode corrosion and polarisation. This was achieved through the use of capacitively coupled impedance measurements, which were realised by placing an insulating layer over the electrode surface and performing capacitively coupled measurements.

In Chapter 3, analytical based simulations showed that the use of insulated electrodes could be applied to parallel-plate measurements to measure soil moisture, a technique which has not been implemented by other research groups. Simulated data concluded that...
the system will have restricted operating limits, based on a relationship between excitation frequency and the conductivity of the medium under test. As the bulk material increased conductivity, the excitation frequency must be also increased. One limitation of this was the requirement of equipment to operate at higher frequencies, which increases hardware costs. The analytical model was not verified above frequencies in the low MHz range, as laboratory equipment was not available to achieve this. Simulation of data was performed predominantly to determine feasibility of the C4D method for measuring the bulk material of soil properties, unlike in a methodology such as ERT in which the forward model information is used to calculate the inverse solution. The information obtained through modelling provides no information required for the analysis of data, other than an indication of typically expected results, and determining limits of operation.

The first challenge experienced was that of the electrode coating used to insulate the electrodes. In order to be sensitive to the properties of the bulk material, insulated electrode methods must feature an insulating layer which has a value of capacitance significantly higher than that of the bulk material, due to the lowest capacitance value dominating the total series capacitance. Through analysis of the electrical model it was determined that a thin electrode coating was required, which would have a higher capacitance. However, this was at the expense of the strength of the insulating layer. The insulating layer chosen for the measurement vessel was a PCB solder mask, chosen for its high permittivity and strength. Through pre-testing it was determined that the high impedance limits of the impedance analyser caused potentially erroneous results. The insulating layer was quoted as having a resistance of $2 \times 10^{12} \Omega$, yet returned a measured impedance of 1.5 MΩ, close to the maximum value of impedance the impedance analyser can measure. While the measured value of impedance was very low compared to the theoretical value, it was deemed insignificant for the research here, since the main focus was to establish the bulk material impedance only and not the impedance of the insulating layer, which should remain constant for all tests. One suggestion for future work is to utilise an electrometer to measure the very high impedance of the insulating layer. This would only be required to characterise the test cell, however, and not for measurement of the bulk material. The impedance analyser, and measured complex impedance, was able to confirm that the capacitance of the insulating layer was as expected when compared to the product datasheet.
Unlike the parallel-plate formation of electrodes, the adjacent electrode formation did not offer a relatively simple analytical solution as current paths are not a simple linear relationship. Therefore FEM was introduced through the use of COMSOL Multiphysics. It was found that the thin insulating layer placed a large demand on the number of mesh elements within the FEM, and that simulations could not be performed with a 75 μm insulating layer on the adjacent-electrode formation as found on the rhizotron due to insufficient memory available in the laboratory computer. Parallel-computing or improvements to computer hardware were not possible due to time and budget constraints.

Simulations for multiple thicknesses of insulating layer, with scaled electrical properties, were explored to determine how varying the insulating layer thickness affected both simulation time and values of simulated complex impedances. It was found that increasing the layer thickness from 75 to 500 μm (0.5mm) reduced the simulation time from 74 minutes to less than 3 minutes and that simulated values for complex impedance with a 500 μm insulating layer were within 1% of the values for a 75μm layer, for all simulation frequencies. This increased simplicity and reduced computational time were the determining factors for choosing the 500 μm layer in the FEM. With a thicker insulating layer used in the FEM, it was found that an adjacent electrode formation, similar to that within the rhizotron, could be successfully modelled and simulated. This use of a thicker insulating layer for FEM simulations was deemed a significant step forward within the research, as previously the thin insulating layer had caused an inability to simulate an adjacent electrode formation.

FEM simulations for an adjacent electrode formation suggested that values of impedance would typically be 30% less than those for a parallel-plate formation with identical bulk materials. However, perhaps most importantly is that the spectroscopic signature from an adjacent electrode measurement is similar in shape and magnitude to that of a parallel-plate measurement, confirming that while the bulk material is not directly attainable with an adjacent electrode measurement, the C4D method was capable of determining changes in soil electrical properties, which will be mostly affected by soil moisture content.

FEM simulations were also performed to determine the region of influence of adjacent-plate measurements by introducing boundaries of contrasting conductivity. It was found
that the region of influence extended by 1, 5 and 2.7 cm in the x, y and z axes respectively, with the simulation parameters used. This region was then simulated with ten conductivities to provide values of impedance. Relating these values to those acquired in measurement data it was possible to backwards estimate the electrical conductivity of rhizotron measurements. Values of electrical conductivity are dimensionless and allow better comparison or the material properties rather than the volume under test. Finally, FEM was used to introduce localised areas of contrasting conductivity to determine the error which may exist from inhomogeneous measurements. It was found that when the localised contrasting conductivity was placed directly between electrodes the influence could be as much as 35% difference from the impedance simulated for a homogeneous medium. However, once the localised area was moved outside of the direct line of current flow the effects dropped to approximately 3% or less.

Further research would investigate such methods utilised in electrical tomography, where multiple electrode excitation strategies are considered to improve spatial resolution and consider inhomogeneity. This may, however, require a redesign of the rhizotron vessel to increase the electrode count by utilising smaller electrodes and also the switching electronics used in the current system.

The simulated data provided confidence that capacitively coupled measurements could be used to determine the changing electrical properties of soil, therefore the next section of research moved onto laboratory based testing.

6.1.2: Parallel-Plate Testing Conclusions

Initial testing looked at characterising the parallel-plate test cell with three water types; an electrolyte of increasing salinity, tap water and deionised water. The electrical conductivity of the water types could be verified through the use of bench conductivity meters and compared to the spectroscopic complex impedance attained through capacitively coupled measurements. Repeatability testing with only bench conductivity meters, for all three water types as the bulk material, determined that the repeatability between test iterations was found to be less than 1%, showing both excellent repeatability in test procedure and equipment.
Accuracy between conductivity meter and capacitively coupled electrode methods was significantly reduced for tests with increasing salinity. It was found that for five salinity levels tested the value of electrical impedance extracted from capacitively coupled measurements was typically less than 25% higher than the measured value from the conductivity meter. The error margin was relatively consistent across all salinity levels, suggesting that a scaling factor could be used. However, it is most likely that the capacitively coupled measurement method will be used for relative measurements, and as the bulk material conductivity changes over time changes would be monitored relative to the initial value and soil conditions. These results showed that the parallel-plate test cell was capable of determining changes in the electrical properties of water.

The largest challenge encountered in this research was the repeatability of soil based measurements. It was found that the difference between measured values of impedance of the bulk material, taken from those values located within the plateau region, was less than 5% between test iterations, compared to less than 1% for water and electrolyte testing with the conductivity meters. While this error is larger and that soil suffers greater heterogeneity than water based testing, it still shows repeatability can be achieved.

It was with soil based measurements that the potential of the MATLAB created SMP GUI was realised. Initially it had been used to estimate parameter values of $R_B$ only, however, during soil testing it was realised that the GUI could be used to quickly estimate values of both $R_B$ and $C_B$. The value of $C_B$ determined the second roll off, which was previously unchanging for water based tests where the relative permittivity was 80. However, in soils the relative permittivity changes significantly, since it is a product of the water content, and therefore the roll off point is important for determining the relative permittivity. Also, knowledge of the bulk material relative permittivity may allow the ability to suggest water content since the bulk resistance may be a function of many parameters, but the permittivity is most affected by water content.

For soils with a gravimetric moisture content greater than 15%, the measurement technique was unable to determine a plateau region through visual inspection alone, as the measurement equipment could not measure at a high enough frequency. Therefore, for these soils, the plateau frequency was estimated based on the relationship between the plateau frequency values at lower frequencies. While this was an estimation based on simple data fitting, it was adequate for determining an approximate value, from which the results provided confidence that the values chosen were correct.
Soil was compacted to four distinct levels of compaction, between 0.05-0.21 kg/cm². This represents a fairly loose compaction compared to that which may be experienced within the field, however, it was deemed typical of the compaction which may be associated with laboratory based tests. The rate of change in electrical impedance due to compaction differed, dependent on residual soil moisture content. Wetter soils suffered less change in electrical impedance as the soil was compacted when compared to drier soils. This was attributed to compaction in drier soils reducing air porosity, which is a large factor in electrical impedance, as the air phase is a dielectric. For 5% gravimetric soil the decrease in electrical impedance relative to the loosest compaction was approximately 40%, whereas for 30% gravimetric soils the decrease was approximately half at 20%.

For temperature based testing a decrease in impedance was experienced for increasing temperature, as was expected. Since the electrical conductivity of the soil was relative to its water content, it was hypothesised that the same relationship between water conductivity and temperature should exist. Scaling of the electrical impedance for a reference temperature of 25°C determined that a scaling factor of 2%/ °C was the more accurate scale, and provided a good reference value.

6.1.3: Rhizotron Testing Conclusions

The final testing performed was that of two long-term growth tests within the rhizotron vessels. Due to test setup procedures being well-defined and controlled, it was expected that any variance in electrical impedance would be predominantly due to the heterogeneity of the soil. However, due to a lack of time available in the research program the rhizotrons weren’t fully characterised with a known electrolyte, so variation in measured impedance may exist due to hardware variations. While the electrodes and insulating layer used for the rhizotron electrodes are the same as those in the parallel-plate measurements, which were previously characterised, the switching electronics will require additional characterisation as impedances may be associated with the electronics. This characterisation of the rhizotron vessels would be a suggestion for future work and would be expected to normalise measurement data, with the aim to improve absolute values of impedance measured.
Both qualitative and quantitative analysis was performed on the rhizotron growth tests, and are discussed interchangeably within this section. Post-test, the vessels were removed from the environmental chamber and the soil visually analysed. Visual analysis determined that the root structure was well established throughout the measurement vessels and that the colour of the soil also indicated that the control vessel was significantly wetter than the measurement vessels, expected due to reduced moisture loss in the control vessel as no plant was present. It was visually determined that measurement vessels had significantly drier soil by the presence of large cracks when compared to that of the control vessels. This drying of the soil was confirmed through gravimetric soil analysis. With a prior knowledge of soil type, approximations could be made of the moisture content relative to the field capacity and wilting point. Approximations placed the control vessels moisture content close to the expected field capacity in localised areas, however, control vessels did suffer from evaporation of moisture from the top surface. In these areas the soil did reach the wilting point. For measurement vessels, the typical moisture content within the soil reached or exceeded the suggested wilting point for the soil type throughout the whole vessels. For measurement vessels the plant system will have removed all available water from the soil around the rhizosphere. Once depleted the root system would continue to grow and extract moisture from the soil elsewhere. It was also anticipated that some additional drying of the soil would occur close to the surface, in the centre, where the plant stem protruded from the soil as it was difficult to completely seal around the stem, as was confirmed through evaporation in the control vessels.

In growth test 1, one of the plants was significantly bigger than the other, which correlated well with the drier soil in one of the measurement vessels, suggesting that the larger plant required more water from the soil, as was again expected. Measurement of the plants showed that the larger plant had a length of 67cm from soil surface to tip of longest leaf, compared to a length of 46cm for the smaller plant. Therefore, the smaller plant was approximately two thirds of the size of the larger one, and as such would have been expected to use less water. For growth test 2 both plants were of a much similar size, and the residual moisture content was also reflected accordingly.

Through a more extensive test program, plant size could be correlated with residual soil moisture content, to determine whether any seeds were more efficient at removal of soil moisture. For example, two plants may reach the same size, yet one uses less water to
obtain the same growth. Rapid phenotyping could then push forward those plant strains with stronger genetic traits.

The following discussions relate to electrical impedance measurements obtained from the rhizotron test vessels. When considering temperature variation relative to measured impedance, the same linear approximation experienced in parallel-plate measurements was implemented. For a 2%/ C° linear approximation it was possible to estimate electrical impedance to within approximately 5% of the measured value.

Movie files were created from the numerical values of measured electrical impedance at each electrode pairing. Multiple ranges were experimented with for the colour bar representation, which provided a visual indicator of soil drying throughout the vessel as it approached wilting point. It also showed the stability and limited moisture loss for the control vessels. However, limited scales remove the ability to determine any change in impedance for those measurements which had exceeded the defined electrical impedance of the wilting point. While the data used to create the movie files was quantitative, the visual analysis was qualitative as it was based on observance of colour transitions over time. The movie files show that the measurement vessels feature increased soil drying, when compared to the control vessel, which was attributed to root movement through the soil and subsequent use of water for plant growth. Despite the visually appealing nature of movie files, they do not provide the necessary data for a quantitative analysis. The final analysis, therefore, was performed by plotting the electrical impedance at several electrode pairings throughout the vessel over the test duration, to determine the change in electrical impedance relative to the other test cells. This is similar to the screenshots of the created movie files, but improved as numerical values are analysed. It was confirmed that closest to the top centre of the measurement vessels the soil dried most, which was attributed to the placement and water use of the plant seed and also evaporation. It can also be seen that electrode pairs towards the bottom of the vessel only experience significant change in impedance towards the end of the test duration, implying that the soil did not dry homogeneously, but that as roots moved down the vessel they exhausted water supplied before growing down in the soil core, systematically using water content in the soil. The numerical values of impedance also confirm that the larger plant in test 1 caused a significantly higher value of electrical impedance, with a maximum value of approximately 65kΩ compared to 30kΩ for the smaller plant. The control vessels had a
much smaller range of impedance throughout the test period, except for the areas which suffered evaporation, as expected due to the limited soil drying.

6.2: Difficulties Encountered and Future Work

Several significant difficulties have been experienced within the research programme which have limited the desired outcome in some way. The most substantial difficulty experienced was working with soil. The heterogeneity experienced even within well-defined test procedures caused difficulties in determining absolute values from which conclusions can be based. Because of this, a large portion of the work discusses relative values of impedance, based on variations over time relative to the initial value of impedance, as the soil is subject to different external conditions. In order to overcome this, a much more robust, substantial set of measurements is required to provide a data set from which a statistical analysis can be performed. Time and lack of facilities prevented this from occurring during this research. The most significant requirement for large scale testing programs would be the requirement of many environmental chambers, or access to a large room with a controlled environment. The current measurement equipment can be used to connect many rhizotrons in parallel, and is only limited by the number of USB ports available on the data acquisition computer, and the duration of each frame of measurements. Currently, hourly measurements are made, and each test takes 15 minutes, indicating that only 12 rhizotrons could be connected before temporal data was lost. However, the majority of data was filtered out to provide only one value of impedance per day, as plant and soil water movement is an inherently slow process. Therefore, it could be possible to connect 20+ rhizotrons together connected in parallel if required.

The heterogeneity experienced in soil based measurements comes predominantly from the structure of the soil, or more specifically the way in which the soil particles are formed within the test cell. Since soil is made up from multiple components of different sizes, when they are removed and replaced back into a test cell they ‘fall’ differently. For electrical resistivity measurements this changes the formation of ionic paths through the soil, changing the resistivity. To overcome this, strict test procedures must be adhered to, such as ensuring the soil quantity used is the same for all repeat tests, temperature does not
vary between tests, the same soil type is used and bulk density (compaction) is kept the same. With thorough test procedures, the variance between test iterations can be improved and was found to be as good as 5% variance between repeat tests within this report. However, it is expected that it will never be as repeatable as water based measurements.

Another limitation of the research was that only one soil type was used. While it was decided to use only one soil type for this preliminary work to try improving repeatability, it does not provide a thorough data set. Therefore, it is proposed that for future work multiple soil types are used. It is hypothesised that while relative measurements of change in electrical impedance over time will provide information relative to soil drying, absolute values could not be compared for measurements of impedance between different soil types unless calibration is performed to characterise the soil.

Further improvements to validity of test data would also come from using soil which is not as well characterised. The soil used throughout this research was sieved to 2mm, to remove all stones and larger soil clods. However, this does not represent a typical soil which would be found within a field based measurement. Using soil from a field will improve validity of data, and determine whether the system is capable of soil moisture analysis in field based measurements, or whether the technique is confined to laboratory and greenhouse trials with controlled soil.

It was proposed in the results section that pre- and post-test moisture contents for growth tests would assist in data analysis. Currently only the post-test moisture content is measured, due to the requirement of destructive sampling. One way to achieve pre-test moisture content would be to implement a sensor such as a TDR probe, to measure the moisture content at multiple locations pre- and post-test.

While the rectangular array of electrodes provides a good spatial resolution in terms of moisture content within the soil, it is not capable of determining root locations. For this reason, the rhizotron test vessel was used, which allows visual observance of root placement. However, future work could implement X-ray technology to correlate root placement with soil drying. Work performed by Grieve (2010) showed that through the use of X-ray it is possible to determine both soil moisture and root placement, however, it was limited by the size of plants available within the X-ray machine therefore other
technologies may be required such as MRI or GPR, but again they do not lend themselves to small-scale and cheap measurements.

Despite electrical resistivity measurements not being capable of locating the fine roots found within plant systems, one suggestion is to use a plant which features a large root, such as a carrot or potato plant. The significant mass within the root may be measurable with electrical resistivity measurements.

During the analysis of rhizotron test data it was concluded that not enough visual verification was performed during plant growth testing. For growth test 1 limited visual observance was performed. For growth test 2 this was improved to weekly photographs, however, they do not provide a thorough data set. While the environmental chamber lighting and dimensions do not allow for easy visual observation, future tests must develop a system in which regular images can be taken to fully benefit from the use of rhizotron vessels. One difficulty in achieving this is the reflections which occur from the rhizotron viewing windows, and the placement of a fixed cameras position, which is difficult to overcome within the small environmental chambers used.

Due to a lack of time available it was also realised that while the functionality of the rhizotron switching electronics had been checked, they had not been electrically characterised. Characterising vessels may improve repeatability as variations due to characterisation may be able to be subtracted from measured impedance values.

In the simulation chapter it was concluded that the impedance analyser was unable to measure electrical impedance higher than 1.5 MΩ. This presented difficulties as the datasheet for the insulating layer quoted a resistance value of \(2 \times 10^{12} \, \Omega\), significantly higher than the maximum measurable limit of the impedance analyser. The value of measured impedance for the insulating layer was found to be approximately 1.5 MΩ confirming that the impedance analyser limited the ability to determine the actual resistance value of the insulating layer. While not ideal, it was decided that it was not a significant fault in the research as the low frequency impedance is ignored when attempting to measure the bulk material impedance. However, for completeness it is suggested that the insulating layer be properly characterised by the use equipment such as an electrometer, able to measure at very high impedances typically up to \(10^{18} \, \Omega\) (Keithley, 2005), significantly higher than the datasheet quoted resistivity of the insulating layer.
Simulation and measurement data also concluded that as conductivity of the bulk material increased, the plateau region tends towards higher frequencies. For very wet soils it was found that the impedance analyser was unable to determine a clear plateau region. Equipment which could measure at frequencies higher than 13 MHz is therefore suggested. Future work could also consider improving the electrical model, however, since the model is only used to provide estimated spectroscopic impedance this is deemed of less importance than other future work suggested.

Simulations also highlighted an issue derived from the parallel-plate test cell, which had a larger cross-sectional area than the electrode area, due to fear of jeopardising the insulating layer. This cause for concern was established as the insulating layer showed signs of brittleness when cut following the curing process, which could cause sections of the insulating layer to break away from the electrode surface, and eliminate the insulating properties. With improved cell design it is anticipated that the cell could be made to match that of the analytical solution, which would improve accuracy between simulation and test data.

References


Bungard, 2013. Laminat Lotstop Dry Film Solder Mask, Bungard Elektronik GmbH


University of Manchester 2013, Available at: http://www.eee.manchester.ac.uk/e-agri/ Last accessed 03 May 2013.


Walter 2007, Dynamics of seedling growth acclimation towards altered light conditions can be quantified via GROWSCREEN: a setup and procedure designed for rapid optical phenotyping of different plant species.


**Appendix 1: MATLAB script files used within analytical solution**

**A1.1: MATLAB code to calculate complex impedance based on multiple insulating layer parameters and bulk materials**

%-------------------------------------------------------------------
% % AUTHOR:         Paul Newill and Dr. Frank Podd
% % MODIFIED:       18th August 2013
% % DESCRIPTION:    Script to calculate the complex impedance for
% %                   the analytical solution of the insulated electrode
% %                   model based on multiple insulating layers and bulk
% % materials.
% %-------------------------------------------------------------------
%clear;                         % Clear all variables from workspace
Elec_Width = 30e-3;            % Electrode width (3cm)
Elec_Height = 30e-3;          % Electrode height (3cm)
Bulk_Thickness = 46e-3;       % Distance between electrodes (4.6cm)
Wall_Thickness = 75e-6;       % Wall insulating layer thickness. Default: 75E-6 (75um)
Wall_Thickness_scaled = 10e-3; % Scaled wall thickness. (10mm)
E0 = 8.85e-12;                % Relative Permittivity of free space
Er_W = 3.56;                  % Relative Permittivity of insulating solder mask layer. Default: 3.56
Er_B = 80;                    % Relative Permittivity of water. Default water: 80
Er_Bdry = 3.98;               % Relative permittivity of dry soil. Default: 3.98
Er_Bmoderate = 25;            % Relative permittivity of moderate soil. Default: 25
Er_Bsaturated = 30; % Relative permittivity of saturated soil. Default: 30

V = 1 + 0j; % Simulation voltage set to 1V to determine current flow

% Calculation of capacitance of various bulk materials
CW = ((Elec_Width*Elec_Height*E0*Er_W)/Wall_Thickness)/2;
CWscaled = ((Elec_Width*Elec_Height*E0*Er_W)/Wall_Thickness_scaled)/2;
CB = (Elec_Width*Elec_Height*E0*Er_B)/Bulk_Thickness;
CBdry = (Elec_Width*Elec_Height*E0*Er_Bdry)/Bulk_Thickness;
CBmoderate = (Elec_Width*Elec_Height*E0*Er_Bmoderate)/Bulk_Thickness;
CBsaturated = (Elec_Width*Elec_Height*E0*Er_Bsaturated)/Bulk_Thickness;

RW = 1.5e6; % Resistance of dielectric. Value taken from laminate datasheet = 1e12. Empirical value = 1.5e6
RBdistilled = 9.3e6; % Default 9.3e6 for distilled water (ref. Lenntech) or 239583 (measured)
RBtap = 5000; % Default 5000 for tap water (ref. Lenntech) or 3593 (measured)
RBsea = 10.2; % Default 10.2 for sea water (ref. Lenntech) or 140 (measured)
RBdry = 4.6e6; % Default value for dry soil
RBmoderate = 46e3; % Default value for moderately wet soil
RBsaturated = 2.3e3; % Default value for saturated soil

% Array of frequencies used for MATLAB, COMSOL, and impedance analyser
MATLAB_Freq = [1e0 2e0 3e0 4e0 5e0 6e0 7e0 8e0 9e0 1e1 2e1 3e1 4e1 5e1 6e1 7e1 8e1 9e1 1e2 2e2 3e2 4e2 5e2 6e2 7e2 8e2 9e2 1e3 2e3 3e3 4e3 5e3 6e3 7e3 8e3 9e3 1e4 2e4 3e4 4e4 5e4 6e4 7e4 8e4 9e4 1e5 2e5 3e5 4e5 5e5 6e5 7e5 8e5 9e5 1e6 2e6 3e6 4e6 5e6 6e6 7e6 8e6 9e6 1e7 2e7];
COMSOL_Freq = [1 2 3 4 5 6 7 8 9 10 20 30 40 50 60 70 80 90 100 200 300 400 500 600 700 800 900 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000 200000 300000 400000 500000 600000 700000 800000 900000 1000000 2000000 3000000 4000000 5000000 6000000 7000000 8000000 9000000 10000000 12000000 13000000];
RS_Freq = [10 20 30 40 50 60 70 80 90 100 200 300 400 500 600 700 800 900 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000 200000 300000 400000 500000 600000 700000 800000 900000 1000000 2000000 3000000 4000000 5000000 6000000 7000000 8000000 9000000 10000000 12000000 13000000];

% Array of measurement values acquired from impedance analyser
Meas_RealImped_TapWater = [1486085 1230992 1171684 1097179 1068233 997033 950347 886792 753174 657547 578703 514770 45487 32053 24273 19501 16244 13792 11989 6100 4823 4323 4081 3920 3826 3750 3664 3628 3453 3356 3284 3197 3118 3019 2922 2828 2726 1739 1078 677 463 326 236 176 134 103 80 63 50];

ZW = []; % Initialise arrays and variables
ZBdistilled = [];
ZBtap = [];
ZBmoderate = [];
ZBsaturated = [];
% Loop to create spectroscopic impedance
while (n<66)
    w=2*pi*MATLAB_Freq(n);
    XW = 1/(w*CW);
    XWscaled = 1/(w*CWscaled);
    XB = 1/(w*CB);
    XBdry = 1/(w*CBdry);
    XBmoderate = 1/(w*CBmoderate);
    XBsaturated = 1/(w*CBsaturated);

    XWall(n) = 1/(w*CW);
    XBulk(n) = 1/(w*CB);

    ZW(n) = ((RW*(XW)^2)/(RW^2+XW^2)) - j*(((RW^2*XW)/(RW^2+XW^2));
    ZBdistilled(n) = ((RBdistilled*(XB)^2)/(RBdistilled^2+XB^2)) - j*(((RBdistilled^2*XB)/(RBdistilled^2+XB^2));
    ZBtap(n) = ((RBtap*(XB)^2)/(RBtap^2+XB^2)) - j*(((RBtap^2*XB)/(RBtap^2+XB^2));
    ZBsea(n) = ((RBsea*(XB)^2)/(RBsea^2+XB^2)) - j*(((RBsea^2*XB)/(RBsea^2+XB^2));
    ZBdry(n) = ((RBdry*(XB)^2)/(RBdry^2+XB^2)) - j*(((RBdry^2*XB)/(RBdry^2+XB^2));
    ZBmoderate(n) = ((RBmoderate*(XB)^2)/(RBmoderate^2+XB^2)) - j*(((RBmoderate^2*XB)/(RBmoderate^2+XB^2));
    ZBsaturated(n) = ((RBsaturated*(XB)^2)/(RBsaturated^2+XB^2)) - j*(((RBsaturated^2*XB)/(RBsaturated^2+XB^2));

    ZTdistilled(n)= (((RW*(XW)^2)/(RW^2+XW^2)) + ((RBdistilled*(XB)^2)/(RBdistilled^2+XB^2)) - j*(((RW^2*XW)/(RW^2+XW^2)) + ((RBdistilled^2*XB)/(RBdistilled^2+XB^2));
    ZTtap(n)= (((RW*(XW)^2)/(RW^2+XW^2)) + ((RBtap*(XB)^2)/(RBtap^2+XB^2)) - j*(((RW^2*XW)/(RW^2+XW^2)) + ((RBtap^2*XB)/(RBtap^2+XB^2));
    ZTsea(n)= (((RW*(XW)^2)/(RW^2+XW^2)) + ((RBsea*(XB)^2)/(RBsea^2+XB^2)) - j*(((RW^2*XW)/(RW^2+XW^2)) + ((RBsea^2*XB)/(RBsea^2+XB^2));

    ZTseascaled(n)= (((RWscaled*(XWscaled)^2)/(RWscaled^2+XWscaled^2)) + ((RBsea*(XB)^2)/(RBsea^2+XB^2)) - j*(((RWscaled^2*XWscaled)/(RWscaled^2+XWscaled^2)) + ((RBsea^2*XB)/(RBsea^2+XB^2));

n=1;
\[ Z_{\text{dry}}(n) = ((R_W^*(X_W)^2)/(R_W^2+X_W^2)) + ((R_{\text{dry}}(X_{\text{dry}})^2)/(R_{\text{dry}}^2+X_{\text{dry}}^2)) - j* \left( ((R_W^2*X_W)/(R_W^2+X_W^2)) + ((R_{\text{dry}}^2*X_{\text{dry}})/(R_{\text{dry}}^2+X_{\text{dry}}^2)) \right) \]

\[ Z_{\text{moderate}}(n) = \left( (R_W^*(X_W)^2)/(R_W^2+X_W^2) \right) + ((R_{\text{moderate}}(X_{\text{moderate}})^2)/(R_{\text{moderate}}^2+X_{\text{moderate}}^2)) - j^* \left( ((R_W^2*X_W)/(R_W^2+X_W^2)) + ((R_{\text{moderate}}^2*X_{\text{moderate}})/(R_{\text{moderate}}^2+X_{\text{moderate}}^2)) \right) \]

\[ Z_{\text{saturated}}(n) = \left( (R_W^*(X_W)^2)/(R_W^2+X_W^2) \right) + ((R_{\text{saturated}}(X_{\text{saturated}})^2)/(R_{\text{saturated}}^2+X_{\text{saturated}}^2)) - j^* \left( ((R_W^2*X_W)/(R_W^2+X_W^2)) + ((R_{\text{saturated}}^2*X_{\text{saturated}})/(R_{\text{saturated}}^2+X_{\text{saturated}}^2)) \right) \]

\[ \theta(n) = \text{atan}((X_W/R_W) + ((X_W*R_W)/(X_B^2)) + (R_B/X_B)) \]

\[ IW(n) = V/ZW(n); \quad % \text{Complex current for dielectric coating} \]

\[ IB_{\text{tap}}(n) = V/ZB_{\text{tap}}(n); \quad % \text{Complex current for bulk material} \]

\[ IT_{\text{tap}}(n) = V/ZT_{\text{tap}}(n); \quad % \text{Complex current for complete analytical solution} \]

\[ n = n + 1; \]

\% Real, imaginary and absolute impedance for all bulk materials

\% Real_ZW=real(ZW); \quad % Absolute as MATLAB won't plot -ve for loglog

\% Imag_ZW=abs(imag(ZW));

\% Real_ZB_{\text{tap}}=real(ZB_{\text{tap}});

\% Imag_ZB_{\text{tap}}=abs(imag(ZB_{\text{tap}}));

\% Real_ZT_{\text{tap}}=real(ZT_{\text{tap}});

\% Imag_ZT_{\text{tap}}=abs(imag(ZT_{\text{tap}}));

\% Real_Z_{\text{distilled}}=real(Z_{\text{distilled}});

\% Imag_Z_{\text{distilled}}=abs(imag(Z_{\text{distilled}}));

\% Real_Z_{\text{sea}}=real(Z_{\text{sea}});

\% Imag_Z_{\text{sea}}=abs(imag(Z_{\text{sea}}));

\% Real_Z_{\text{seascaled}}=real(Z_{\text{seascaled}});

\% Imag_Z_{\text{seascaled}}=abs(imag(Z_{\text{seascaled}}));

\% Real_Z_{\text{dry}}=real(Z_{\text{dry}});

\% Imag_Z_{\text{dry}}=abs(imag(Z_{\text{dry}}));

\% Real_Z_{\text{moderate}}=real(Z_{\text{moderate}});

\% Imag_Z_{\text{moderate}}=abs(imag(Z_{\text{moderate}}));

\% Real_Z_{\text{saturated}}=real(Z_{\text{saturated}});
Imag_ZTsaturated=abs(imag(ZTsaturated));
Abs_ZTsaturated=abs(ZTsaturated);

Real_IW=real(IW);
Imag_IW=imag(IW);
Abs_IW=abs(IW);

Real_IBtap=real(IBtap);
Imag_IBtap=imag(IBtap);
Abs_IBtap=abs(IBtap);

Real_ITtap=real(ITtap);
Imag_ITtap=imag(ITtap);
Abs_ITtap=abs(ITtap);

% Code used to plot calculated impedance values. Insert parameter names as necessary
figure(1)
axes('FontSize',18);
hold on;
plot(MATLAB_Freq, Real_ZTdistilled, 'r-');
plot(MATLAB_Freq, Real_ZTtap, 'b-');
plot(MATLAB_Freq, Real_ZTsea, 'g--');
plot(MATLAB_Freq, Real_ZTdry, 'c-o');
plot(MATLAB_Freq, Real_ZTmoderate, 'm-^');
plot(MATLAB_Freq, Real_ZTsaturated, 'k-s');
legend('Distilled','Tap','Sea','Dry','Moderate','Saturated', 'FontSize',18)
xlabel('Frequency (Hz)', 'FontSize',18);
ylabel('Impedance (Ohms)', 'FontSize',18);
title('Simulated real impedance of the complex solution for the full analytical model. Varying bulk material.', 'FontSize',18)
set(h1, 'LineWidth',3);
set(h2, 'LineWidth',3);
set(h3, 'LineWidth',3);
set(h4, 'LineWidth',3);
set(h5, 'LineWidth',3);
set(h6, 'LineWidth',3);

figure(2)
hold on;
plot(COMSOL_Freq, COMSOL_RealImped_75um, 'b-');
plot(MATLAB_Freq, Real_ZTtap, 'r');
plot(MATLAB_Freq, Real_ZTsea, 'g-');
plot(MATLAB_Freq, Real_ZTdry, 'c-o');
plot(MATLAB_Freq, Real_ZTmoderate, 'm-^');
plot(MATLAB_Freq, Real_ZTsaturated, 'k-s');
legend('MATLAB','COMSOL', 'FontSize',18)
xlabel('Frequency (Hz)', 'FontSize',18);
ylabel('Impedance (Ohms)', 'FontSize',18);
title('Comparison of MATLAB and COMSOL simulated real impedance. Bulk material of saline solution.', 'FontSize',18)
set(h1, 'LineWidth',2);
set(h2, 'LineWidth',2);
set(h3, 'LineWidth',2);
set(h4, 'LineWidth',2);
A1.2: MATLAB script file used to create the SMP GUI
'gui_Callback', []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargin
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

% --- Executes just before v6 is made visible.
function v6_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% varargin   command line arguments to v6 (see VARARGIN)
% Choose default command line output for v6
handles.output = hObject;
handles.text1 = 70e-12;  % CW
handles.text2 = 1.1e6;   % RW
handles.text3 = 5e-12;   % CB
handles.text4 = 10000;   % RB
refresh(hObject, eventdata, handles);
% Update handles structure
guidata(hObject, handles);
% UIWAIT makes v6 wait for user response (see UIRESUME)
% uiwait(handles.figure1);

% --- Outputs from this function are returned to the command line.
function varargout = v6_OutputFcn(hObject, eventdata, handles)
% varargout    cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes on slider movement.
function slider1_Callback(hObject, eventdata, handles)
% hObject    handle to slider1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
% Hints: get(hObject,'Value') returns position of slider
%        get(hObject,'Min') and get(hObject,'Max') to determine
%        range of slider
handles.text1 = get(handles.slider1, 'value');
refresh(hObject, eventdata, handles);
guidata(hObject, handles);
% --- Executes during object creation, after setting all properties.
function slider1_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to slider1 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    empty - handles not created until after all CreateFcns called

    % Hint: slider controls usually have a light gray background.
    if isequal(get(hObject, 'BackgroundColor'),
                get(0, 'defaultUicontrolBackgroundColor'))
        set(hObject, 'BackgroundColor', [.9 .9 .9]);
    end

% --- Executes on slider movement.
function slider2_Callback(hObject, eventdata, handles)
    % hObject    handle to slider2 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)

    % Hints: get(hObject,'Value') returns position of slider
    %        get(hObject,'Min') and get(hObject,'Max') to determine
    %        range of slider
    handles.text2 = get(handles.slider2, 'value');
    refresh(hObject, eventdata, handles);
    guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function slider2_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to slider2 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    empty - handles not created until after all CreateFcns called

    % Hint: slider controls usually have a light gray background.
    if isequal(get(hObject, 'BackgroundColor'),
                get(0, 'defaultUicontrolBackgroundColor'))
        set(hObject, 'BackgroundColor', [.9 .9 .9]);
    end

% --- Executes on slider movement.
function slider3_Callback(hObject, eventdata, handles)
    % hObject    handle to slider3 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
    % handles    structure with handles and user data (see GUIDATA)

    % Hints: get(hObject,'Value') returns position of slider
    %        get(hObject,'Min') and get(hObject,'Max') to determine
    %        range of slider
    handles.text3 = get(handles.slider3, 'value');
    refresh(hObject, eventdata, handles);
    guidata(hObject, handles);

% --- Executes during object creation, after setting all properties.
function slider3_CreateFcn(hObject, eventdata, handles)
    % hObject    handle to slider3 (see GCBO)
    % eventdata  reserved - to be defined in a future version of MATLAB
Temperature_05  = evalin('base','Temperature_Empirical(:,8)');
Temperature_10  = evalin('base','Temperature_Empirical(:,7)');
Temperature_15  = evalin('base','Temperature_Empirical(:,6)');
Temperature_20  = evalin('base','Temperature_Empirical(:,5)');
Temperature_25  = evalin('base','Temperature_Empirical(:,4)');
Temperature_30  = evalin('base','Temperature_Empirical(:,3)');
Temperature_35  = evalin('base','Temperature_Empirical(:,2)');
Temperature_40  = evalin('base','Temperature_Empirical(:,1)');

Pi = 3.14159265359;
F = [10,20,30,40,50,60,70,80,90,100,200,300,400,500,600,700,800,900,1000]
<table>
<thead>
<tr>
<th>FreqRedScreen</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 20 30 40 50 60 70 80 90 100 200 300 400 500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RealImpDeionisedWater01</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 2.7E+06 1.2E+06 6.9E+05 1.5E+06 9.0E+05 6.7E+05 7.3E+05 7.1E+05 7.3E+05 6.8E+05 5.8E+05 4.8E+05 4.5E+05 4.2E+05 3.9E+05 2.8E+05 2.5E+05 2.4E+05 6.4E+01 3.1E+01 1.8E+01 1.0E+01 5.6E+00 8.0E+00 7.2E+00 6.1E+00 6.2E+00 6.5E+00 6.1E+00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RealImpDeionisedWater02</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0 0.0 1219512.2 2162162.2 873362.4 900900.9 875273.5 764331.2 421300.1 275713.4 173395.9 115198.4 78923.5 56163.5 41740.3 31964.7 25224.1 20397.9 16794.9 4487.1 2028.8 1156.0 743.4 523.6 389.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RealImpTapWater</th>
</tr>
</thead>
<tbody>
<tr>
<td>1486085 1230992 1176924 753174 657547 578703 514770 459075 413005 369680 332115 301317 254555 223401 192337 163585 137921 11989 6100 41349 3447 300 176</td>
</tr>
</tbody>
</table>
2779.090231 2600.426907 2459.365085 2339.879691 1732.488089
1476.084618 1328.209254 1
229.425337 1158.641146 1104.887406
1062.367975 1027.889408 999.187563 850.473986 678.484601
598.837755 549.499534 525.276866 502.175875]

fontsize = 18;
handles.axes1 = loglog (FreqRedScreen, Temperature_05,'b-o');
set(handles.axes1, 'LineWidth',3);

for x=1:58
   Freq = F(x);
   W = (2*Pi*Freq);
   Xs = (1/(2*Pi*Freq*handles.text3));
   Xw = (1/(2*Pi*Freq*handles.text1));

   z(x)=(((handles.text2*(Xw)^2)/(handles.text2^2+Xw^2))+((handles.text4*(Xs)^2)/(handles.text4^2+Xs^2)))+j*(((handles.text2^2*Xw)/(handles.text2^2+Xw^2))+((handles.text4^2*Xs)/(handles.text4^2+Xs^2)));
   a(x)=real(z(x));
   b(x)=imag(z(x));
   c(x)=abs(z(x));
end
hold on;
handles.axes1 = loglog (F, a,'r');
hold off;
xlim([10 10e7]); % Limit x-axis to 1 - 10 MHz
ylim([1e1 10e8]); % Limit y-axis to 1000 Ohm - 1000 MOhm
title('Fitting Measurement Data to Determine Parameter Values for Soil Temperature. 15% Moisture Content.', 'Fontsize',18)
xlabel('Frequency (Hz)','Fontsize',18);
ylabel('Impedance (Ohms)','Fontsize',18);
legend('Measured','Simulated');
set(handles.axes1, 'LineWidth',3);
guidata(hObject, handles);

function edit1_Callback(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit1 as text
%       str2double(get(hObject,'String')) returns contents of edit1 as a double
handles.text1 = str2double(get(handles.edit1, 'String'));
refresh(hObject, eventdata, handles);

% --- Executes during object creation, after setting all properties.
function edit1_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% ---------------------------------------------------------------------
function File_Callback(hObject, eventdata, handles)
% hObject    handle to File (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% ---------------------------------------------------------------------
function exit_menu_Callback(hObject, eventdata, handles)
% hObject    handle to exit_menu (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
close

function edit2_Callback(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit2 as text
%        str2double(get(hObject,'String')) returns contents of edit2 as a double
handles.text2 = str2double(get(handles.edit2, 'String'));
refresh(hObject, eventdata, handles);

% --- Executes during object creation, after setting all properties.
function edit2_CreateFcn(hObject, eventdata, handles)
% hObject    handle to edit2 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns
called

% Hint: edit controls usually have a white background on Windows.
% See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'),
get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit3_Callback(hObject, eventdata, handles)
% hObject    handle to edit3 (see GCBO)
functions (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit3 as text
% str2double(get(hObject,'String')) returns contents of edit3
% handles.text3 = str2double(get(handles.edit3, 'String'));
refresh(hObject, eventdata, handles);

% --- Executes during object creation, after setting all properties.
function edit3_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit3 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function edit4_Callback(hObject, eventdata, handles)
% hObject handle to edit4 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit4 as text
% str2double(get(hObject,'String')) returns contents of edit4
% as a double
handles.text4 = str2double(get(handles.edit4, 'String'));
refresh(hObject, eventdata, handles);

% --- Executes during object creation, after setting all properties.
function edit4_CreateFcn(hObject, eventdata, handles)
% hObject handle to edit4 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% ---------------------------------------------------
function Untitled_1_Callback(hObject, eventdata, handles)
% hObject handle to Untitled_1 (see GCBO)
% eventdata reserved - to be defined in a future version of MATLAB
% handles structure with handles and user data (see GUIDATA)
function file_exit_Callback(hObject, eventdata, handles)
    close
end

function radiobutton1_Callback(hObject, eventdata, handles)
end

function text4_CreateFcn(hObject, eventdata, handles)
end

function Untitled_2_Callback(hObject, eventdata, handles)
end
Appendix B: Rhizotron System Documents and MATLAB Scripts

B1.1: Rhizotron Switching Electronics Schematics
B1.1.1: Switch PCB Schematic

Dr. Frank Podd

Table:

<table>
<thead>
<tr>
<th>Document Numbers</th>
<th>SEL+</th>
</tr>
</thead>
<tbody>
<tr>
<td>354</td>
<td>SEL+</td>
</tr>
</tbody>
</table>

Legend grid: 1mm/L=10mm

Notes:

- T00A: Disable switch on (on 1.0) Pass #8 through MM0 gate to switch enable
- T002: Have option to be always enabled so can use the full 36 channels

Parts:
- S200-200-20-515-30: 06
- Samec cable FFS0-200-00-01: 01-N 5-1

Tomography
B1.1.2: Power/ Demux PCB Schematic
B1.1.3: GPIO PCB Schematic

TODD: Add bottom connector for pass through for Cap board and RF cons board
TODD: Now has a LCD_NCS line - change in firmware

Used:
- UP_SOC
- LCD_NCS, UP_FLASH_NCS
- DB-3
- LCD_RESET
- SDO1, SDO2, SG2 (GND)
- U23 RX, TX, CTS, RTS

Future's some NFT devices have ADCs - use these to measure pressure (could we also measure gamma rays?)
TODD: Add switch to change from being a USB-com device to a usb-storage device

Modifications to Pic32 board: remove G4 (LED), add C15, 16 (12pF), V3 (33KOhm).

Dr. Frank Podd
Title: gpaw6
Document Numbers: S74
Date not saved: Sheets 3/3
B1.2: Rhizotron Switching Electronics Photographs

B1.2.1: Switch PCB

B1.2.2: Power/Demux PCB
B1.2.3: GPIO PCB
B1.3: Rhizotron Data Manipulation Scripts

B1.3.1: MATLAB script to read raw rhizotron data

```matlab
%------------------------------------------
%  AUTHOR:         Frank Podd
%  AMMENDMENTS:    Paul Newill
%  MODIFIED:       18th August 2013
%  DESCRIPTION:    Script to read in all rhizotron data and
%                  separate into
%                  three arrays. Data is then converted from
%                  conductance
%                  and susceptance to complex impedance.
%------------------------------------------

%Clear the screen, all previous variables and read in the file.
clear all
filename = 'Growth Test 2_1MHz_interpollated.csv'; % Read in .csv file

% Set variables
NumSwitchPatternsPerFreq = 1; % Set to 1 as we only use one
frequency per test.
NumSwitchCols = 2; % No. of columns per switch pattern, e.g. Elec 1-2
GreenScreen = 1; % Set to 1 to include the status
column, which the green screen adds automatically.
NumOfMeasEach = 95; % Number of measurements per
rhizotron for a full set (WAS 104)
NumMeasPerSwitch = 2; % In-phase and quadrature (Cond and
Susc)
NumDescCols = 4; % Row Index, Description, Start and
Stop time. (This may need changing when multiple rhizotrons are
connected in parallel.)
FreqKHz = 1e6; % Set the Frequency used (in kHz).

[fid message] = fopen(filename);
if fid < 0, error('MATLAB:dlmread:FileNotOpened', 'The file ''%s''
could not be opened because: %s',filename,message); end

% Find out how many columns (commas) in header and data
LoopHeader = fgets(fid);
NumColsInHeader = sum(LoopHeader==',')+1;
LoopData = fgets(fid);
NumColsInData = sum(LoopData==',')+1;

% Reset the position indicator.
rewind(fid); % Sets the file position indicator to the beginning
of the file.
```
LoopHeader = fgets(fid); % read line from file, keeping the newline character

% Assuming Set Freq, change all switches and measure each, then next freq
if ( NumSwitchPatternsPerFreq > 0), NumColsPerFreq = (NumMeasPerSwitch+NumSwitchCols) * NumSwitchPatternsPerFreq; else NumColsPerFreq = NumMeasPerSwitch; end
if ( GreenScreen ) NumColsPerFreq = NumColsPerFreq+1; end % Requires the +1 for the 'status' column.

%Calculate total No. of measurements from total columns.
NumTotalMeas = (NumColsInData-NumDescCols)/NumColsPerFreq;

% How many rows of data?
LoopData = fgets(fid);
NumDataRows = 0;
while ( LoopData ~= -1 )
    NumDataRows = NumDataRows+1;
    LoopData = fgets(fid);
end

%Need to seperate data for rhizotrons 1/2/3.
NumOfRhiz=NumTotalMeas/NumOfMeasEach; % Set as 104, as this is a full frame of measurements for 60 electrodes

% Go back to the start of the data
frewind(fid);
LoopHeader = fgets(fid);

% Sets the array variables, determined by previous code.
Row(NumDataRows)=0; % Total measurement iterations
StartTime(NumDataRows)=0; % Test start time
StopTime(NumDataRows)=0; % Test end time
NSPpF = NumSwitchPatternsPerFreq;
if ( NSPpF == 0 ) NSPpF = 1; end;
Desc(NumDataRows,NumTotalMeas,NSPpF)='-';
AllAbsImpedOhm(NumDataRows,NumTotalMeas,NSPpF)=0;
AllResistOhm(NumDataRows,NumTotalMeas,NSPpF)=0;
AllReactanceOhm(NumDataRows,NumTotalMeas,NSPpF)=0;
FreqKHz(NumDataRows,NumTotalMeas)=0;
Sw(NumSwitchCols,NumDataRows,NumTotalMeas,NSPpF)=0;
AllCap_pF(NumDataRows,NumTotalMeas,NSPpF)=0;
AllCond(NumDataRows,NumTotalMeas)=0; % An array to store all values of conductance
AllSusc(NumDataRows,NumTotalMeas)=0; % An array to store all values of susceptance
CommentCell = cell(NumDataRows, 1);

% Calculates the impedance for each loop value.
for C=1:NumDataRows
    Row(C) = fscanf2( fid, '%d', [1,1] );
    StartTime(C) = fscanf2( fid, '%f', [1,1] );
    n=1;
clear A;
    A(n)=fread(fid,1); % Read first comma ','
    A(n)='

360
while (A(n) ~= ','), % Read up to and including the comma after the description
  n = n+1;
  A(n) = fread( fid, 1 );
end

CommentCell{C} = char(A(2:end-1)); % Copy the description but lose the commas.
  fseek( fid, -1, 0 ); % Put the comma back

for F=1:NumTotalMeas % Stores ALL test data in two arrays; AllCond and AllSusc
  for S=1:NumSwitchPatternsPerFreq
    for i=1:NumSwitchCols
      Sw(i,C,F,S) = fscanf( fid, ',%i', [1,1] );
      % records electrode switching pattern eg elec 1-2,3-4 etc
    end
    cond = fscanf( fid, ',%f', [1,1] ); if isempty(cond), cond=0; end % conductance
    susc = fscanf( fid, ',%f', [1,1] ); if isempty(susc), susc=0; end % susceptance
  end
  FreqKHHz(C,F) = 1e3;
  AllCond(C,F) = cond;
  AllSusc(C,F) = susc;

  AllAdmittS(C,F) = complex(cond, susc);
  AllAbsAdmittS(C,F,S) = abs(AllAdmittS(C,F,S));

  AllCap_pF(C,F,S) = 1e12 .* susc ./ (2.*pi.*FreqKHHz(C,F)*1000);

  AllImped(C,F,S) = 1./AllAdmittS(C,F,S);
  AllAbsImpedOhm(C,F,S) = abs(AllImped(C,F,S));
  AllResistOhm(C,F,S) = real(AllImped(C,F,S));
  AllReactanceOhm(C,F,S) = imag(AllImped(C,F,S));
end
  if ( GreenScreen ) status = fscanf( fid, ',%i', [1,1] ); end
end
  StopTime(C) = fscanf( fid, ',%f', [1,1] );
end

AllCond = AllCond'; % Transpose the data to a column for each test, rather than by row.
AllSusc = AllSusc';
AllAdmittS = AllAdmittS';
AllAbsAdmittS = AllAbsAdmittS';
AllCap_pF = AllCap_pF';
AllImped = AllImped';
AllAbsImpedOhm = AllAbsImpedOhm';
AllResistOhm = AllResistOhm';
AllReactanceOhm = AllReactanceOhm';
% Split the total data for each rhizotron.
for P=1:NumOfMeasEach
    for X=1:NumDataRows
        CondRhiz1(P,X) = AllCond (P,X);
        CondRhiz2(P,X) = AllCond ((P+95),X);
        CondRhiz3(P,X) = AllCond ((P+190),X);
        SuscRhiz1(P,X) = AllSusc (P,X);
        SuscRhiz2(P,X) = AllSusc ((P+95),X);
        SuscRhiz3(P,X) = AllSusc ((P+190),X);
        AdmittSRhiz1(P,X) = AllAdmittS (P,X);
        AdmittSRhiz2(P,X) = AllAdmittS ((P+95),X);
        AdmittSRhiz3(P,X) = AllAdmittS ((P+190),X);
        Cap_pFRhiz1(P,X) = AllCap_pF (P,X);
        Cap_pFRhiz2(P,X) = AllCap_pF ((P+95),X);
        Cap_pFRhiz3(P,X) = AllCap_pF ((P+190),X);
        ImpedRhiz1(P,X) = AllImped (P,X);
        ImpedRhiz2(P,X) = AllImped ((P+95),X);
        ImpedRhiz3(P,X) = AllImped ((P+190),X);
        ResistOhmRhiz1(P,X) = AllResistOhm (P,X);
        ResistOhmRhiz2(P,X) = AllResistOhm ((P+95),X);
        ResistOhmRhiz3(P,X) = AllResistOhm ((P+190),X);
    end
end

durationsS = StopTime - StartTime;
TimeS = StartTime - StartTime(1);
TimeMins = (TimeS/60);
TimeHrs = (TimeS/3600);

% Return information relative to computation time and allow saving of data
disp( ['Total number of Rhizotrons: ' num2str(NumOfRhiz)] );
disp( ['Number of test iterations: ' num2str(NumDataRows)] );
disp( ['Mean duration (secs): ' num2str(mean(durationsS))] );
disp( ['Finished reading: ' filename] );
savename=upper(input( 'Enter the save filename (Note: Will save all workspace variables as a *.mat file for future reference in the working directory): ', 's'));
save(savename);
B1.3.2: MATLAB script to create movie files

```matlab
%-------------------------------------------------------------------
% AUTHOR: Frank Podd
% AMMENDMENTS: Paul Newill
% MODIFIED: 18th August 2013
% DESCRIPTION: This script is used to create a movie based on
% measurement data from the rhizotron measurement
% system.
% The user can choose the parameter to create into
% a
% movie, based on those created within the
% ReadUMCData_FreqsSwitches script, by adjusting
% the
% parameter saved to the variable; MeasData.
% Depending on the test duration, the user may
% also wish
% to adjust the number of frames per second to
% speed up,
% or decrease the rate at which the files are
displayed.

aviFileName = 'Growth Test 2_1MHz_FNS5.avi'    % Specified filename
to save movie to.
MeasData = FNS5_Filtered_1MHz;       % Variable taken from the MATLAB
workspace
NumMeasRows = 19;    % Number of measurement rows. 10 horizontal + 9
vertical
NumMeasCols = 5;    % Number of measurement columns
interpSize = 30;    % Interpolation factor. Therefore produces a
570x150 array
imBig = zeros(size(MeasData,1), NumMeasRows*interpSize,
NumMeasCols*interpSize);   % Creating an array of 570x150 for each
measurement frame.
StartFrame = 1;     % Which iteration is the first frame? Can be used
to discard first frames if required

for iT=StartFrame:size(MeasData,1)    % Loop to create
    C = squeeze(MeasData(iT,:,:));    % Squeeze
function used to extract data for each frame, each loop iteration.
    im = reshape(C,NumMeasCols,NumMeasRows)';    % Data is in a
one dimensional array, and is reshaped to represent rhizotron.
    im = imrotate(im,180);    % Data is
rotated to be displayed in the correct formation.
    imBig(iT, :, :) = imresize( im, interpSize );    % Create imBig
based on interpolation factor and image frame.
end
```
% maxBig = max(max(max(imBig))); % Finding the largest value in order to determine the range of values
% minBig = min(min(min(imBig))); % Finding the smallest value
% Range = (maxBig - minBig); % Range is the difference between largest and smallest
maxBig=4000; % Test 1: FNS3 25938, FNS4 4487, FNS5 58772
minBig=1000; % Test 1: FNS3 1013, FNS4 1053, FNS5 1533
Range = maxBig-minBig; % Difference between minBIG and maxBIG

figure;
colormap(jet);
colormap(flipud(colormap))
for iT=StartFrame :size(imBig,1) % Loop creates an image based on no interpolation, for reference.
    C = squeeze(MeasData(iT,:,:))';
    im = reshape(C,NumMeasCols,NumMeasRows)';
    im = imrotate(im,180);
    image( 1 + ((im - minBig)*(length(colormap())-1) ./ Range) ) % Image is based on calculated range.
    pause(0.01) % Small delay to slow down loop for visual reference of image.
end

%% Scale the image to the colourmap
fig=figure;
axis off
disp('Adjust the figure size then press a key') % User currently determines the video aspect ratio by selecting window size.
pause
aviobj = avifile( aviFileName ) % defining filename, as selected at start of script.
aviobj.Quality = 100;
aviobj.fps = 2; % was 4
aviobj.compression = 'None';
colormap(jet) % Declare colour scheme
colormap(flipud(colormap)) % Invert colormap

% Loop to scale each value within the interpolated image
for iT=StartFrame :size(imBig,1)
    imTempZeroOffset = squeeze(imBig(iT, :, :)) - minBig;
    imTempZeroOffsetNeg = maxBig - imTempZeroOffset;
    imScaled = (2 + ((imTempZeroOffsetNeg*(length(colormap())-1) ./ Range)))+10; % This may need to be manually adjusted to suit each measurement.
    image( imScaled ); axis off
    F = getframe(fig);
    aviobj = addframe(aviobj,F);
    pause(0.01) % Can implement a small delay to slow down movie print('-f2', '-dpng', celldata{iT}) % Saves figure2 to .png filename.
%processing
end
close(fig)
aviobj = close(aviobj);
Appendix C: Miscellaneous Documents

C1.1: Soil PSD Report

AGVISE Soil Characterization Report

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submitting firm</td>
<td>PTRL WEST/SYNGENTA</td>
</tr>
<tr>
<td>Protocol or Study No</td>
<td>2287W</td>
</tr>
<tr>
<td>Sample ID.</td>
<td>2287W-023</td>
</tr>
<tr>
<td>Trial ID.</td>
<td>TX0002309</td>
</tr>
<tr>
<td>Date Received</td>
<td>10-4-12</td>
</tr>
<tr>
<td>Date Reported</td>
<td>10-17-2012</td>
</tr>
<tr>
<td>AGVISE Lab No</td>
<td>12-1188</td>
</tr>
<tr>
<td>Percent Sand</td>
<td>61</td>
</tr>
<tr>
<td>Percent Silt</td>
<td>20</td>
</tr>
<tr>
<td>Percent Clay</td>
<td>19</td>
</tr>
<tr>
<td>USDA Textural Class (hydrometer method)</td>
<td>Sandy Loam</td>
</tr>
<tr>
<td>Bulk Density (disturbed) gm/cc</td>
<td>1.03</td>
</tr>
<tr>
<td>Cation Exchange Capacity (meq/100 g)</td>
<td>17.0</td>
</tr>
<tr>
<td>% Moisture at 1/10 Bar</td>
<td>23.5</td>
</tr>
<tr>
<td>% Moisture at 2.0 pF Units</td>
<td>23.5</td>
</tr>
<tr>
<td>% Moisture at 1/3 Bar</td>
<td>18.7</td>
</tr>
<tr>
<td>% Moisture at 2.5 pF Units</td>
<td>18.7</td>
</tr>
<tr>
<td>% Organic Matter---Walkley Black</td>
<td>5.4</td>
</tr>
<tr>
<td>pH in 1:1 soil:water ratio</td>
<td>5.6</td>
</tr>
<tr>
<td>pH in 0.01 M CaCl2 (1:1)</td>
<td>5.3</td>
</tr>
<tr>
<td>Olsen Phosphorus (ppm)</td>
<td>30</td>
</tr>
<tr>
<td>Total Nitrogen (Analyzer) (%)</td>
<td>0.29</td>
</tr>
<tr>
<td>Soluble Salts (meq/cm)</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Base Saturation Data

<table>
<thead>
<tr>
<th>Cation</th>
<th>Percent</th>
<th>ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium</td>
<td>66.6</td>
<td>2260</td>
</tr>
<tr>
<td>Magnesium</td>
<td>6.0</td>
<td>123</td>
</tr>
<tr>
<td>Sodium</td>
<td>0.6</td>
<td>24</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.3</td>
<td>151</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>24.5</td>
<td>42</td>
</tr>
</tbody>
</table>

These tests were completed in compliance of 40 CFR Part 160.

Larry Wilkoff
Analytical Investigator

Date: 8/7/11

Agricultural Testing
C1.2: Temperature Testing Protocol

The temperature program was set to ramp the temperature in 5°C steps as quickly as the environmental chamber would allow, and then hold that temperature for 2 hours. The chamber was found to be capable of ramping in 5°C steps in approximately 7-8 minutes for both heating and cooling.

Within 2 hours, the soil would have time to reach the set point temperature. The soil was slower to reach temperature due to its high thermal mass. Pre-tests showed that on average the soil took approximately 30 minutes to both increase and decrease by approximately 5°C.

The test started at 25°C to reduce soil temperature change at the start, as the soil was prepared in the laboratory, with an ambient temperature of approximately 25°C also.

The duration of the test was set to 24 hours, to maximise the number of temperatures possible. Since the cycle also ended at 25°C, the following test could begin as soon as the previous one had ended.

Start temperature: 25°C, End temperature: 25°C

<table>
<thead>
<tr>
<th>Chamber Set Point Temperature (°C)</th>
<th>Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>35</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>6</td>
</tr>
<tr>
<td>35</td>
<td>8</td>
</tr>
<tr>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>20</td>
<td>14</td>
</tr>
</tbody>
</table>