AES/GE/09-21  Hybrid Rowe cell for measurement of complex conductivity

August 2009  Suguru Shirasagi
Title : Hybrid Rowe cell for measurement of complex conductivity

Author(s) : Suguru Shirasagi

Date : August 2009
Professor(s) : Prof. dr. J. Bruining (TU Delft)
Supervisor(s) : Dr. ir. T. J. Heimovaara (TU Delft)
               Dr. ir. D. J. M. Ngan-Tillard (TU Delft)
               Ir. M. Ponziani (TU Delft)
               Dr. ir. J. van Deen (Deltares)

TA Report number : AES/GE/09-21

Postal Address : Section for Geo-Engineering
                Department of Applied Earth Sciences
                Delft University of Technology
                P.O. Box 5028
                The Netherlands

Telephone : (31) 15 2781328 (secretary)
Telefax : (31) 15 2781189

Copyright ©2009    Section for Geo-Engineering

All rights reserved.
No parts of this publication may be reproduced,
Stored in a retrieval system, or transmitted,
In any form or by any means, electronic,
Mechanical, photocopying, recording, or otherwise,
Without the prior written permission of the
Section for Geo-Engineering
ABSTRACT

Peat is sediment consisting of incompletely decomposed organic matter deposited in swamp and marsh. It has served for a long time as benefits for human beings. Meanwhile, it has posed huge challenges to geotechnical engineers because of its unique characteristics such as anisotropy, low stiffness, high compressibility and strong creep susceptibility. In an attempt to realise more economical, effective and efficient site investigations, it is highly expected to apply geophysical techniques as well as core-boring, CPTs, sampling and laboratory tests because the techniques promise to be great contributions not only for two- or three-dimensional mapping but also for accurate interpretation of its physical, chemical and engineering properties in non-destructive way.

Then, a new apparatus has been developed, called hybrid Rowe cell. It combines the functions of a traditional hydraulic cell and an electrical capacitor. This can simultaneously measure electrical properties and physical, mechanical and hydrological properties of soil samples, allowing to investigate their correlation accurately.

This work focuses on the study of the applicability and calibration of the new hybrid cell, and the relationship between electrical conductivities of bulk peat and pore water which saturates the sample. The applicability of the hybrid cell was examined by using water as calibration. The results were then compared with values reported earlier and the experimental set-up was also compared with similar one found in literature. As a result, it was proven that the new cell successfully prevented electrode polarization and was applicable for this type of measurements. The electrical measurements on peat showed a relationship between the electrical conductivities of bulk peat and pore water which could be well predicted by a model previously developed for peat as well as the modified Archie’s law. In addition, the modified Archie’s law could be considered to be a persuasive model for the electrical behaviours observed in this study.

This is a first step towards better understanding of the relationship between the electrical and the geo-engineering properties of peat. For the future research, it is highly expected that the frequency of input currents is extended to lower range (< 20 Hz), input electric currents are properly controlled to avoid non-linear effects, and also hydraulic consolidation tests are performed in parallel with electrical measurements.

Keywords: Rowe cell, electrical conductivity, electrical double layer, induced polarisation, Archie’s law, peat, hydraulic conductivity
# TABLE OF CONTENTS

ABSTRACT ...................................................................................................................... i  
TABLE OF CONTENTS................................................................................................. iii  
LIST OF FIGURES ........................................................................................................ v  
LIST OF TABLES .......................................................................................................... vii  

1  INTRODUCTION ................................................................................................. 1  
1.1 Problem definition .............................................................................................. 1  
1.2 Goals and objectives ......................................................................................... 2  
1.3 Contents of the thesis ....................................................................................... 3  

2  LITERATURE REVIEW ON ELECTRICAL MODELS OF SOIL ........... 5  
2.1 Introduction........................................................................................................ 5  
2.2 Conductivity, complex conductivity and other terminology ......................... 5  
2.3 Electrical double layer (EDL) .......................................................................... 7  
2.4 Electrokinetic phenomena ................................................................................ 8  
2.5 Induced polarisation (IP) effect ......................................................................... 11  
2.6 Non-organic material ....................................................................................... 14  
2.6.1 Archie’s law ................................................................................................. 14  
2.6.2 Cole-Cole model ......................................................................................... 15  
2.6.3 Constant phase model ................................................................................ 16  
2.6.4 Generalised Cole-Davidson model ............................................................ 18  
2.6.5 Madden-Marshall model ............................................................................ 19  
2.6.6 Bruggeman-Hanai-Sen model ................................................................. 20  
2.6.7 EDL-based S-model and D-model ........................................................ 21  
2.6.8 Short narrow pore model .......................................................................... 22  
2.6.9 Vinegar-Waxman model ........................................................................... 23  
2.7 Organic material ............................................................................................. 25  
2.8 Summary .......................................................................................................... 29  

3  METHODOLOGY OF MEASUREMENT ..................................................31  
3.1 Description of new cell .................................................................................... 31  
3.2 Experimental set-up and electrical model ..................................................... 33  
3.3 Data analysis method ....................................................................................... 35  
3.4 Sample description and preparation ............................................................. 37  
3.5 Experimental procedure .................................................................................. 37  
3.5.1 Calibration with water ............................................................................... 37  
3.5.2 Tests on peat ............................................................................................... 38  

4  RESULTS AND DATA ANALYSIS ......................................................... 41
4.1 Calibration with water ................................................................. 41
4.1.1 Distance-control test ................................................................. 41
4.1.2 Conductivity-control test .......................................................... 44
4.1.3 Summary..................................................................................... 47
4.2 Tests on peat.................................................................................. 48
4.2.1 Properties of the samples .......................................................... 48
4.2.2 Measurement steps and its conductivities................................. 48
4.2.3 Duration of sample saturation.................................................. 49
4.2.4 Analysis of parameters as a function of frequency ..................... 52
  4.2.4.1 Different behaviour of resistance.......................................... 52
  4.2.4.2 Relationship between calculated and measured conductivity... 52
  4.2.4.3 Reliable $\sigma_w$ range and frequency for conductivity measurement ...... 53
4.2.5 Analysis of real and imaginary part of conductivity as a function of conductivity of water ................................................................. 54
5 DISCUSSION ....................................................................................... 59
5.1 Introduction................................................................................... 59
5.2 Comparison between new cell and other apparatus....................... 59
5.3 Negative capacitance .................................................................... 62
5.4 Data correction using data of water .............................................. 63
5.5 Discontinuous $\sigma'$ of Peat 1 ......................................................... 64
5.6 Curve fitting with modified Archie’s law ....................................... 65
5.7 Difference between $\sigma_w$ and $\sigma'$ ............................................. 69
6 CONCLUSIONS AND RECOMMENDATIONS .................................... 71
6.1 Conclusions.................................................................................. 71
6.2 Recommendations for future work .............................................. 72
REFERENCES ......................................................................................... 73
APPENDIX 1: PHOTOGRAPHS OF PARTS OF NEW CELL ....................... 77
APPENDIX 2: PRECISION COMPONENT ANALYSER 6440a .................... 79
APPENDIX 3: VON POST CLASSIFICATION ........................................... 81
APPENDIX 4: SUMMARY OF TEST RESULT ON WATER 1 .................... 83
APPENDIX 5: SUMMARY OF TEST RESULT ON WATER 2 .................... 84
APPENDIX 6: SUMMARY OF TEST RESULT ON PEAT 1 ....................... 85
APPENDIX 7: SUMMARY OF TEST RESULT ON PEAT 2 ....................... 88
APPENDIX 8: SUMMARY OF TEST RESULT ON PEAT 3 ....................... 90
LIST OF FIGURES

Figure 1.1  Distribution of Holocene deposit in the Netherlands and locations of referenced sites (A = Amsterdam, R = Rotterdam, H = Hague, M = Marken, OVP = Oostvaardersplassen, RW = Rijpwetering, W = Wilnis, Z = Polder Zegveld and S=Sliedrecht) [den Haan and Kruse, 2007]....................................................................... 1

Figure 2.1  Electrical double layer surrounding clay particle [after Brandes 2005]. ................ 8
Figure 2.2  Electro-osmosis (left) and electrophoresis (right)................................................. 10
Figure 2.3  Example of measured voltage decay by time-domain method. ......................... 11
Figure 2.4  Phase shift between applied current and measured voltage.............................. 12
Figure 2.5  Electrode polarisation......................................................................................... 13
Figure 2.6  Membrane polarisation..................................................................................... 13
Figure 2.7  (a) Small section of a mineralized rock which has both blocked and unblocked pore passages, (b) equivalent circuit for the mineralized rock, (c) Typical frequency domain response for the equivalent circuit [after Pelton et al. 1978]............................. 16
Figure 2.8  SIP responses of silty sand measured at laboratory and field in the frequency range from 0.01 to 100 Hz, showing frequency-independence [Börner et al. 1996]. .... 18
Figure 2.9  Ion motion and concentration changes by current flow through a membrane system [Marshall and Madden, 1959]. ......................................................................................... 20
Figure 2.10  Comparison of numerical conductivity dispersion with experimental data on dilute suspension of kaolinite [Lima and Sharma, 1992]................................. 21
Figure 2.11  Schematic geometry of pure water-saturated sand (left), and system concept and ion concentration distribution (right) [Titov et al. 2002]............................ 23
Figure 2.12  Comparison between the C-C and SNP models in frequency domain [Titov et al. 2002]......................................................................................................................... 23
Figure 2.13  Complex conductivity model in equivalent circuit (left) and in vectorial relation (right) [after Vinegar and Waxman, 1984]. ................................................................. 25
Figure 2.14  Equivalent circuit for general model [Lesmes and Frye, 2001]......................... 26
Figure 2.15  (a) Real ($\sigma'$, primary axis) and imaginary ($\sigma''$, secondary axis) conductivity as a function of $\sigma_w$ for peat samples saturated with different NaCl concentrations (1 Hz measurement frequency). (b) Real ($\sigma'$) and imaginary ($\sigma''$) conductivity as a function of NaCl $\sigma_w$ for sand samples [from Slater and Glaser, 2003] at 1 Hz [Comas and Slater, 2004]. ......................................................................................................................... 27
Figure 2.16  Dependence of imaginary conductivity $\sigma''$ on fluid conductivity $\sigma_w$ [Comas and Slater, 2004]. ......................................................................................................................... 28
Figure 3.1  Schematic diagram (upper) and photo (lower) of hybrid Rowe cell..................... 32
Figure 3.2  Current and voltage electrodes on plate.............................................................. 33
Figure 3.3  Experimental set-up .................................................................................................. 34
Figure 3.4  Schematic model (left) and equivalent circuit (right). ............................................ 35
Figure 3.5  Parallel circuit with resistor and capacitor. ........................................................... 36
Figure 4.1  Plots of measured capacitance (left) and resistance (right)................................... 41
Figure 4.2  Proportionality between $C_{mea}$ (upper)/$R_{mea}$ (bottom) and distance ............... 42
Figure 4.3  Measured and residual capacitance (left) and relative error of capacitance (right) as a function of frequency. ............................................................................. 43
Figure 4.4  Real part of conductivity compared to measured one (1.0 mS/m) in semi-log (left) and double log (right) scale .................................................................................. 43
Figure 4.5  Phase angle (upper left), its close-up in phase angle (upper right) and imaginary part of conductivity (lower left) as a function of frequency, and complex impedance plane (upper right). ............................................................... 44
Figure 4.6  Measured capacitance (left) and resistance (right), Arrows show the point at which the resistance starts deflecting from its constant value........................................ 45
Figure 4.7  Real part of conductivity compared to measured one in semi-log (left) and double log (right) scale. Arrows show the point at which the resistance starts deflecting from its constant value. ........................................................................ 46
Figure 4.8  Phase angle (upper left), its close-up in phase angle (upper right) and imaginary part of conductivity (lower left) as a function of frequency, and complex impedance plane (upper right). ........................................................................... 47
Figure 4.9  Relationship between step and conductivity. .......................................................... 49
Figure 4.10  Distribution of measured conductivities in log scale ........................................... 49
Figure 4.11  Trends of hydraulic conductivity of Peat 3 and electrical conductivity of water with time. .................................................................................................................... 51
Figure 4.12  Relative difference between $\sigma_m$ and $\sigma'$ as a function of $\sigma_m$ at the frequency of 10 kHz ........................................................................................................................... 53
Figure 4.13  Real part of conductivity as a function of frequency for Peat 1, 2 and 3.......... 54
Figure 4.14  Real part of conductivity as a function of conductivity of water at 10 kHz (upper left), 50 kHz (upper right) and 100 kHz (lower left). ...................................................... 56
Figure 4.15  Imaginary part of conductivity as a function of conductivity of water at 10 kHz, 50 kHz and 100 kHz in double log (left) and semi-log (right) scale ............................. 57
Figure 5.1  Schematic arrangement of Rowe cell-like apparatus [Blewett et al. 2003]. .......... 61
Figure 5.2  (a) Typical impedance response for clay slurry measured by Blewett cell and (b) schematic impedance plot of ionically conducting porous medium [Blewett et al. 2003]. ................................................................................................................. 61
Figure 5.3  Influence of lead inductance on measured result [Blewett et al. 2003]. .......... 62
Figure 5.4  Comparison of frequency-dependent behaviour of $\sigma'$ (upper) and $\sigma''$ (middle)
and \(\varepsilon_r\) (bottom) between Lesmes and Frye [2001] (left column) and the results of this
study (right column). ................................................................. 64

Figure 5.5  Distribution of \(\sigma_w\) in the cell at the beginning stage (left) and presumable
correlation of Peat 1 data (right). .................................................. 65

Figure 5.6  Comparison between C&S fitting (left) and mAl fitting (right) for Peat 2 and
Peat 3 data at 10 kHz (top), 50 kHz (middle) and 100 kHz (bottom). ......................... 68

Figure 5.7  Curve fitting on \(F - n\) relationship at 10, 50 and 100 kHz................................. 69

LIST OF TABLES

Table 2.1  Field IP and normalised IP parameters [Lesmes and Friedman, 2005]. .......... 13
Table 2.2  Summary of electrical models ........................................................................ 30
Table 3.1  Characteristics of peat. ..................................................................................... 37
Table 4.1  Properties of all peat samples. .......................................................................... 48
Table 4.2  Sequence of conductivities and number of steps.............................................. 49
Table 4.3  Regression expression for each graph with references...................................... 58
Table 4.4  Fitting parameters of C&S model for Peat 1, 2 and 3 with reference parameters
from Comas and Slater [2004]. ..................................................................................... 58
Table 5.1  Average relative errors..................................................................................... 69
Table 5.2  Summary of curve fitting on \(\sigma' - \sigma_w\) relationship. ........................................ 69
INTRODUCTION

1.1 Problem definition

Peat is sediment consisting of incompletely decomposed vegetation matter, which is predominantly formed in swamp and marsh. Peatlands cover an estimated area of 4 million km$^2$, equivalent to 3% of the Earth’s land surface. Most (ca. 3.5 million km$^2$) are in the northern hemisphere, covering large areas in North America, Russia and Europe [Strack, 2008]. The western and northern areas of the Netherlands are covered by peat and soft organic clays as shown in Figure 1.1 [den Haan and Kruse, 2007].

![Figure 1.1](image)

Figure 1.1  Distribution of Holocene deposit in the Netherlands and locations of referenced sites (A = Amsterdam, R = Rotterdam, H = Hague, M = Marken, OVP = Oostvaardersplassen, RW = Rijpwetering, W = Wilnis, Z = Polder Zegveld and S=Sliedrecht) [den Haan and Kruse, 2007].

Peat has served for a long time as benefits for human beings. It has been used as a fuel for cooking, heating and even drying malted barley to get its smoky flavour into Scotch whiskey. It has also been utilised as a material for agriculture, horticulture and forestry because of its high capacity of retaining moisture. Furthermore, peatlands are one of the most exciting fields which attract many ecologists, hydrogeologists and ecosystem engineers because they play an important role in the biospheric global carbon cycle and affect the concentrations of the greenhouse gases such as CO$_2$ and CH$_4$ in the atmosphere [e.g. Gorham, 1991].
On the other hand, humans have experienced many problems with peat. In the Netherlands, the distribution of peat coincides with densely populated areas as shown in Figure 1.1. Since peat is characterised as an unconsolidated anisotropic soil of low stiffness, low shear strength, high water content, high compressibility and strong creep susceptibility [den Haan and Kruse 2007], various kinds of construction projects in the peatlands require geotechnical engineers to pay special attention to the structures, the properties and the behaviours of the peat.

In order to obtain such information in advance of a project, a site investigation is usually performed by means of core-boring, CPTs, sampling and laboratory tests. The results provide detailed properties of the peat. However, it is necessary to conduct a significant number of tests to reasonably interpret its conditions in two or three dimensions, particularly in case the ground conditions are known to be complicated. Thus, geophysical methods, such as seismic, electrical and electromagnetic surveys, are often associated with these tests to interpolate the results because they can produce two-dimensional images, though their resolution is less than pinpoint tests like CPTs. However, the integration between geophysical and geological data remains highly empirical and requires qualitative interpretations.

It is well studied by geophysicists in the field of petroleum and mineral exploration or hydrogeologists in the field of environmental remediation that electrical and electromagnetic surveys, such as ground penetrating radar (GPR) and electrical resistivity imaging (ERI), have a potential not only to depict two-dimensional ground stratigraphy but also to estimate physical properties (e.g. porosity, surface area, grain size, clay content, gas content, water content and saturation degree)¹, chemical properties (e.g. mineralisation type, cation exchange capacity (CEC) and pore fluid chemistry)², engineering properties (e.g. hydraulic conductivity and degree of consolidation)³, and hydrocarbon contamination⁴ of soils and rocks.

Most of the correlations have been studied on sand, shaly sand, mixture of sand and clay, and even artificial mixture of glass beads and clay. It is now highly required and expected that the concepts are applied to peat in order to find correlations of the electrical properties of peat with its index (organic content, degree of humification) and geomechanical properties (permeability, compressibility).

### 1.2 Goals and objectives

In this study, by means of a newly invented hybrid apparatus that consists of a Rowe cell combined with a capacitor, electrical properties of water and peat are measured in order to firstly assess and verify the applicability and appropriateness of the apparatus by using water as calibration. Secondly, by changing the electrical conductivity of pore
water in peat, the relationship between the electrical conductivity of whole peat and of pore water is derived in an empirical manner. Finally, recommendations are made for the future research.

1.3 Contents of the thesis

In Chapter 2, after background information about electrical properties and electrical phenomena in soils, electrical models of soils are introduced with respect to organic and non-organic materials. Chapter 3 presents the methodology of measurements, describing the new cell and the experimental set-up as well as the electrical model assumed in this study. Then the data analysis methods, preparation and characterization of the samples and the experimental procedures for water and peat are shown. In Chapter 4, the results of the measurements and data analysis are clarified for water and peat, together with detailed accounts of an actual experiment process to measure electrical conductivity of pore water and hydraulic conductivity of peat. Subsequently, 6 items are discussed in Chapter 5; comparison between the new cell and similar experimental set-up developed by others, negative capacitance, data correction/calibration, discrepant data between peat samples, curve fitting, and a difference between electrical conductivity of bulk peat and pore water. Finally, Chapter 6 concludes this study and some recommendations are made.

---

i For example, Archie, 1942; Klein and Sill, 1982; Vinegar and Waxman, 1984; Bryant and Pallatt, 1996; Lesmes and Morgan, 2001; Slater and Lesmes, 2002a, 2002b; Titov et al. 2002; Slater and Glaser, 2003; Ulrich and Slater, 2004; Comas and Slater, 2007; Kazemzadeh et al. 2007

ii For example, Waxman and Smits, 1968; Pelton et al. 1978; Vinegar and Waxman, 1984; Börner et al. 1996; Lesmes and Frye, 2001; Slater and Lesmes, 2002b; Slater and Glaser, 2003; Comas and Slater, 2004

iii For example, Börner et al. 1996; Slater and Lesmes, 2002; Blewett et al. 2003; Slater and Glaser, 2003; McCarter et al. 2005; Binley et al. 2006

iv For example, Weller and Börner, 1996; Vanhala, 1997
2 LITERATURE REVIEW ON ELECTRICAL MODELS OF SOIL

2.1 Introduction

In this chapter, overviews on electrical conductivity and complex conductivity, electrical double layer, electrokinetic processes and induced polarisation (IP) effect are given in 2.2 to 2.5. Based on the background, electrical models of soil are reviewed. The models are mainly separated into two fields, concerning respectively non-organic materials, such as sand and mixture of sand and clay (2.6), and organic materials such as peat (2.7). The former models have been abundantly proposed mostly by the oil/gas and mineral/metallurgic industries, whereas the latter models are scarce though there is a pile of problems and requirements about peat to be solved.

In addition, the models for non-organic materials are divided into three sections: empirical models (2.6.1 to 2.6.4), theoretical models based on interfacial and electrochemical polarization mechanism and short narrow pores model (2.6.5 to 2.6.8), and semi-theoretical model (2.6.9).

2.2 Conductivity, complex conductivity and other terminology

Conduction current density $J_C$ [A/m$^2$] and the electric displacement $D$ [C/m$^2$] are related to the applied electric field $E$ [V/m] by the constitutive equations [Lesmes and Frye, 2001]:

$$J_C = \sigma E \quad \text{and} 
D = \varepsilon_r \varepsilon_0 E, \quad (2.1)$$

where $\sigma$ = electrical conductivity [S/m],
$\varepsilon_0$ = vacuum permittivity [F/m] = $8.854 \times 10^{-12}$,
$\varepsilon_r$ = relative permittivity of dielectric [-] = $\varepsilon / \varepsilon_0$ and
$\varepsilon$ = permittivity of dielectric [F/m].

Electrical conductivity is the ability of a material to conduct an electric current in response to an applied electric field. Permittivity is a physical property of a dielectric to clarify how much an applied electric field is disturbed by a polarisation phenomenon (2.5) of the dielectric in response to the field. Both properties are specific to a material.

The displacement current density $J_D$ [A/m$^2$] under a time-varying electric field is expressed as:

$$J_D = \frac{\partial D}{\partial t} = i \omega \varepsilon_r \varepsilon_0 E, \quad (2.3)$$

where $i$ = imaginary unit = $\sqrt{-1}$.
$\omega$ = angular frequency of applied electric field [Hz] and
$\epsilon',_r = \text{real part of complex relative permittivity [-]}.$

The total current density $J^*$ can be finally expressed as:

$$J^* = J_c + J_d = (\sigma' + i\omega\epsilon',_0) E = \sigma^* E = (\sigma' + i\sigma'') E,$$

where

- $\sigma^*$ = complex conductivity [S/m] = $\sigma' + i\sigma''$,
- $\sigma'$ = real part of conductivity [S/m] and
- $\sigma''$ = imaginary part of conductivity [S/m].

When an alternating electric field is impressed to a material, it is required to introduce the concept of complex conductivity because the complex conductivity is a frequency-dependent parameter. As an alternating electric current is applied to a material, the material responds with a time-delay in the voltage compared to the current frequency because of its polarisation phenomenon (2.5). The time-delay, i.e. phase shift, of dissipation is regarded as the capacitance of the material. The complex conductivity is expressed in the polar form as well:

$$\sigma^*(\omega) = |\sigma|e^{i\phi},$$

where

- $|\sigma|$ = magnitude of conductivity [S/m] and
- $\phi$ = phase shift [radian].

The magnitude of conductivity and the phase angle can be expressed as:

$$|\sigma| = \sqrt{(\sigma')^2 + (\sigma'')^2}$$

$$\phi = \arctan\left(\frac{\sigma''}{\sigma'}\right)$$

In the same way, complex permittivity is also defined as follows:

$$\epsilon^*(\omega) = \epsilon'\omega + i \epsilon''(\omega),$$

where

- $\epsilon'(\omega)$ = complex permittivity [F/m],
- $\epsilon'(\omega)$ = real part of complex permittivity [F/m] and
- $\epsilon''(\omega)$ = imaginary part of complex permittivity [F/m].

The real part of the complex conductivity relates to the in-phase conductivity component, i.e. ohmic conduction or energy loss term, whereas the imaginary part of the complex conductivity corresponds to the out-of-phase conductivity component, i.e. polarisation or energy storage term. On the other hand, the real part of complex permittivity is relevant to polarisation or energy storage, and the imaginary part
represents energy loss.

Electrical resistivity $\rho$ [Ωm] is the reciprocal of electrical conductivity. The Ohm’s law is valid for a direct current (DC) with the concept of resistance $R$:

$$R = \frac{V}{I},$$ (2.9)

where $R =$ resistance [Ω] = $\rho \frac{l}{A}$,
$V =$ voltage [V],
$I =$ current [A],
$\rho =$ electrical resistivity of material [Ωm],
l = length of resistive material [m] and
$A =$ cross-sectional area of resistive material [m²].

When an alternating current is however applied to a circuit, the concept of electrical impedance $Z$ is required, which is expressed as a complex number as follows:

$$Z = R + Xi,$$ (2.10)

where $Z =$ impedance [Ω],
$R =$ resistance or real part of impedance [Ω],
$X =$ reactance or imaginary part of impedance [Ω] and
$i =$ imaginary unit = $\sqrt{-1}$.

Capacitance is the ability of a material to store an electric charge. The capacitance, normally represented as two parallel plates separated by a dielectric, is expressed by means of relative permittivity as follows:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d},$$ (2.11)

where $C =$ capacitance [F],
$\varepsilon_0 =$ vacuum permittivity [F/m] = $8.854 \times 10^{-12}$,
$\varepsilon_r =$ relative permittivity of dielectric [-] = $\varepsilon / \varepsilon_0$, 
$A =$ overlap area of two parallel plates [m²] and
$d =$ distance between the plates [m].

2.3 Electrical double layer (EDL)

An electrochemical interaction is established between an electrolytic solution and the solid particles immersed in it. This is due to the surface charge of the particles, which induces an ion concentration layer around the particle, called the electrical double layer (EDL). The layer can be divided into two: a fixed layer or Stern layer, and a diffuse
layer or Gouy layer. The example for a clay particle is shown in Figure 2.1. The fixed layer is formed with packed positive ions. Because the ions are strongly attracted by the negative surface charge immediately next to the particle, they can move in tangential direction but not in radial direction. Therefore hardly any ion exchanges occur between the fixed layer and the other areas. On the other hand, the diffuse layer consists of a relatively loose ion cloud and then the ions can freely migrate in any direction. It extends into the solution, exponentially reducing its ionic concentration with the distance from the particle surface.

The electrical potential at the plane which separates mobile fluid from the fluid that remains attached to the particle surface is called electrokinetic potential or zeta potential \( \zeta \). The zeta potential is related to the stability of the colloidal suspensions; colloids with high zeta potential (negative or positive) are electrically stabilized, while colloids with low zeta potentials tend to coagulate or flocculate.

![Electrical double layer surrounding clay particle](after Brandes 2005).

### Figure 2.1    Electrical double layer surrounding clay particle [after Brandes 2005].

#### 2.4 Electrokinetic phenomena

The presence of the EDL gives rise to several electrokinetic phenomena in soils, which
are the result of the movement of different phases with respect to each other [Asadi et al. 2009]. Electrokinetic phenomena can be defined as all those phenomena involving tangential fluid motion adjacent to a charged surface. They are manifestations of the electrical properties of interfaces under steady-state and isothermal conditions [Delgado et al. 2007]. Electrokinetic processes include electro-osmosis, electrophoresis, streaming potential and sedimentation potential.

Electro-osmosis is defined as a fluid movement with respect to a solid wall in response to an applied electric field. Pore water in clay flows along the charged surface of the clay particles when an electric field is impressed. This is due to the excess of cations that are present inside the diffuse layers of the clay particles. The applied electric field causes these cations to migrate from the anode towards the cathode as shown in Figure 2.2. Water molecules that are attached to these cations as hydration water are also transported towards the cathode. This results in a transport of water. Thus, electro-osmosis effect is often studied in the geotechnical field and utilised for dewatering of clay, reducing clay adhesion and extracting contaminants in soil etc [e.g. Alshawabkeh et al. 1999; van Baalen et al. 2000; Asadi et al. 2009].

The liquid flow takes place along any section of the double layer under the action of the tangential component of an external electric field $E$ and it is described by its electro-osmotic velocity $v_{eo}$ [Delgado et al. 2007]. The Helmholtz-Smoluchowski theory, one of the earliest and still widely used models of electro-osmosis, defines $v_{eo}$ at a large distance from the charged interface as:

$$v_{eo} = -\frac{\varepsilon_r \varepsilon_0 \zeta}{\eta} E , \quad (2.12)$$

where $\varepsilon_r = \text{relative permittivity of electrolyte solution}$, $\varepsilon_0 = \text{electric permittivity of vacuum}$, $\zeta = \text{zeta potential}$, $E = \text{electric field}$ and $\eta = \text{dynamic viscosity of the solution}$.

The rate of electro-osmotic flow is controlled by the coefficient of electro-osmotic permeability of the soil, $k_{eo}$ [Asadi et al. 2009]. It is a measure of the fluid flux per unit area of the soil per unit electric gradient and is given by:

$$k_{eo} = \frac{\varepsilon_r \varepsilon_0 \zeta}{\eta} n , \quad (2.13)$$

where $n = \text{porosity of the soil}$. 

The coefficient of electro-osmotic permeability thus depends mainly on porosity.
and zeta potential, while the hydraulic conductivity is influenced by the pore size and its distribution in the medium.

Electrophoresis is the counterpart of electro-osmosis. In fact, it is the movement of charged colloidal particles with respect to a fluid under the influence of an external electric field. Therefore the expression for the electrophoretic velocity is obtained changing the sign in Equation (2.12):

$$v_e = \frac{\varepsilon \varepsilon_0 \sigma \zeta}{\eta} E.$$ (2.14)

In the case of natural sediments, electrophoresis is the flux of negatively charged clay particles towards the anode, as shown in Figure 2.2. This process requires a sediment clay-fluid system sufficiently viscous.

![Figure 2.2 Electro-osmosis (left) and electrophoresis (right).](image)

Streaming potential is the converse phenomenon of electro-osmosis. It is an electric potential generated at both ends of capillaries when an electrolyte solution is forced to flow through them. This phenomenon is thus caused by the charge displacement in the electrical double layer in an extremely narrow pathway as a result of an applied pressure inducing the liquid phase to move tangentially to the solid [Delgado et al. 2007].

Sedimentation potential is the potential difference occurring in a downward direction while particles in a suspension are deposited under the effect of gravity or centrifugation. The difference arises due to the fact that charged particles sink in viscous fluid, leaving ionic clouds in diffuse layers on their way to sedimentation because of the friction between the ionic clouds and the viscous fluid.
2.5 Induced polarisation (IP) effect

The induced polarisation response of rocks and soils is controlled by electrochemical polarisation mechanisms that are a function of pore solution chemistry, sample micro-geometry and surface chemical properties [Lesmes and Frye, 2001]. Ions in the saturating fluid of the material are attracted to the mineral surface, forming an EDL (2.3). At the application of an electric field, the ions in the EDL migrate tangentially to the grain surface and the grain becomes polarised. This leads to a frequency-dependent complex surface conductivity ($\sigma_{surf}^*$), which is a function of the surface charge density, the surface ionic mobility and the grain size distribution. The complex surface conductivity is usually assumed to act in parallel with the bulk electrical properties of the sample.

In the field, IP surveys can be conducted using three different types of measurements: time-domain, frequency-domain and complex resistivity.

In the time domain method a direct current is artificially applied to the ground and interrupted. The voltage across the potential electrodes does not drop to zero instantaneously, but it is found to take some time to dissipate, as shown in Figure 2.3. The IP effect measured by time-domain method is quantified by the chargeability $m$:

$$m = \frac{1}{V_p} \int_{t_1}^{t_2} V(t)dt = \frac{A}{V_p}, \quad (2.15)$$

where $m =$ chargeability,
$V_p =$ initial voltage,
$V(t) =$ decay curve of voltage as a function of time,
$t_1, t_2 =$ arbitrary time interval and
$A =$ integral of decay voltage = area.

![Figure 2.3](image)

*Figure 2.3  Example of measured voltage decay by time-domain method.*

An analogous behaviour can be observed in a frequency-domain measurement, where a phase shift between applied current and measured voltage can be observed.
In this case the measured field parameter is the percent frequency effect (PFE), which quantifies the relative dispersion in the conductivity response measured between a low frequency $\omega_0$ and a higher frequency $\omega_1$:

$$PFE = 100 \times \frac{\sigma(\omega_1) - \sigma(\omega_0)}{\sigma(\omega_0)}. \tag{2.16}$$

The phase shift is a measure of the induced polarization response in terms of complex conductivity of the material:

$$\theta = \tan^{-1}\left(\frac{\sigma''}{\sigma'}\right) \approx \frac{\sigma''}{\sigma}. \tag{2.17}$$

The commonly measured field IP parameters ($m$, PFE and $\theta$) are dependent on both the surface and bulk electrical properties of the material. Dividing the IP field parameters by the formation resistivity (or multiplying by the conductivity), normalised IP parameters are obtained as given in Table 2.1 [Lesmes and Friedman, 2005]: normalised chargeability, also called “specific capacity” (MN), metal factor (MF) and quadrature conductivity ($\sigma''$). They are more directly related to the surface chemical properties of the material.

The useful bandwidth in the field is restricted to the frequency range between $10^{-2}$ and $10^2$ Hz by instrumentation limitations and effects of electromagnetic coupling between wiring and earth.
Table 2.1  Field IP and normalised IP parameters [Lesmes and Friedman, 2005].

<table>
<thead>
<tr>
<th>Field IP Parameters</th>
<th>Normalised IP Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ m = \frac{1}{V_p} \int_0^t V(t) dt = \frac{A}{V_p} ]</td>
<td>[ MN = M \sigma' ]</td>
</tr>
<tr>
<td>[ PFE = 100 \times \frac{\sigma(\omega_t) - \sigma(\omega_0)}{\sigma(\omega_0)} ]</td>
<td>[ MF = a(\sigma(\omega_t) - \sigma(\omega_0)) ]</td>
</tr>
<tr>
<td>[ \theta = \tan^{-1}\left(\frac{\sigma''}{\sigma'}\right) \approx \frac{\sigma''}{\sigma'} ]</td>
<td>[ \sigma'' = \sigma' \tan (\theta) \approx \sigma' \theta ]</td>
</tr>
</tbody>
</table>

Note: \( a \) = dimensionless constant.

The induced polarisation effects are attributed to the presence of the EDL at which local charge concentration gradients result in a delayed voltage response. Two distinct polarisation effects are commonly acknowledged: electrode (or metallic) polarisation and membrane (or boundary layer) polarisation (2.6.5) [Slater and Glaser 2003]. The former occurs at interfaces between charged particles and electrolyte, namely EDL, when an electric field is externally applied as shown in Figure 2.5. The latter occurs because of the fact that ionic transport is hindered by cation blockage, leading to unequal ionic distribution as shown in Figure 2.6.

**Figure 2.5** Electrode polarisation.

**Figure 2.6** Membrane polarisation.
2.6 Non-organic material

2.6.1 Archie’s law

Archie’s law is the most prevailing relationship between the resistivity of a geological material and that of the pore water of the material, which is empirically derived by Archie [1942] for sand completely saturated with brine and for sand partly saturated with brine, oil and gas. Although the original Archie’s law does not include a coefficient \( a \) in the formation factor, Winsauer et al. [1952] and Wyllie and Gregory [1953] modified the law by adding the coefficient as an influence of tortuosity [Kazemzadeh et al. 2007]. The equations for saturated and unsaturated sand can be expressed in terms of conductivity respectively:

\[
\sigma_{\text{sat}} = \sigma_w / F = \sigma_w n^m / a,
\]
\[
\sigma_{\text{unsat}} = \sigma_{\text{sat}} s^d,\]

where

- \( \sigma_{\text{sat}} \) = conductivity of saturated sand [S/m],
- \( \sigma_{\text{unsat}} \) = conductivity of unsaturated sand [S/m],
- \( \sigma_w \) = conductivity of pore water [S/m],
- \( F \) = formation factor [-] = \( a / n^m \),
- \( a \) = tortuosity index in porous medium [-],
- \( m \) = cementation index [-],
- \( n \) = porosity [-],
- \( s \) = saturation degree [-] and
- \( d \) = saturation index [-].

The formation factor \( F \) is often assumed as an indicator of the hydraulic tortuosity of a porous medium [Lesmes and Friedman, 2005]:

\[
T = (L_a / L)^2 = nF,\]

where

- \( T \) = hydraulic tortuosity,
- \( L_a \) = effective pass length and
- \( L \) = macroscopic length of sample.

From a study of many groups of data sets, Archie [1942] has found that \( m \) ranges between 1.8 and 2.0 for consolidated sandstones, and is about 1.3 for clean unconsolidated sands packed in the laboratory while \( a = 1 \). The equation for unsaturated sand is valid for saturation degrees down to about 0.15 or 0.20. The value of \( d \) appears to be close to 2 for both consolidated sand and clean unconsolidated sand.

In addition, Lesmes and Friedman [2005] presents the extended form of Archie’s law for partially saturated rocks and soils:
\[ \sigma_{\text{unsat}} = \sigma_w n^m s^d. \] (2.21)

### 2.6.2 Cole-Cole model

One of the most important electrical dispersion/relaxation models that describe the frequency-dependent complex conductivity is the Cole-Cole (C-C) model [Pelton et al. 1978]. This empirical model was originally proposed by Cole and Cole [1941] to derive complex dielectric behaviour. Pelton et al. [1978] represented the C-C model of complex resistivity with the help of conceptual diagrams of a material (Figure 2.7 (a)), the equivalent circuit (Figure 2.7 (b)) and the typical frequency domain response for the circuit (Figure 2.7 (c)), and formulated the equation as follows:

\[ \rho^* (\omega) = \rho_0 \left[ 1 - m \left( 1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right]. \] (2.22)

When it is converted to the formula in complex conductivity by means of \( \sigma = 1/\rho \),

\[ \sigma^* (\omega) = \sigma_0 \left[ 1 + m \left( 1 + \frac{(i\omega\tau)^c}{1 + (1 - m)(i\omega\tau)^c} \right) \right], \] (2.23)

where

- \( \rho_0 = \) resistivity at very low frequency, i.e. direct current,
- \( \sigma_0 = \) conductivity at very low frequency, i.e. direct current,
- \( m = \frac{1}{1 + \frac{R_1}{R_0}}: \) chargeability,
- \( R_0 \) and \( R_1 \) = resistances in the circuit in Figure 2.7 (b),
- \( \omega = \) angular frequency = \( 2\pi f \),
- \( \tau = X \left( \frac{R_0}{m} \right)^{1/c} = \) time constant or relaxation time,
- \( X = \) reactance (imaginary part of impedance) and
- \( c = \) frequency dependence in Figure 2.7 (c).

As shown in Figure 2.7, the spectrum of the phase shows frequency-dependence and a maximum phase angle. Pelton et al. [1978] used this model to discriminate various kinds of minerals which have similar electrical properties but different lithological properties, e.g. grain size, texture and concentration of minerals. Laboratory measurements for artificial and natural samples were conducted over the frequency from 0.01 Hz to 100 kHz. In situ field measurements were also made over three kinds of mineralization deposits at the same frequency range. As a result of laboratory
measurements, it is concluded that the change in concentration and grain size have minor effect on $R_0$ and $c$ but pronounced effect on $m$ and $\tau$.

Binley et al. [2005] carried out spectral induced polarization (SIP) measurements over the frequency from 0.01 Hz to 1 kHz on saturated/unsaturated sandstone samples taken from aquifer in UK in order to check whether or not the Kozeny-Carman (K-C) type model by Börner et al. [1996] (2.6.3), which represents the relationship between hydraulic conductivity and electrical conductivity of rocks and soils, is applicable to the case. They concluded that the K-C type model is inappropriate because the model consists of only a single frequency (1 Hz) measurement of imaginary electrical conductivity as representative of the SIP responses based on the constant phase angle model (2.6.3), whereas the measured SIP responses show a maximum phase angle, i.e. they consist of various relaxation time. On the other hand, the application of the C-C model demonstrated that $\tau$ had strong correlation with the specific surface area, hydraulic conductivity and saturation degree.

![Diagram of mineralized rock and equivalent circuit]

Figure 2.7 (a) Small section of a mineralized rock which has both blocked and unblocked pore passages, (b) equivalent circuit for the mineralized rock, (c) Typical frequency domain response for the equivalent circuit [after Pelton et al. 1978].

2.6.3 Constant phase model

The C-C model requires a very broad frequency range to accurately estimate the model parameters. However, some sedimentary soils and rocks may present a constant phase angle over a relatively narrow band in low frequency area. The constant phase angle (CPA) model can be useful to simulate such frequency-independent electrical behaviour of soils and rocks. The advantage of the model is that two independent electrical parameters can be derived from only one frequency scan.

Börner et al. [1996] applied the CPA model to laboratory SIP measurements on a
variety of shaly sands, silts and clays in an attempt to interpret surface and borehole SIP measurements quantitatively. The general behaviour of the measured complex conductivity in the frequency range from 0.01 to 100 Hz appeared frequency-independence as shown in Figure 2.8. It can be described by the equation below:

\[
\sigma^*(\omega) = \sigma_n (i \omega)^{1-p},
\]

(2.24)

where \( \sigma_n \) = constant amplitude factor, 
\( \omega \) = angular frequency normalized at \( \omega = 1 \) s\(^{-1} \) and 
\( 1-p \) = frequency dependence.

Equation (2.24) can be divided into real and imaginary parts as follow:

\[
\sigma'_n = \sigma_n \cos \left( \frac{\pi}{2} (1 - p) \right) \quad \text{and} \quad \sigma''_n = \sigma_n \sin \left( \frac{\pi}{2} (1 - p) \right)
\]

(2.25)

where \( \sigma'_n \) = real part of conductivity and 
\( \sigma''_n \) = imaginary part of conductivity.

Using Equation (2.7), the relationship between the frequency dependence \( 1-p \) and the frequency-independent phase angle \( \phi \) is given by:

\[
\phi = \tan^{-1} \left( \frac{\sigma''_n}{\sigma'_n} \right) = \frac{\pi}{2} (1 - p).
\]

(2.26)

The authors experimentally formulated the relationships between electrical conductivity and formation factor \( F \), surface-area-to-porosity ratio \( S_{por} \). Based on the equations, the authors proposed the interpretation algorithm for the calculation of aquifer properties, i.e. hydraulic conductivity and cation exchange capacity (CEC), from SIP measurement:

\[
K = \frac{1}{FS_{por}^{S}},
\]

(2.27)

\[
CEC_{por} = sS_{por},
\]

(2.28)

where \( K \) = hydraulic conductivity, 
\( CEC_{por} \) = CEC relative to pore volume, 
\( F \) = formation factor = \( \frac{\sigma_w}{\sigma'_n - \sigma''_n} / l \), 
\( \sigma_w \) = electrical conductivity of pore water, 
\( l \) = ratio of interface conductivity in EDL to \( \sigma'_n \), 
\( S_{por} \) = surface-area-to-porosity = \( a \sigma''_n \),
\[ a = \text{experimentally determined constant} = 8.6 \times 10^4, \]
\[ c = 2.8 - 4.6 \text{ depending on the permeability measurement and} \]
\[ s = \text{experimentally determined mean surface-charge density} \]
\[ \text{for silicate matrix components.} \]

**Figure 2.8** SIP responses of silty sand measured at laboratory and field in the frequency range from 0.01 to 100 Hz, showing frequency-independence [Börner et al. 1996].

### 2.6.4 Generalised Cole-Davidson model

Klein and Sill [1982] attempted to evaluate the dependence of electrical responses on matrix grain size, clay type and its content by the generalised Cole-Davidson (GCD) model:

\[
Z(\omega) = R_0 \left[ 1 - m \left( \frac{1}{1 + (i\omega \tau)^\eta} \right) \right],
\]

where \( m = 1 - \frac{R_c}{R_0} \): chargeability,
\( R_0 = \) low-frequency asymptote,
\( R_c = \) high-frequency asymptote,
\( \omega = \) angular frequency \( = 2\pi f \),
\( \tau = \) time constant or relaxation time and
\( \eta = \) frequency dependence.

Using laboratory-measured SIP responses on artificial mixtures of kaolinite, montmorillonite and various sizes of glass beads, the authors compared the empirical GCD model with the theoretical Madden-Marshall (M-M) model (2.6.5) and the
semi-theoretical Waxman-Smits model (2.6.9). As a result, it is concluded that the GCD model is consistent with the M-M model and is more convenient than the M-M model in terms of simplicity of equations and number of parameters. Besides, the time constant $\tau$ and the chargeability $m$ show clear relationships between the grain size of the glass beads and the amount of clay or CEC respectively. In regard to the comparison with Waxman-Smits model, the possibility of its invalidity for low-clay content soils and rocks was implied. Moreover, a limited number of measurements indicated that the chargeability might distinguish clay types based on their valence number. However, it must be noted that these findings were derived from artificial glass beads samples and further studies on other samples are required.

### 2.6.5 Madden-Marshall model

Madden-Marshall (M-M) model is the one theoretically proposed by Marshall and Madden [1959]. Its aim is to simulate a membrane polarisation phenomenon occurring in non-metallic rock materials due to inducing electric current. The membrane polarisation was conceptualized as shown in Figure 2.9. It is assumed that strongly cation selective zones (Zone II), or so-called membrane zones, alternates with non-selective zones (Zone I). Thus, Zone II and Zone I can be regarded as a clay-rich zone and a clay-free zone respectively. When electric current is applied, cations will accumulate at the left end of Zone II, whereas deficiency of ions will take place at the right end of Zone II. This causes concentration gradients and leads to the modification of ion flow until a balance is reached. As mentioned above, the equation of the impedance of the membrane zone is rather complicated:

$$
Z = \frac{\Delta L_i}{U_{p3}CF} \left\{ t_i^+ + \frac{B}{A} t_i^- + \frac{(S_{i+} - S_{i-})^2}{X_i S_i} + \frac{A}{B} \frac{X_{i+} S_{i+}}{t_i^+ (t_i^-)^2 \tanh X_i} \right\}, \quad (2.30)
$$

where $Z =$ impedance of membrane zone,
$\Delta L_i =$ zone length,
$U_{p3} =$ mobility of cation,
$C =$ capacitance,
$F =$ Faraday’s constant,
$t_i^+ =$ cation transference number,
$t_i^- =$ anion transference number,
$A = \Delta L_i / \Delta L_{i+},$
$B = D_{pl} / D_{pl+},$
$D =$ diffusion coefficient,
\[ S_i = \frac{t_i^-}{t_i^+}, \]
\[ X_i = \left( \frac{j \omega}{2 D_{pt} t_i} \right)^{1/2} \frac{\Delta L_i}{2}, \]
\[ j = \sqrt{-1} \quad \text{and} \]
subscription \( i = \) zone number I or II.

Figure 2.9  Ion motion and concentration changes by current flow through a membrane system [Marshall and Madden, 1959].

2.6.6 Bruggeman-Hanai-Sen model

The Bruggeman-Hanai-Sen (BHS) model [Bruggeman, 1935; Hanai, 1960; Sen et al. 1981] is a theoretically based effective medium theory. It was developed to model the dielectric and electrical properties of a porous solid saturated with a single fluid phase [Knight and Endres 2003]. It can model total dielectric or complex conductivity response of porous media, which is composed of grain/surface phase mixture and the bulk pore solution [Lesmes and Morgan 2001]. The model is given as a self-similar, asymmetric and two-phase mixture effective media theory [Lesmes and Friedman 2005] by:

\[ \sigma^* = \sigma_w^* n^m \left( \frac{1 - \sigma_m^* / \sigma_w^*}{1 - \sigma_w^* / \sigma} \right)^m, \quad (2.31) \]

where \( \sigma_w^* = \) complex conductivity of pore water,
\( \sigma_m^* = \) complex conductivity of grain/surface phase mixture,
\( n = \) porosity and
\( m = \) cementation index, function of grain shape.
2.6.7 EDL-based S-model and D-model

Although the BHS model describes the bulk properties of grains and pore water system, it is known that electrochemical interaction between solids and solutions has significant influence on electrical behaviour of soils and rocks at low frequency range. The concept of electric double layer (EDL) based diffusive polarisation, composed of a fixed layer model or S-model and a diffuse layer model or D-model, is introduced to facilitate the understanding of the IP phenomena. Lima and Sharma [1992] defined the two polarisation mechanisms. The first as a surface conductivity related with a modified Stern double layer model (S-model) according to Schurr-Schwarz theory* and the second as a coupled electro-diffusion mechanism occurring in a Guoy-Chapman double layer using Fixman’s approach† (D-model). The authors extended then the formulation of both models based on Maxwell-Wagner theory, to shaly sands and compared numerical and experimental results. Consequently, it is concluded that the D-model is more suitable for clay-water suspension, shale and shaly sandstones to simulate measurements obtained in the frequency range from 100 Hz to 10 MHz as shown in Figure 2.10.

![Figure 2.10](image)

Figure 2.10 Comparison of numerical conductivity dispersion with experimental data on dilute suspension of kaolinite [Lima and Sharma, 1992].

Lesmes and Morgan [2001] made an interesting attempt to integrate three types of polarization mechanisms in one. First, S-model and D-model were superposed by the

* Schurr-Schwarz theory assumes that charges in fixed layer are only free to move tangentially and no charge exchange with bulk electrolyte; no polarisation occurs in diffuse layer because ions in the layer immediately dissipate into electrolyte; no ions exchange between fixed and diffuse layer.

† An approximate theory based on the polarisation of a diffuse Guoy-Chapman model to account for the motion of ions both tangentially and radially.
bounding method, in which a volumetric (parallel) mixing formula (as an upper bound) and a geometric mean mixing formula (as a lower bound) were calculated. In this way the grain/surface phase mixture was derived. Subsequently, the grain/surface phase mixture and the bulk pore solution polarisation were superimposed again by the BHS effective mixing formula in order to obtain the bulk effective mixing medium. As a result of inverse modelling, it is concluded that every estimation was less than the measured response because the model did not take into account surface roughness effect, grain-grain interactions and variations in mineralogy with grain size.

2.6.8 Short narrow pore model

Titov et al. [2002] proposed a physical model, called the short narrow pore (SNP) model. This model, which describes similar mechanism to the membrane polarization by Marshall and Madden [1959], assumes that long and wide pores are serially connected with short and narrow pores. This is abstracted from single-grained sand just like Figure 2.1. The intergranular water-filled space (denoted by \( l_1 \)) and the grain-contact area (denoted by \( l_2 \)) can be regarded as non-selective and ion-selective zone respectively. These are analogue of Zone I and Zone II in M-M model. The SNP model is formulated in frequency domain as follows:

\[
\rho^*(\omega) = \rho_0 \left[ 1 - \eta_0 \left\{ 1 - \frac{1 - \exp(-2(i\omega\tau)^{1/2})}{2(i\omega\tau)^{1/2}} \right\} \right],
\]

(2.32)

where \( \rho_0 \) = resistivity at very low frequency, i.e. direct current, \( \eta_0 \) = chargeability, \( \omega \) = angular frequency and \( \tau \) = time constant.

The equation appears quite similar to C-C model (Equation (2.22)). In fact, an agreement on the phase shift between both models was found as shown in Figure 2.12. It is concluded that the SNP model represents a special case of the M-M model and also shows an agreement with C-C model. In addition, the time constant \( \tau \) has a good correlation with the grain size. However, it is necessary to note that the model is based on clean sieved, i.e. single-grained sand. For water-saturated natural sand, i.e. well-graded/poorly-sorted sand, the SNP model is not valid any more.
2.6.9 Vinegar-Waxman model

There is also a semi theoretical model presented by Vinegar and Waxman [1984] (V-W). They modelled the complex conductivity with a system consisting of two conductive elements and a polarisation mechanism in parallel, as shown in Figure 2.13. The two conductive elements, i.e. real or in-phase part of conductivity, were modelled by Waxman and Smits [1968]:

\[
\sigma_{\text{water-sat}}' = \frac{1}{F}(\sigma_w + BQ_{\text{c}}) \quad \text{for water-saturated shaly sands and} \quad (2.33)
\]

\[
\sigma_{\text{oil}}' = \frac{S_d}{F}(\sigma_w + BQ_{\text{c}}) \quad \text{for oil-bearing, i.e. unsaturated}, \quad (2.34)
\]
where  
\[ F = \text{formation factor}, \]
\[ \sigma_w = \text{conductivity of the equilibrating electrolyte solution}, \]
\[ B = \text{equivalent ionic conductance of clay cation exchange as a function of } \sigma_w, \]
\[ Q_v = \text{CEC per unit pore volume}, \]
\[ S_w = \text{saturation degree and } \]
\[ d = \text{saturation exponent}. \]

The polarisation mechanism can be represented by two mechanisms in series, one is clay counterion displacement and the other is membrane polarization. Assuming that both are proportional to \( Q_v \) and considering the effect of pore cross-sectional area and tortuosity, a general equation for the polarisation mechanism, i.e. quadrature/imaginary part of or 90°-out-of-phase conductivity, can be given by:

\[
\sigma''_{\text{water-satu}} = \frac{\lambda Q_v}{Fn} \quad \text{for water-saturated shaly sand and} \tag{2.35}
\]
\[
\sigma''_{\text{oil}} = \frac{\lambda Q_v S_w^{d-1}}{Fn} \quad \text{for oil-bearing, i.e. unsaturated}, \tag{2.36}
\]

where  
\[ \lambda = \text{equivalent quadrature conductance and } \]
\[ n = \text{porosity}. \]

Therefore, the V-W model is given by:

\[
\sigma^*_{\text{water-satu}} = \sigma' + i \sigma'' = \frac{1}{F} (\sigma_w + BQ_v) + i \frac{\lambda Q_v}{Fn} \quad \text{for water-saturated,} \tag{2.37}
\]
\[
\sigma^*_{\text{oil}} = \sigma' + i \sigma'' = \frac{S_w^d}{F} (\sigma_w + \frac{BQ_v}{S_w}) + i \frac{\lambda Q_v S_w^{d-1}}{Fn} \quad \text{for oil-bearing}. \tag{2.38}
\]

Consequently, it is found that the quadrature conductivity depends on CEC and weakly on salinity. Moreover, the quadrature conductivity and the phase are frequency independent from 1 to 1000 Hz.
2.7 Organic material

Surprisingly, there are not so many papers on complex conductivity or IP measurement for organic materials like peat and humus so far. Particularly, the papers on the models of electrical properties for organic sediments are seldom published. In such a situation, Comas and Slater [2004] has presented notable results on electrical properties of peat in the frequency range from 0.1 to 1000 Hz. Electrical measurements were modelled by assuming that the real part of conductivity ($\sigma'$) is a summation of electrolytic current flow through an interconnected pore matrix ($\sigma_{el}$) and surface conduction through the EDL ($\sigma_{surf}'$), and the imaginary part of conductivity ($\sigma''$) is identical to surface polarisation ($\sigma_{surf}''$). The authors attempted to constrain the multi-parameter model of $\sigma'$ by means of directly measureable $\sigma_{surf}'$ and assuming a linear proportionality between $\sigma_{surf}'$ and $\sigma_{surf}''$ which was demonstrated by a great deal of past work [e.g. Lima and Niwas, 2000; Börner et al. 1996]. This model is established on the basis of the general model in which $\sigma_{el}$ and $\sigma_{surf}'$ are in parallel conduction paths as shown in Figure 2.14 [Lesmes and Frye, 2001], and the general model is given by:

$$\sigma' = (\sigma_{el} + i\omega\varepsilon_{e}\varepsilon_{0}) + \sigma_{surf}'(\omega)$$

$$= (\sigma_{el} + i\omega\varepsilon_{e}\varepsilon_{0}) + [\sigma_{surf}'(\omega) + i\sigma_{surf}''(\omega)],$$

(2.39)

where $\sigma'$ = complex conductivity, $\sigma_{el}$ = low-frequency (or DC) conductivity, $i$ = imaginary unit, $\omega$ = angular frequency of applied electric current, $\varepsilon_{e}$ = high-frequency relative permittivity of sample, $\varepsilon_{0}$ = vacuum permittivity, $\sigma_{surf}'(\omega)$ = real part of complex surface conductivity and $\sigma_{surf}''(\omega)$ = imaginary part of complex surface conductivity.
This model assumes that $\sigma_{el}$ is purely resistive; $\varepsilon_\infty$ represents the capacitance of the system at high frequency; and $\sigma^\prime_{surf}(\omega)$ accounts for low-frequency IP effects. Combining the real and the imaginary parts in Equation (2.39) gives:

$$\sigma^* = [\sigma_{el} + \sigma^\prime_{surf}(\omega)] + i[\omega\varepsilon_\infty\varepsilon_0 + \sigma^\prime_{surf}(\omega)].$$  \hspace{1cm} (2.40)

In low frequency range, the component $\omega\varepsilon_\infty\varepsilon_0$ is much less than $\sigma^\prime_{surf}(\omega)$. Therefore, the former component vanishes at low frequencies and the complex conductivity of saturated inorganic sediments is expressed as:

$$\sigma^* = [\sigma_{el} + \sigma^\prime_{surf}(\omega)] + i\sigma^\prime_{surf}(\omega).$$  \hspace{1cm} (2.41)

Then,  \hspace{0.5cm} $\sigma = \sigma_{el} + \sigma^\prime_{surf}(\omega) = \sigma_w + \sigma^\prime_{surf}(\omega)$ and  \hspace{1cm} (2.42)

$$\sigma^\prime = \sigma^\prime_{surf}(\omega),$$  \hspace{1cm} (2.43)

where $F$ = formation factor and $\sigma_w$ = electrical conductivity of pore water in samples.

Equation (2.42) is a modified Archie’s law (cf. Equation (2.18)).

As a result of the measurements of IP responses from 0.1 to 1000 Hz and hydraulic conductivity as a function of $\sigma_w$, it was found that:

$\sigma^\prime_{peat} \propto \sigma_w^{1.3}$ (Figure 2.15).

$\sigma^\prime_{sand} \propto \sigma_w^{0.5}$ over the entire $\sigma_w$ range, whereas the similar proportionality for $\sigma^\prime_{sand}$ is observed only below 0.3 S/m (Figure 2.15).

Vertical hydraulic conductivity $K_v$ increases with increasing $\sigma_w$. Taking into account a Kozeny-Carman type equations as shown below, increasing $K_v$ means every petrophysical parameters increases. This phenomenon is called pore dilation [Ours et al. 1997].
2 Literature Review on Electrical Models of Soil

\[ K = \frac{cl^2}{F} = cl^2 n^m, \]  \hspace{1cm} (2.44)

where \( c = \text{constant}, \)

\( l_c = \text{pore space length}, \)

\( F = \text{formation factor}, \)

\( n = \text{porosity and} \)

\( m = \text{cementation factor}. \)

Archie’s power law \( F = n^m \) is not applicable because \( F \) varies with \( \sigma_n \), i.e. it is not constant any more.

Based on these findings, the following empirical model for organic sediments is proposed:

\[ \sigma'_{\text{peat}} (\sigma_w) = \sigma'_{\text{el}} + \sigma'_{\text{surf}} (\sigma_w) = A \sigma_w^b + C \sigma_{\text{surf}} (\sigma_w), \]  \hspace{1cm} (2.45)

where \( A, b, C = \text{fitting parameters}. \)

---

**Figure 2.15** (a) Real (\( \sigma' \), primary axis) and imaginary (\( \sigma'' \), secondary axis) conductivity as a function of \( \sigma_w \) for peat samples saturated with different NaCl concentrations (1 Hz measurement frequency). (b) Real (\( \sigma' \)) and imaginary (\( \sigma'' \)) conductivity as a function of NaCl \( \sigma_w \) for sand samples [from Slater and Glaser, 2003] at 1 Hz [Comas and Slater, 2004].

In addition, the study shows similar behaviour of \( \sigma''_{\text{peat}} (\sigma_w) \) with \( \sigma''_{\text{sand}} (\sigma_w) \) as \( \sigma'' \) increases with increasing \( \sigma_w \) to some extent, beyond which it starts decreasing as shown in Figure 2.16. Referring to some literature, e.g. Vinegar and Waxman [1984] and Slater.
and Glaser [2003], this phenomenon can be attributed to the same mechanism observed for inorganic materials. Thus, $\sigma_w$ is proportional to EDL charge density $\Omega$, while it is inversely proportional to ion mobility $\mu$. Besides, $\sigma_w - \Omega$ relationship is predominant in low $\sigma_w$ range while $\sigma_w - \mu$ relationship is predominant in high $\sigma_w$ range. Since surface conductivity proportionally varies as a function of $\Omega$ and $\mu$ [Lima and Sharma, 1992], $\sigma''$ increases in low $\sigma_w$ range and decreases in high $\sigma_w$ range.

Lesmes and Frye [2001] suggested two hypotheses about this mechanism; one is after Vinegar and Waxman [1984] and affirms that at high salinity the diffuse part of the EDL is compressed due to high charge density. This makes easier for anions to migrate through the clay blockages, thus decreasing the magnitude of the membrane polarisation effect. The other hypothesis comes from the point of view of the electrochemical polarisation of the EDL and states that the diffuse layer, in which ions can move easily, is compressed at high salinity. This makes it dense just like the fixed layer, in which ions are less mobile. To test these hypotheses, the authors proposed analysing whether the real part of the surface conductivity increases or not at high salinity. If yes, increased anion mobility through the clay blockage is responsible, and if not, a reduction in surface ionic mobility in the EDL is responsible.

Figure 2.16 Dependence of imaginary conductivity $\sigma''$ on fluid conductivity $\sigma_w$ [Comas and Slater, 2004].

Mansoor and Slater [2007] conducted SIP measurements between 0.1 and 1000 Hz on samples of organic-rich clay (C group) and peat (P group) taken from a freshwater wetland in an attempt to predict an iron content in natural soils. Applying the C-C model, they found that all the samples fit the C-C model well with a maximum root-mean-square error of 1.45 %. Moreover, they compared the normalized chargeability $m_n$ with the specific surface area derived by the tailor-made equation
accounting for a polarisable iron fraction. A linear relationship could be seen with a
correlation coefficient ($R^2$) of 0.90 and 0.74 for C group and P group respectively.
Furthermore, comparison of $m_n$ with volumetric iron concentration exhibited a clearer
linear relationship with $R^2 = 0.94$ even for both groups. It was consequently found that
$m_n$ has a possibility to predict not only a specific surface area but also an iron content of
soils.

Slater and Reeve [2002] and El-Qady et al. [2005] present the results of peatland
mapping by means of electrical and electromagnetic survey methods as well as core
borings. Slater and Reeve [2002] concluded that GPR, in spite of some limitations of
penetration depth, could detect the boundary between peat and underlying organic-rich
lake sediment at the depth of about 5 m. Additionally, chargeability was a better
indicator of peat thickness than conductivity in terms of survey resolution. El-Qady et al.
[2005] also appreciated chargeability obtained from IP measurement as a clearer
characteristic than resistivity to distinguish a peat layer, occurring with maximum
thickness of 3 m at the depth of about 12 m, from clay layers which have similar
resistivity to the peat.

2.8 Summary

There are 10 electrical models reviewed in this chapter. These are summarised in terms
of whether empirical or theoretical, modelled soil and rock, target frequency, a shape of
phase angle or conductivity as a function of frequency, and equations as shown in Table
2.2. As can be seen here, all the models are built for non-organic materials except
Comas and Slater [2004]. Hence, it is plausible for this study to follow Comas and
Slater [2004] as the closest reference model, keeping the other models in perspective.
<table>
<thead>
<tr>
<th>Model</th>
<th>Empirical / theoretical</th>
<th>Modelled soil and rock</th>
<th>Target frequency [Hz]</th>
<th>Shape of phase angle</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archie</td>
<td>Empirical</td>
<td>Sandstone</td>
<td>-</td>
<td>-</td>
<td>[ \sigma_{\text{sat}} = \sigma_N / F = \sigma_N n^w / a ] (2.18)</td>
</tr>
<tr>
<td>Cole-Cole</td>
<td>Empirical</td>
<td>Mineralised rock, sandstone</td>
<td>(10^{-2} - 10^5)</td>
<td>Freq. depend.</td>
<td>[ \sigma'(\omega) = \sigma_N \left[ 1 + m \left{ \frac{1 + (\omega \tau)^m}{1 + (1 - m)(\omega \tau)^m} \right} \right] ] (2.23)</td>
</tr>
<tr>
<td>Constant phase angle</td>
<td>Empirical</td>
<td>Shaly sand, silt and clay</td>
<td>(10^{-2} - 10^5)</td>
<td>Freq. independ.</td>
<td>[ \sigma'(\omega) = \sigma_n (i\omega)^{1-\phi} ] (2.24)</td>
</tr>
<tr>
<td>Generalised Cole-Davidson</td>
<td>Empirical</td>
<td>Glass beads with clay</td>
<td>(10^{-3} - 10^3)</td>
<td>Freq. depend.</td>
<td>[ Z(\omega) = R_0 \left[ 1 - m \left{ \frac{1}{[1 + (\omega \tau)^m]} \right} \right] ] (2.29)</td>
</tr>
<tr>
<td>Madden-Marshall</td>
<td>Theoretical</td>
<td>Membrane polarisable rock</td>
<td>(10^{-2} - 10^3)</td>
<td>Freq. depend.</td>
<td>[ Z = \frac{\Delta L}{U_{\rho} CF} \left{ t_1 + \frac{B}{A} n^w + \frac{X_1 S_1}{(t_{e})^2 t_1 + \text{tanh} X_1} \left[ \frac{4 X_1 S_1}{B t_{e}^2 (t_{e})^2 \text{tanh} X_1} \right] \right} ] (2.30)</td>
</tr>
<tr>
<td>Bruggeman-Hanai-Sen</td>
<td>Theoretical</td>
<td>Grained soil and rock</td>
<td>-</td>
<td>-</td>
<td>[ \sigma' = \sigma_n^w \left( \frac{1 - \sigma'_n / \sigma'}{1 - \sigma_n / \sigma'} \right) ] (2.31)</td>
</tr>
<tr>
<td>EDL-based S-model &amp; D-model</td>
<td>Theoretical</td>
<td>Membrane polarisable shaly sand</td>
<td>(10^{-3} - 10^{4})</td>
<td>Freq. independ.</td>
<td>[ \rho'(\omega) = \rho_0 \left[ 1 - \eta_i \left{ \frac{1}{[1 - \exp(-2(i\omega)^{1/2})]} \right} \right] ] (2.32)</td>
</tr>
<tr>
<td>Lesmes &amp; Morgan</td>
<td>Theoretical</td>
<td>Sedimentary rock</td>
<td>(10^{4} - 10^{8})</td>
<td>Freq. independ.</td>
<td>[ \rho'(\omega) = \rho_0 \left[ 1 - \eta_i \left{ \frac{1}{[1 - \exp(-2(i\omega)^{1/2})]} \right} \right] ] (2.32)</td>
</tr>
<tr>
<td>Short narrow pore</td>
<td>Theoretical</td>
<td>Sieved clean sand</td>
<td>-</td>
<td>Freq. depend.</td>
<td>[ \sigma^* = \sigma_n^w + i\sigma'_n = \frac{1}{F} (\sigma_c + BQ) + i\frac{2Q}{F_n} ] (2.37)</td>
</tr>
<tr>
<td>Vinegar-Waxman</td>
<td>Theoretical / empirical</td>
<td>Shaly sand</td>
<td>(1 - 10^3)</td>
<td>Freq. independ.</td>
<td>[ \sigma_{\text{water-surf}} = \sigma_c^w + i\sigma'_n ] (2.37)</td>
</tr>
<tr>
<td>Comas and Slater</td>
<td>Empirical</td>
<td>Peat</td>
<td>(10^{-1} - 10^3)</td>
<td>-</td>
<td>[ \sigma_{\text{peat}}(\omega) = \sigma_{\text{el}} + \sigma_{\text{surf}}(\omega) = A \sigma_n^w + C \sigma'_n ] (2.45)</td>
</tr>
</tbody>
</table>
3 METHODOLOGY OF MEASUREMENT

3.1 Description of new cell

The hybrid Rowe cell is a new apparatus functioning not only as a Rowe cell but also as an electrical capacitor. A schematic diagram and a photo are shown in Figure 3.1. The parts indicated in round brackets were not mounted for this study. The cell makes it possible to correlate the electrical properties of a sample with its physical, mechanical and hydrological properties by measuring them simultaneously on the same sample.

The Rowe cell, developed by Professor P. W. Rowe at Manchester University, has many advantages over the conventional oedometer apparatus when performing consolidation tests on low-permeability soils, including non-uniform sediments [Head 1986]. The main advantages are the hydraulic loading system, the control facilities and the capability of testing large samples. In this thesis, the description of this part does not go in detail because the new cell was not used as a Rowe cell in this study.

Another function of the cell is to act as a capacitor to achieve measurements of electrical properties. As can be seen in Figure 3.1, a sample that fills in the cell is constricted by two porous plates at the top and bottom of the sample. The top plate moves up and down by pushing/pulling the hollow drainage spindle or inflating/deflating the diaphragm with air or water. For the experiments in this study, the back pressure valve through the flexible lead (at the top) and the pore pressure valve through the drainage tube (at the bottom) are used to apply/discharge water into the sample through the porous plates.

The apparatus employs a four-electrode system. Two circuits are printed with copper (Cu) on the surface of each plate as they inter-finger with each other as shown in Figure 3.2. Each circuit works as a current electrode or a voltage electrode, thus it can be considered as the analogue of electrode coordinates for a field resistivity measurement like the dipole-dipole and the Schlumberger configurations. This works very effectively to eliminate interfacial impedance between the electrodes and the sample in the cell. Because the current transport mechanism changes from electrolytic to electronic at the electrode-sample interface, it produces apparent increase in impedance with decreasing frequency and this is a source of noise. This spurious phenomenon is known as electrode polarisation [Vinegar and Waxman, 1984; Olhoeft, 1985; Vanhara and Soininen, 1995; Lesmes and Friedman, 2005], which is different concept from the polarisation explained in 2.5.

The cell is made of polyvinyl chloride (PVC). Since the electrical resistivity of PVC is about $10^{12}$ to $10^{14}$ [Ωm], which is similar to that of air, the cell hardly works as a short circuit between the two electrodes.
Photographs taken before the assemblage of the cell are shown in Appendix 1. Besides, the comparison between the new cell and a similar experimental set-up developed by others is discussed in 5.2. Next sections present the whole experimental system including the component analyser needed to input and measure currents and voltages.
3.2 Experimental set-up and electrical model

The experimental set-up is shown in Figure 3.3. It mainly consists of four elements: a water tank, a drain receptacle, a component analyser and the cell, which has already been described in the previous section.

The water tank is used not only for storing but also regulating the conductivity of water with sodium chloride (NaCl), which was measured by an electrical conductivity meter. The water tank is placed at a higher level than the cell base to make use of a gravity gradient. The water is applied from the bottom of the cell. As the electrode plates are regularly perforated with tiny holes, the applied water uniformly permeates into (or drain out from) the sample. The discharging water is stored in a drain receptacle to monitor its conductivity. Besides, the discharge rate is measured with a stopwatch.

The electrodes are connected to a precision component analyser (6440A, Wayne Kerr Electronics Ltd.) in order to apply an electric current and to measure the electrical properties of the sample in the cell. This instrument can operate in the frequency range from 20 Hz to 3 MHz and accept arbitrary multi-frequency steps. In this study, 56 steps were arbitrarily set, which were evenly distributed within the frequency range. The drive level in AC measurements is maintained at constant input voltage and current by the automatic level control (ALC). Also, any of the following parameters can be measured regardless of series or parallel circuit: capacitance (C), resistance (R), impedance (Z) and phase angle (φ). Further information about the component analyser can be checked in Appendix 2.

The electrical model assumed in this study is equal to an equivalent circuit consisting of a conductive (resistive) and a capacitive element in parallel, as shown in Figure 3.4. The conductive element represents the summation of the conduction through
free electrolyte in the pores ($\sigma_{el}$) and through the EDL ($\sigma'_{surf}$) in the sample. The capacitive element is attributed to a polarisation effect of ions (or energy storage) in the EDL ($\sigma'_{surf}$). The resistance and the capacitance of the sample are measured by the instrument. The resistance can be considered not to be affected by ambient noise because the cell hardly works as a short circuit between the two electrodes as mentioned in 3.1. In reality, however, the measured capacitance includes a residual capacitance ($C_{res}$) as well, due to the apparatus (electrodes) or background noise, which acts in parallel with the sample capacitance as shown in Figure 3.4. An analysis of $C_{res}$ to determine its magnitude as a function of frequency and the reliable range of the measurements is shown in 4.1.1. For the range of frequency in which $C_{res}$ has a small influence, the electrical model for the experiments can be expressed as shown in Equation (2.41) to (2.43) after Comas and Slater [2004] in 2.7. It means that the real part of the conductivity of the system is the summation of $\sigma_{el}$ and $\sigma'_{surf}$, while the imaginary part of the conductivity of the system is solely determined by $\sigma''_{surf}$.
3.3 Data analysis method

As mentioned in 3.2, the data measured from this system are the capacitance and the resistance of the sample. From these two measured values, the real part of conductivity, the phase shift and the imaginary part of conductivity can be derived. Firstly, these parameters are analysed as a function of frequency. Besides, the complex impedance planes are drawn in order to find into which type of model the measured data can be classified. Secondly, the real and the imaginary parts of conductivity are analysed as a function of the conductivity of the pore water in the peat sample in order to define the relationship between the two and compare it with Figure 2.15 by Comas and Slater [2004].

The distance between the electrodes and the cross-sectional area of the specimen are known. Then, the real part of the conductivity of the specimen can be expressed as:

$$\sigma' = \frac{1}{R_{\text{mea}}} \frac{d}{A} = 1/\rho', \quad (3.1)$$

where

- $\sigma'$ = real part of conductivity [S/m],
- $\rho'$ = real part of resistivity [Ohm-m],
- $R_{\text{mea}}$ = measured resistance [Ohm],
- $d$ = distance between electrodes [m] and
- $A$ = cross-sectional area of specimen [$m^2$] = 0.0172.

The total impedance of the system is expressed as follows because the components are assumed in this study to be connected in parallel as shown in Figure 3.5:

$$\frac{1}{Z_{\text{tot}}} = \frac{1}{Z_R} + \frac{1}{Z_C}. \quad (3.2)$$
Then,\[Z_{tot} = \frac{Z_R Z_C}{Z_R + Z_C}, \quad (3.3)\]

where \(Z_{tot}\) = total impedance of the system [Ohm],
\(Z_R\) = resistor impedance [Ohm] and
\(Z_C\) = capacitor impedance [Ohm].

![Parallel circuit with resistor and capacitor.](image)

**Figure 3.5** Parallel circuit with resistor and capacitor.

The impedances of the resistor and the capacitor are expressed as follows:
\(Z_R = R_{mea}\) and \(Z_C = \frac{1}{i \omega C_{mea}}, \quad (3.4)\)
\(Z_C = \frac{1}{i \omega C_{mea}}, \quad (3.5)\)

where \(C_{mea}\) = measured capacitance [F],
\(\omega = \) angular frequency [Hz] = \(2\pi f\) and
\(i = \) imaginary unit = \(\sqrt{-1}\).

Substituting Equation (3.4) and (3.5) into (3.3), and transforming it into the style as Equation (2.10),
\[Z_{tot} = \frac{R_{mea}}{1 + R_{mea}^2 \omega^2 C_{mea}^2} + \frac{-R_{mea}^2 \omega C_{mea}}{1 + R_{mea}^2 \omega^2 C_{mea}^2} i. \quad (3.6)\]

The real and the imaginary parts of the impedance are called calculated resistance \((R_{cal})\) [Ohm] and calculated reactance \((X_{cal})\) [Ohm] respectively. In polar form, the phase shift \(\theta\) [radian] is expressed as:
\[\theta = \arctan \left(\frac{X_{cal}}{R_{cal}}\right) = \arctan \left(-\frac{R_{mea} \omega C_{mea}}{1 + R_{mea}^2 \omega^2 C_{mea}^2}\right) = \arctan \left(-2\pi f R_{mea} C_{mea}\right). \quad (3.7)\]

According to Equation (2.7), the imaginary part of the conductivity \(\sigma''\) [S/m] can be given as:
\[\sigma'' = \sigma' \tan \theta. \quad (3.8)\]
3.4 Sample description and preparation

The samples prepared for the experiments are water and peat. The water is initially distilled and NaCl is added to increase its salinity and consequently to regulate the water conductivity to a desired value. The water is not degassed.

Peat samples were collected in the testing field of Ijkdijk (Groningen) from a layer of 1 to 2 metres in thickness, situated under a superficial layer of clay of about 1 metre and over a sand layer. It has been carefully preserved in a climate room at 10°C to avoid degradation. The peat characteristics in Table 3.1 were acquired according to the von Post classification in Appendix 3 and concern the peat collected in the sampling site, though not directly the peat used in the experiments. The electrical conductivity of the pore water in the peat was obtained from the water drained out of the peat sample during a consolidation test.

The peat samples are remoulded. The peat is mixed with distilled water, after removing relatively large remnants of plants.

<table>
<thead>
<tr>
<th>Humification</th>
<th>H₇</th>
<th>Wet unit weight</th>
<th>10.5 kN/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic content</td>
<td>N₂</td>
<td>Dry unit weight</td>
<td>1.69 kN/m³</td>
</tr>
<tr>
<td>Wood and shrub</td>
<td>W₆₅, N₀</td>
<td>Specific gravity of solid</td>
<td>1.42</td>
</tr>
<tr>
<td>Smell</td>
<td>A₂</td>
<td>Void ratio</td>
<td>7.23</td>
</tr>
<tr>
<td>Acidity</td>
<td>pH₀</td>
<td>Porosity</td>
<td>0.878</td>
</tr>
<tr>
<td>Plasticity</td>
<td>P₀</td>
<td>Saturation degree</td>
<td>0.968</td>
</tr>
<tr>
<td>Water content</td>
<td>B₂ (4.93 (w₆₅/w₆₅))</td>
<td>Electrical conductivity of pore water</td>
<td>0.119 S/m</td>
</tr>
</tbody>
</table>

3.5 Experimental procedure

3.5.1 Calibration with water

As mentioned in 3.2, measurements are always influenced by ambient noises caused by the cell, the electrodes, the cables and external disturbances, acting in parallel with the true capacitance of samples. Thus, two different tests are done on water in order to calibrate the system and to find the frequency range in which the magnitude of the adverse effects is substantially reduced. In the first series of tests, the conductivity of water is kept constant while the distance of the electrodes changes (distance-control). In the second series of tests, the distance is kept constant while the conductivity of water changes (conductivity-control).

The procedure for the distance-control test is as follows; after closing the cell, the
top electrode is fixed at a predetermined height (distance to the bottom electrode). Then, distilled water is applied from the water tank. The conductivity of the water measured at the drain receptacle was 0.9 to 1.0 mS/m. This slightly high conductivity for true distilled water is the result of several circulations of the water through the entire set-up, which were required to make the drained water conductivity stable. It would have been caused by micro particles of metals and dust within the set-up. Subsequently, the capacitance and the resistance are measured a few times by the component analyser. When consistent data is measured, the distance between the electrodes is changed to the next predetermined step and measurements are done again. The predetermined distances between the electrodes are 6 to 10 cm at intervals of 1 cm, i.e. the cycle is iterated 5 times.

Regarding the conductivity-control test, the procedure is as follows; after closing the cell, the distance between the electrodes is fixed at 6.0 cm. Then water is applied, with a conductivity which has been regulated to a predetermined value in the water tank. The water should be circulated to bleed air inside the cell. When the conductivity of the water-in and the water-out becomes consistent, the capacitance and the resistance are measured a few times by the component analyser. After constant data are measured, the conductivity of the water is changed to the next predetermined step and the water is circulated again until the conductivity of the water-in and the water-out becomes constant. Subsequently, the capacitance and the resistance are once again measured a few times by the component analyser. The predetermined conductivities of the water are 0.01, 0.1, 1 and 10 S/m, i.e. the cycle is repeated 4 times.

3.5.2 Tests on peat

A conductivity-control test has been performed for three peat samples. First, the sample is prepared as mentioned in 3.4 and then manually placed in the cell, putting paper filters on the surface of the perforated plates (electrodes). When the thickness of the sample has reached 6.5 cm, the cell is closed. Air should not be trapped within the cell. The top electrode is lowered until it is in contact with the surface of the sample, and fixed. No load is applied on the peat. The conductivity of water is then regulated to a certain value in the water tank, and afterwards the water is circulated. Although drainage was done from the top of the cell for the second and third sample, it was done from the bottom of the cell for the first sample. The discharge rate is roughly measured to estimate the hydraulic conductivity of the sample until the conductivity of the water-out becomes constant. The capacitance and the resistance are measured a few times by the component analyser when the conductivity of the water-out approaches asymptotically to a constant value. After stable data is measured, the conductivity of the
water is changed to the next target and the water is circulated again until the conductivity of the water-out becomes constant. Subsequently, the capacitance and the resistance are once again measured a few times by the component analyser. Although the exact target water conductivity for the measurements was not determined in advance, the process was repeated several times in order to collect as many data as possible within the conductivity range between 0.001 S/m and 1 S/m, which is similar to that of Comas and Slater [2004]. After the measurements, the weight and the volume of the wet samples are immediately measured. The dry weight of the sample is also measured after drying in an oven for 24 hours at 105 °C [Skempton and Petley, 1970] in order to calculate the water content ($w_{\text{water}} / w_{\text{solid}}$) and the unit weight of the wet and the dry sample.
4 RESULTS AND DATA ANALYSIS

4.1 Calibration with water

4.1.1 Distance-control test

All the raw and processed data sets are plotted in Appendix 4. The appendix gives a table containing all the parameters measured and calculated as a function of frequency. The distances between the electrodes increases in a vertical direction and the parameters are arranged in the horizontal direction of the table. The distances were fixed at 6, 7, 8, 9 and 10 cm. Regarding the graphs of measured capacitance $C_{mea}$ and resistance $R_{mea}$, three measurements and their average are reported and labelled in the legend as “a”, “b”, “c” and “Ave” respectively. The conductivity of water in the drain receptacle was measured at every step and was consistently between 0.9 and 1.0 mS/m. The measured capacitance and resistance as a function of the frequency are shown in Figure 4.1. The distances indicated in the legend are expressed in metre and every measurement is plotted in the graphs. As expected, the larger the distance is, the smaller the resistance is. The capacitance does not change so much though it also depends on the distance. The proportional relation between $C_{mea}/R_{mea}$ and the electrodes distance is shown in Figure 4.2. The legend expresses the frequency of input currents in Hertz.

A peculiar phenomenon is observed in Figure 4.1; the capacitance rapidly increases in the low frequency range, whilst the resistance decreases in the high frequency range. This phenomenon might be induced by the residual capacitance ($C_{res}$) of the system because the capacitance and the resistance should be constant over the entire frequency for water [Stacheder et al. 2005]. Therefore, the accuracy of the data is examined by comparing the measured capacitance with the theoretical capacitance of water.

Figure 4.1 Plots of measured capacitance (left) and resistance (right).
Hybrid Rowe Cell for Measurement of Complex Conductivity

The theoretical capacitance of the water can be calculated by the equation below:

\[ C_{\text{theo}} = \varepsilon_0 \varepsilon_{r,w} \frac{A}{d} \]  

(4.1)

where \( C_{\text{theo}} \) = theoretical capacitance [F],
\( \varepsilon_0 \) = permittivity of free space [F/m] = \( 8.854 \times 10^{-12} \),
\( \varepsilon_{r,w} \) = relative permittivity of water [F/m] = 80 (20 °C),
\( A \) = area of electrode [m²] = 0.0172 and
\( d \) = distance between electrodes [m].

The relative error of the capacitance is expressed as:

\[ \text{err} = \frac{C_{\text{res}}}{C_{\text{mea}}} \]  

(4.2)

where \( \text{err} \) = relative error of capacitance [-],
\( C_{\text{res}} \) = residual capacitance = \( C_{\text{mea}} - C_{\text{theo}} \) and
\( C_{\text{mea}} \) = measured capacitance.

The comparison between the measured and the residual capacitance, and the relative error of the capacitance plotted as a function of the frequency are shown in
Figure 4.3. As shown here, the error is fairly low and stable in the frequency range of 10 kHz to 600 kHz, while it is significant in the other frequency range. Therefore, the reliable frequency range in which $C_{res}$ has a small influence on the measurements can be determined to be about from 10 kHz to 600 kHz.

![Capacitance and Error Graphs](image)

Next, the real part of conductivity calculated as a function of the frequency is shown in both semi-logarithmic and double logarithmic scale in Figure 4.4, which is compared to the measured one (1.0 mS/m) at the drain receptacle. As can be seen here, all the data sets are consistent and close enough to the measured one until the frequency of about 600 kHz. Thus, it can be said that the new cell is able to measure the right resistance of samples in the frequency range below 600 kHz. The abrupt increase above 600 kHz results from the decrease of the measured resistances (see Figure 4.1).

![Conductivity Graphs](image)

Finally, three graphs; phase angle and the imaginary part of conductivity as a function of the frequency, and the complex impedance plane are shown in Figure 4.5.

![Graphs](image)
The trends of the phase angle and the complex impedance plane mean that the water in this circuit behaves as a capacitor [Brandes, 2005]. In addition, Blewett et al. [2003] presents a typical complex impedance response of clay slurry, suggesting a manifestation of electrode polarisation or spurious impedance at electrode/soil interface in low frequency range. The response is not observed in this case; therefore this indicates that electrode polarisation did not occur. This is elaborated in 5.2.

Because the phase starts lagging from the frequency of about 300 Hz, the polarisation of the water starts from this frequency. The capacity of the energy storage is constantly small until about 100 kHz (phase shift $\approx -34^\circ$) according to the imaginary part of conductivity. Subsequently, it grows exponentially; however, the behaviour above 600 kHz is not reliable.

![Figure 4.5 Phase angle (upper left), its close-up in phase angle (upper right) and imaginary part of conductivity (lower left) as a function of frequency, and complex impedance plane (upper right).](image)

**Figure 4.5** Phase angle (upper left), its close-up in phase angle (upper right) and imaginary part of conductivity (lower left) as a function of frequency, and complex impedance plane (upper right).

### 4.1.2 Conductivity-control test

All the raw and processed data sets are plotted in Appendix 5. The appendix gives a table containing all the parameters measured and calculated as a function of frequency. The conductivity of the water in samples increases in a downward direction, and the parameters are arranged in a horizontal direction of the table. Regarding the graphs of
measured capacitance $C_{mea}$ and resistance $R_{mea}$, three measurements and their average are reported and labelled in the legend as “a”, “b”, “c” and “Ave” respectively. The distance between the electrodes was fixed at 6.0 cm. The water for the tests was prepared at four different conductivities: 0.0149, 0.1018, 0.993 and 4.87 S/m. As can be seen in Appendix 5, the data obtained from the higher two conductivity steps show an anomalous behaviour. While there are no clear reasons, it might be attributed that the last two conductivities are too high for the apparatus to measure true properties. Thus, the other two sets are only discussed here.

The measured capacitance and resistance as a function of the frequency are shown in Figure 4.6. The unit of the legend is expressed in Siemens per metre (S/m) and every measurement is plotted in the graphs. As expected, it shows that the larger the water conductivity is, the smaller the measured resistance is. An unusual phenomenon is observed that the capacitance rapidly decreases and goes negative in the frequency range less than 300 Hz. The capacitance should remain positive unless the sample functions as an inductor. Another unexpected behaviour is observed that, in the frequency range more than 100 kHz, the trend of the resistance measured for the water with a conductivity of 0.0149 S/m is opposite to that for the water with a conductivity of 0.1018 S/m. In addition, the frequency at which the resistance start deflecting from its constant value becomes smaller with the increase of the conductivity. In the intermediate frequency range (300 Hz – 100 kHz), both values are stable. This result is consistent with the result of the distance-control test.

![Figure 4.6](image)

**Figure 4.6** Measured capacitance (left) and resistance (right). Arrows show the point at which the resistance starts deflecting from its constant value.

Next, the real part of the calculated conductivity is shown as a function of the frequency in Figure 4.7. The measured conductivity at the drain receptacle is also shown. As can be seen here, all the data sets are consistent and close enough to the measured one except for the frequency range above 100 kHz. The frequency at which
the conductivity starts deflecting from its constant value becomes smaller with the increase of the conductivity as the same as the resistance. Thus, it can be said again that the new cell is able to correctly measure the conductivity of the samples, though the reliability of the data is low above 100 kHz.

![Figure 4.7](image)

**Figure 4.7** Real part of conductivity compared to measured one in semi-log (left) and double log (right) scale. Arrows show the point at which the resistance starts deflecting from its constant value.

Finally, the phase angle and the imaginary part of conductivity as a function of the frequency, and the complex impedance plane are shown in Figure 4.8. The trends of the phase angle and the complex impedance plane for the water of $\sigma_w = 0.0149$ S/m mean that the sample in the circuit behaves as a capacitor. However, for the water of $\sigma_w = 0.1018$ S/m, the sample in the circuit acts like a “negative” capacitor [Brandes, 2005]. Besides, there is no indication of electrode polarisation or spurious impedance at electrode/soil interface in the complex impedance response [Blewett et al. 2003]. According to the phase and the imaginary part of conductivity, it can be said that the polarisation effect does not take place until the frequency of about 2 kHz.
4.1.3 Summary

The distance-control test reveals the influence of the residual capacitance on the measurement. By examining the relative error of the residual capacitance over the measured capacitance, the reliable frequency range for capacitance measurements are determined to be from 10 kHz to 600 kHz. Observation of the real part of conductivity also suggests that the new cell can measure the right conductivity until about 600 kHz. Regarding the conductivity-control test, the behaviour of the real part of conductivity shows that the reliable frequency range for the measurements is from 300 Hz until 100 kHz up to the conductivity of 0.1018 S/m. However, the frequency at which the resistance or the conductivity starts deflecting from its constant value becomes smaller with the increase of the conductivity. In conclusion, the reliable frequency range for the measurement of capacitance and resistance on the water with this experimental set-up is determined to be 10 kHz to 100 kHz up to the conductivity of 0.1018 S/m.

In addition, the complex impedance plane demonstrates that no electrode polarisation takes place in the measurements with the new cell.

It is also observed that the water with the conductivity of 0.1018 S/m behaves as a negative capacitor, whilst the water with the conductivity of 0.0149 S/m acts like a
positive capacitor. The new cell could not measure true properties of the water of 0.993 and 4.87 S/m. It might be caused by too high conductivity for the apparatus to measure.

4.2 Tests on peat

4.2.1 Properties of the samples

The properties of all the three peat samples are shown in Table 4.1. They were measured and calculated after the test, considering a specific solid gravity for peat of 1.42 obtained with a pycnometer. The samples were remoulded to increase the consistency of the data set; the properties of the three samples are different from those of the “intact” material given in Table 3.1, and show a low variability.

<table>
<thead>
<tr>
<th></th>
<th>Peat 1</th>
<th>Peat 2</th>
<th>Peat 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content ((w_{water} / w_{solid}) [-])</td>
<td>9.18</td>
<td>9.02</td>
<td>8.75</td>
</tr>
<tr>
<td>Wet unit weight ([kN/m^3])</td>
<td>10.7</td>
<td>10.8</td>
<td>10.0</td>
</tr>
<tr>
<td>Dry unit weight ([kN/m^3])</td>
<td>1.05</td>
<td>1.08</td>
<td>1.02</td>
</tr>
<tr>
<td>Void ratio [-]</td>
<td>12.3</td>
<td>11.9</td>
<td>12.6</td>
</tr>
<tr>
<td>Porosity [-]</td>
<td>0.925</td>
<td>0.922</td>
<td>0.926</td>
</tr>
<tr>
<td>Saturation degree [-]</td>
<td>1.00</td>
<td>1.00</td>
<td>0.987</td>
</tr>
</tbody>
</table>

4.2.2 Measurement steps and its conductivities

As mentioned in 3.5.2, the target range for water conductivity is 0.001 to 1 S/m and many steps were performed in order to collect data thoroughly within the range. The sequence of conductivities adopted for each peat sample is indicated in Table 4.2. The numbers of measurement steps were 17, 10 and 19 for Peat 1, 2 and 3 respectively, i.e. 46 steps in total.

Figure 4.9 illustrates the measurement steps indicated in Table 4.2. The water applied at the beginning of the measurements was distilled water. It was continuously applied until step 4 for Peat 1 and 3, and until step 2 for Peat 2. After that, the water was regulated by adding NaCl.

According to Figure 4.10, it can be also said that the measurements were evenly spread over the target frequency, though data from 0.01 to 0.02 S/m are somewhat scarce. It was impossible to reach conductivities below 0.002 S/m because of the initially high electrical conductivity (0.119 S/m as mentioned in 3.4) and low hydraulic conductivity of peat (see 4.2.3).
Table 4.2  Sequence of conductivities and number of steps

<table>
<thead>
<tr>
<th>Conductivities of water [S/m]</th>
<th>Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat 1</td>
<td></td>
</tr>
<tr>
<td>0.122 → 0.087 → 0.051 → 0.018 → 0.121 → 0.177 → 0.211 → 0.235 → 0.26 → 0.375 → 0.469 → 0.568 → 0.652 → 0.766 → 0.857 → 0.97 → 1.02</td>
<td>17</td>
</tr>
<tr>
<td>Peat 2</td>
<td></td>
</tr>
<tr>
<td>0.117 → 0.086 → 0.218 → 0.314 → 0.408 → 0.515 → 0.619 → 0.713 → 0.808 → 0.933</td>
<td>10</td>
</tr>
<tr>
<td>Peat 3</td>
<td></td>
</tr>
<tr>
<td>0.00244 → 0.00268 → 0.00288 → 0.00361 → 0.00409 → 0.00619 → 0.00811 → 0.01005 → 0.023 → 0.035 → 0.05 → 0.064 → 0.07 → 0.099 → 0.15 → 0.198 → 0.302 → 0.465 → 0.545</td>
<td>19</td>
</tr>
<tr>
<td>Sum</td>
<td>46</td>
</tr>
</tbody>
</table>

Figure 4.9  Relationship between step and conductivity.

Figure 4.10  Distribution of measured conductivities in log scale.

4.2.3 Duration of sample saturation

During the test on Peat 3, the electrical conductivity of drained water and its discharge rate were continuously recorded. The discharge rate was used for rough calculation of hydraulic conductivity. The representative head for the calculation was approximately determined with the mean value of the initial and final head of one measurement, as it was not kept constant like during a constant head permeability test.
Figure 4.11 shows the trend of the hydraulic conductivity of Peat 3 in the left vertical axis and the electrical conductivity of the drained water in the right vertical axis in chronological order. The “s_w applied”, “s_w drained” and “s_w measured” are referred to as the conductivity of the applied water, drained water and that at which the electrical properties were measured, respectively. As mentioned above, distilled water was initially applied and it took about 2 days to reach the lowest conductivity ($\sigma_w = 0.00244 \text{ S/m}$). It totally took about 8 days to arrive at the last step ($\sigma_w = 0.545 \text{ S/m}$). As shown here, the electrical measurements were conducted when the conductivity of the drained water had approached that of the applied water.

Meanwhile, the hydraulic conductivity shows an interesting behaviour. It asymptotically declines after some time; however, it comes back to its initial or even becomes higher value after few days’ interruptions. Although there are no strong clues, this behaviour might be explained by the fact that the water was applied while the drainage valve was closed, giving rise to high pore water pressure in the sample, and then the hydraulic conductivity apparently rises immediately after opening the drainage valve. The hydraulic conductivity asymptotically approaches to about $2.0 \times 10^{-7} \text{ m/s}$.

The bottom figure in Figure 4.11 shows a close-up from 10:00 on 20th of May to 16:00 on 22nd of May to better illustrate the observations. Subsequent to the application of the water of $\sigma_w = 0.2$ and 0.262 S/m at 10:30 and 13:15 respectively, the measurement was done at 21:03 at $\sigma_w = 0.198 \text{ S/m}$. Then the water of $\sigma_w = 0.357 \text{ S/m}$ was applied and the drainage valve was closed at 21:12. The hydraulic conductivity was $2.46 \times 10^{-7} \text{ m/s}$ at that time. One and a half days later, the valve was opened applying the water of $\sigma_w = 0.37 \text{ S/m}$ at 8:44, 22nd of May. The hydraulic conductivity and the electrical conductivity had increased to $1.17 \times 10^{-6} \text{ m/s}$ and 0.220 S/m respectively. The former increase might be caused by excess pore water pressure in the sample as mentioned above. The latter slight increase might result from ionic diffusion in the sample. Afterwards, the measurement was done at 10:20 at $\sigma_w = 0.302 \text{ S/m}$. The hydraulic conductivity had already declined to $6.82 \times 10^{-7} \text{ m/s}$.

Comas and Slater [2004] have found that the vertical hydraulic conductivity of peat has a power law dependence on the conductivity of the fluid inside the peat from 0.01 S/m to 1 S/m. In other words, the vertical hydraulic conductivity of the peat samples is linearly related to the fluid conductivity in the samples from 0.01 S/m to 1 S/m on a log-log plot. They have concluded that the behaviour can be attributed to the concept of dilation of pores in peat with increasing NaCl concentration due to the interaction of ions with the organic functional groups as proposed by Ours et al. [1997]. However, such behaviour was not observed in this study. For instance, the hydraulic conductivity decreases as the electrical conductivity of water increases from 18th to
20th of May. Clogging of the paper filters and/or the electrodes porous plates with fine particles from the sample might occur, though there is no evidence of such clogging. It appears certain that the hydraulic conductivity of the perforated electrodes with paper filters is much higher than the peat samples.

Figure 4.11   Trends of hydraulic conductivity of Peat 3 and electrical conductivity of water with time.
4.2.4 Analysis of parameters as a function of frequency

All the results from the tests on Peat 1, 2 and 3 are shown in Appendix 6, 7 and 8 respectively. Each appendix gives a table containing all the parameters measured and calculated as a function of frequency. The conductivity of the water in samples increases in a vertical direction, and the parameters are arranged in a horizontal direction of the table. Regarding the graphs of measured capacitance \( C_{\text{mea}} \) and resistance \( R_{\text{mea}} \), three measurements and their average are reported and labelled in the legend as “a”, “b”, “c” and “Ave” respectively. Following sections are discussed based on these Appendixes.

4.2.4.1 Different behaviour of resistance

When all the results are briefly examined, it is found that there are mainly two behaviours in the measured resistance. At lower conductivity of water, the resistance gently declines with the frequency and suddenly goes down at the frequency of about 100 kHz. At higher conductivity of water, it slightly declines or is constant until the frequency of about 100 kHz and abruptly increases at higher frequency. The sudden decrease and increase at high frequency above 100 kHz were also seen in the result of the conductivity-controlled test on water.

When the data of Peat 3 is analysed, smooth transition from the first to the second behaviour can be observed and the threshold between the behaviour as a positive and a negative capacitor [Brandes et al. 2005] would appear between 0.35 S/m and 0.50 S/m. From this threshold, the phase and the reactance start shifting towards positive, and the imaginary part of conductivity starts turning to negative at the conductivity in high frequency range above 100 kHz, which is the case for the test on water as well.

4.2.4.2 Relationship between calculated and measured conductivity

The relationship between the calculated real part of the conductivity of peat samples (\( \sigma' \) or sigma’) and the conductivity of the fluid measured from the water discharged into the drain receptacle (\( \sigma_w \) or sigma_w) presents an interesting behaviour. The relationship for Peat 1 and Peat 2 shows that the conductivity of water is always higher than that of the peat samples as shown in Appendix 6 and 7. However, it is observed in the result of Peat 3 that the relationship is the opposite when the conductivity of water is equal to 0.01005 S/m or less than that as can be seen in Appendix 8.

To highlight this observation, the relative difference between \( \sigma_w \) and \( \sigma' \) is taken at the frequency of 10 kHz and is plotted as a function of \( \sigma_w \) as shown in Figure 4.12. As can be seen here, the relative difference between \( \sigma_w \) and \( \sigma' \) for Peat 3 increases until \( \sigma_w = 0.023 \) S/m, whilst it becomes constant above \( \sigma_w = 0.023 \) S/m. This behaviour is discussed in 5.7. The slight discrepancy between Peat 1 and Peat 2, 3 might be
attributed to the difference in the way of applying water as mentioned in 3.5.2. The reason of this discrepancy is elaborated in 5.5.

![Figure 4.12](image)

**Figure 4.12** Relative difference between $\sigma_w$ and $\sigma'$ as a function of $\sigma_w$ at the frequency of 10 kHz.

### 4.2.4.3 Reliable $\sigma_w$ range and frequency for conductivity measurement

For Peat 1, the measured capacitance ($C_{mea}$) and resistance ($R_{mea}$) above the $\sigma_w$ of 0.766 S/m start showing an anomalous behaviour as shown in Appendix 6. For Peat 2, a similar anomalous behaviour appears at the $\sigma_w$ of 0.933 S/m in the $C_{mea}$ as shown in Appendix 7. There is not such behaviour for Peat 3 as shown in Appendix 8. The reason why the threshold of Peat 1 is less than that of Peat 2 may be attributed to the rough and hasty saturation process for Peat 1. Although sufficient data is not really available to determine a reliable $\sigma_w$ range, it can be said that it is likely to be less than 1 S/m if a peat sample is successfully and homogeneously saturated by the water.

The real part of conductivity should be calculated constant, i.e. frequency independent, based on the model in this study. Surveying it all through every peat sample in the Appendixes, it seems that a reliable frequency range is below 100 kHz as shown in Figure 4.13.
4.2.5 Analysis of real and imaginary part of conductivity as a function of conductivity of water

In this section, the relationship between the real or imaginary part of conductivity ($\sigma'$ or $\sigma''$) and the conductivity of the pore water in the samples ($\sigma_w$) are analysed after Comas and Slater [2004]. The graphs in Figure 4.14 and Figure 4.15 present $\sigma'$ and $\sigma''$ as a
function of $\sigma_w$ at 10 kHz, 50 kHz and 100 kHz respectively. The frequencies are chosen from the reliable range determined in 4.1.1, 4.1.2 and 4.2.4.3, i.e. from 10 kHz to 100 kHz. In addition to the plots, two approximation curves are fitted to the data sets: least square regression (LSR) and the empirical model proposed by Comas and Slater [2004] (C&S) given in Equation (2.45). These approximation curves are determined to make an average relative error between the plots and a curve minimum.

The LSR and C&S for $\sigma'$ is determined for only Peat 2 and Peat 3 because of the discrepancy between Peat 1 and Peat 2, 3. This is elaborated in 5.5. Since the plots are not linear in the low $\sigma_w$ range, the C&S fits closer to them than the LSR. In fact, the average relative error between the data and the LSR is about 0.16, whilst that between the data and the C&S is about 0.089. However, it is observed that there are slight differences between the data and the C&S in the high $\sigma_w$ range at 50 kHz and 100 kHz. The discrepancies can be attributed to the behaviour of $\sigma''$ because the C&S includes $\sigma''$ term in Equation (2.45) and also $\sigma''$ goes negative in high $\sigma_w$ range as shown in Figure 4.15. The regression expressions for all the graphs are summarised in Table 4.3, accompanied by the slope found by Comas and Slater [2004] which are derived from their data at 1 Hz given in Figure 2.15. In addition, the fitting curve suggested by Rikala and Heiskanen [1997] is also presented. The curve has been obtained from electrical conductivity measurements on press-water extracted from peat versus TDR (time-domain reflectometer) measurements on bulk peat. The fitting parameters of C&S are also listed in Table 4.4, together with those derived at 1 Hz by Comas and Slater [2004] as a reference.

Compared to the real part of conductivity shown in Figure 4.14, the imaginary part in Figure 4.15 shows rather dispersed images. However, a relatively linear relationship with $\sigma_w$ can be seen in the plot of Peat 3 below 0.1 S/m. Thus, the LSR for $\sigma''$ is determined by using the first 14 data of Peat 3. The average relative error between the data and the LSR is about 0.082. After the peak of $\sigma'$ around 0.1 S/m, it starts declining with increasing $\sigma_w$. This behaviour is also observed by Vinegar and Waxman [1984] on shaly sands at 30 Hz, Lesmes and Frye [2001] on sandstone at 1 to 10 Hz, Slater and Glaser [2003] on sandy unconsolidated sediments at 1 Hz and Comas and Slater [2004] on peat at 1 Hz as shown in Figure 2.16. The regression expressions for all the graphs are summarised in Table 4.3, accompanied by the slope found by Comas and Slater [2004] which are derived from the data at 1 Hz given in Figure 2.15.

As shown in Figure 4.14, there is a discontinuity in the conductivity of Peat 1 at the water conductivity of about 0.1 S/m. In addition, even the data above the boundary are slightly different from the measurement of Peat 2 and Peat 3, though the two are almost completely consistent with each other. The reason of this behaviour is discussed
in 5.5.

Figure 4.14 Real part of conductivity as a function of conductivity of water at 10 kHz (upper left), 50 kHz (upper right) and 100 kHz (lower left).
Figure 4.15  Imaginary part of conductivity as a function of conductivity of water at 10 kHz, 50 kHz and 100 kHz in double log (left) and semi-log (right) scale.
### Table 4.3  Regression expression for each graph with references.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma'$ vs. $\sigma_w$</th>
<th>$\sigma''$ vs. $\sigma_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kHz</td>
<td>$\sigma' = 0.42 \sigma_w^{0.77}$</td>
<td>$\sigma'' = 0.005 \sigma_w^{0.39}$</td>
</tr>
<tr>
<td>50 kHz</td>
<td>$\sigma' = 0.42 \sigma_w^{0.76}$</td>
<td>$\sigma'' = 0.009 \sigma_w^{0.40}$</td>
</tr>
<tr>
<td>100 kHz</td>
<td>$\sigma' = 0.42 \sigma_w^{0.75}$</td>
<td>$\sigma'' = 0.009 \sigma_w^{0.34}$</td>
</tr>
<tr>
<td>Comas &amp; Slater [2004] (1 Hz)</td>
<td>$\sigma' \propto \sigma_w^{1.3}$</td>
<td>$\sigma'' \propto \sigma_w^{0.5}$</td>
</tr>
<tr>
<td>Rikala &amp; Heiskanen [1997]</td>
<td>$\sigma' = 1.040 \sigma_w^{0.714}$</td>
<td>-</td>
</tr>
</tbody>
</table>

### Table 4.4  Fitting parameters of C&S model for Peat 1, 2 and 3 with reference parameters from Comas and Slater [2004].

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$b$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kHz</td>
<td>0.70</td>
<td>1.32</td>
<td>12</td>
</tr>
<tr>
<td>50 kHz</td>
<td>0.83</td>
<td>1.27</td>
<td>6</td>
</tr>
<tr>
<td>100 kHz</td>
<td>1.04</td>
<td>1.34</td>
<td>5</td>
</tr>
<tr>
<td>Comas &amp; Slater [2004] (1 Hz)</td>
<td>$1.29 \pm 0.07$</td>
<td>$1.42 \pm 0.05$</td>
<td>$63 \pm 5$</td>
</tr>
</tbody>
</table>
5 DISCUSSION

5.1 Introduction
As mentioned in 1.2, the purposes of this study are firstly to assess and verify the adequacy and appropriateness of the newly invented hybrid Rowe cell, and secondly to derive the relationship between the electrical conductivity of whole peat and of pore water by changing the electrical conductivity of pore water in peat. Thus, to begin with, comparison between the new cell and the other similar apparatus is made in 5.2.

Although the validity of the new cell is confirmed with respect to the electrode polarisation and lead inductance, the strange behaviours of the capacitance are observed at the low and high frequencies in the measurement range (20 Hz – 3 MHz), namely the negative capacitance and the residual capacitance. The former is examined from the point of view of input current density in 5.3. Regarding the latter, a data correction is attempted in 5.4.

It is also found during the data analysis that the sample preparation and the saturation process are significant to obtain good results. In 5.5, possible causes of the discontinuous $\sigma'$ of Peat 1 are deduced.

For the data analysis on the peat samples in 4.2.5, the model of Comas and Slater [2004] is applied for the curve fitting. However, some assumptions postulated by them are not likely to be valid for this study. Then, the modified Archie’s law are recalled and compared with the model of Comas and Slater [2004] in 5.6. Finally, the difference between $\sigma_w$ and $\sigma'$ observed in the results on the peat samples is clarified based on the applicability of the modified Archie’s law in 5.7.

5.2 Comparison between new cell and other apparatus
Some apparatus have been developed to concurrently measure physical and electrical properties of soil in laboratories. Blewett et al. [2003] measured the electrical conductivity of Kaolin slurry in vertical and horizontal directions during diffusion of NaCl and consolidation of a sample by using a Rowe cell-like apparatus. McCarter et al. [2005] measured the electrical conductivity of Kaolin slurry in vertical and horizontal directions under a load-unload-reload regime by using a Rowe cell-like apparatus. Comina et al. [2008] developed an oedometer cell accomplishing for monitoring the spatial and temporal evolution of different physical quantities inside soil samples by seismic and electric non-destructive measurements in 3D. In this section, the new cell in this study is compared with the cell of Blewett et al. [2003] because it is the closest system to the new cell.

The apparatus developed by Blewett et al. [2003] is shown in Figure 5.1. Although
it seems similar to the new cell in this study, there are some noteworthy differences between the two. Firstly, the number of electrodes in a vertical direction is 2 at the top and the bottom of the Blewett cell, whilst the new cell has 4 electrodes; 2 each at the top and the bottom. Besides, the material of electrodes is a stainless-steel wire-mesh placed on the plates for the Blewett cell, while the electrodes of the new cell are made from copper printed on the plates in an interfingering manner. When a typical impedance behaviour measured by the Blewett cell shown in Figure 5.2 is examined, it obviously shows that the measurement in low frequency is strongly affected by the electrode polarisation mentioned in 3.1. On the other hand, this behaviour is not observed in the results from the new cell as shown in Appendix 4 to 8.

Secondly, Blewett et al. [2003] discusses a lead inductive effect which progressively degrades data with increasing frequency. The effect is caused by an electromagnetic effect generated around electrical leads in the system and gives rise to an artificial behaviour of reactance as shown in Figure 5.3. Thus, Blewett et al. [2003] suggests nulling or removing the effect by a calibration algorithm developed by them; however, this effect does not also occur with the new cell. Therefore, the system including the new cell is said to be appropriate for this kind of measurements.

There are some useful features which can be fitted in the new cell. A thermistor mounted in the base of the cell is useful to directly measure temperature in the cell. Also, the electrodes mounted in the wall of the cell as shown in Figure 5.1 will be required to measure horizontal electrical properties for anisotropic samples. A point to notice is that there is a possibility to measure the electrode polarisation as mentioned above because these electrodes diametrically face each other and work as 2 pairings, i.e. 2 electrodes system.
Figure 5.1   Schematic arrangement of Rowe cell-like apparatus [Blewett et al. 2003].

Figure 5.2   (a) Typical impedance response for clay slurry measured by Blewett cell and (b) schematic impedance plot of ionically conducting porous medium [Blewett et al. 2003].
5.3 Negative capacitance

As mentioned in 4.1.2 and 4.2.4.1, unexpected behaviour of the capacitance and the related parameters are observed when the conductivity of the samples is higher than a certain value. This negative capacitance is, however, not a new phenomenon in field measurements. This phenomenon, also called negative IP, negative chargeability or positive phase shift, is observed in field measurements and its utility has sometimes been appreciated for accurate geophysical interpretation in the industry for mineral/metallic resource exploration [Rathor 1978]. On another occasion, it has been associated with an appropriate indication for subsurface hydrocarbon contamination [Weller and Börner 1996]. It has also been attributed to a geometric effect such as electrodes arrays and multiple layering structure of the earth [Souza and Sampaio 2001].

In laboratories as well, it has been measured on clay and oil-contaminated clay by Olhoeft [1985]. However, the reason is not clarified there. Patella [2008] shows a possibility to express a non-resonant negative IP model as a true physical property of rocks. His equivalent circuit consists of a single resistor in parallel with a series of a resistor and an inductor. This electrical model is different from the one assumed in this study because it includes an inductor as well.

Brandes [2005] also tried to explain the observed negative capacitance, building a model of negative chargeability of clays. Although his model, composed of a resistor and a Warburg element* in parallel, is different from the one considered in this study, an interesting point is noted: non-linear complex conductivity with respect to frequency. It should be noted that Olhoeft [1985] carried out the measurements at non-linear current densities (100 – 200 A/m²), whilst Vinegar and Waxman [1984] maintained current densities below 0.001 A/m² to avoid non-linear effects. Unfortunately, the

---

* Warburg elements are commonly used to model the effect of one-dimensional ionic diffusion processes in an electrode at low frequency on impedance measurements.
component analyser used in this study cannot adjust current manually. Therefore, this aspect could not been checked.

5.4 Data correction using data of water

In 4.1.1, the residual capacitance ($C_{res}$) is calculated using the data obtained by the distance-control tests. Given that this is a unique property for the new cell, true capacitance of the peat samples can be obtained by subtracting it from the measured capacitance ($C_{mea}$) of the peat samples.

The distance between the electrodes for the peat samples was 65 mm, whilst that for the water samples was 60 mm and 70 mm. Then, the residual capacitance for the distance of 65 mm are estimated by taking an average of the residual capacitance of 60 mm and 70 mm. Afterwards, the measured capacitance of the peat samples is subtracted by the average. However, there is hardly any difference between $C_{mea}$ and ($C_{mea} - C_{res}$) because there is a two-order difference between $C_{mea}$ and $C_{res}$. Therefore, it is presumed that $C_{res}$ significantly affects $C_{mea}$ of water but can be negligible for peat.

Here, the real and imaginary parts of conductivity and the relative permittivity as a function of frequency measured by Lesmes and Frye [2001] on the sandstone saturated with pH 8, 0.1 M NaCl solution are compared with the results of Peat 3 saturated with $\sigma_w = 0.00244$ S/m as shown in Figure 5.4. The shaded frequency range in both columns (20 Hz – 3 MHz) corresponds to the range of this study. The relative permittivity $\varepsilon_r$ of Peat 3 can be calculated by means of Equation (2.11) where $C = C_{mea} - C_{res}$, $A = 0.0172$ [m$^2$] and $d = 0.065$ [m]. As shown here, both behaviours agree to some extent, even though the left column is for the sandstone and the right column is for the peat. Particularly, the behaviour of $\varepsilon_r$ looks alike. Thus, there is a possibility that the exponential increase of the peat capacitance in the low frequency range (< 1 kHz) reflects true capacitance of the samples.

However, in addition to the fact that this study does not have sufficient data to step further, the behaviour of peat capacitance has not yet been demonstrated so much in the previous literature. Therefore, in this study, 10 to 100 kHz was designated as the reliable frequency range, in which the influence of $C_{res}$ is small on $C_{mea}$ and the resistance (or the real part of conductivity) is always constant as discussed in 4.1.1, 4.1.2 and 4.2.4.3.
5.5 Discontinuous $\sigma'$ of Peat 1

The data from Peat 1 shows different behaviour from Peat 2 and Peat 3 and is excluded from the fitting as mentioned in 4.2.4.2 and 4.2.5. The reason can be attributed to rough and hasty saturation process, and the difference in the way of applying water. In this section, this will be clarified more in detail.

For Peat 1, the first 4 data were obtained in several hours while applying distilled water from the top of the cell. When the applied distilled water dilutes and pushes down the original pore water in the sample, the conductivity of drained water should be higher than $\sigma_w$ in the cell as a certain gradient at the beginning stage is present, as shown in Figure 5.5. Therefore, if the measurement is executed when the conductivity of drained water is not stable, it does not represent $\sigma_w$ in the cell. That means that $\sigma_w$ in the cell...
would have been smaller than $\sigma_w$ measured in the drain receptacle, and could be corrected as shown in Figure 5.5. It is conversely the case for the data above $\sigma_w$ of 0.1 S/m. In the process of increasing $\sigma_w$, water in the receptacle shows lower conductivity than that in the cell. Thus the data could be shifted towards right.

This would be the case for the tests on Peat 2 and Peat 3 as well, however, the tests took a great deal of time to saturate a sample with desired water in order to make the $\sigma_w$-gradient as gentle as possible. It is considered that the time was indispensable to achieve the accurate measurements for Peat 2 and Peat 3.

![Figure 5.5 Distribution of $\sigma_w$ in the cell at the beginning stage (left) and presumable correlation of Peat 1 data (right).](image)

### 5.6 Curve fitting with modified Archie’s law

Regarding the modified Archie’s law given in Equation (2.42), based on the premise that the formation factor ($F$) and the real part of surface conductivity ($\sigma'_{surf}$) are constants at a certain frequency, Comas and Slater [2004] have suggested that the equation is not applicable to their case for two reasons. Firstly, the power law dependence of hydraulic conductivity ($K$) on pore water conductivity ($\sigma_w$) demonstrates that $F$ is no longer a constant due to the pore dilation effect. As mentioned in 2.7, Equation (2.44) manifests that $F$ is not an invariant any more when $K$ changes. Recalling the equation below:

$$K = \frac{cl^2}{F} = cl^2n^m,$$

where $c = \text{constant}$, $l_c = \text{pore space length}$, $F = \text{formation factor}$, $n = \text{porosity}$ and

$$K = \frac{cl^2}{F} = cl^2n^m,$$
$m$ = cementation factor.

As mentioned in 4.2.3, however, the measured hydraulic conductivity during the test on Peat 3 does not show such a trend that it increases with increasing pore water conductivity. Secondly, it is also postulated that the strong (compared to the sands) dependence of the imaginary part of surface conductivity ($\sigma''_{surf}$) on $\sigma_w$ indicates that it is not possible to simply ignore the complex conductivity ($\sigma^*_{surf}$) dependence on $\sigma_w$ for the organic sediments, implying that $\sigma^*_{surf}$ is also $\sigma_w$-dependent. It is possible that $\sigma^*_{surf}$ is affected by $\sigma_w$, as the EDL characteristics are known to be influenced by chemical interaction between the solid and the fluid around it. However, there are no decisive clues in this study. It can be at least said that the dependence of $\sigma''_{surf}$ on $\sigma_w$ is smaller than that in Comas and Slater [2004] as shown in Table 4.3. Moreover, the plots in Figure 4.14 show that the data with high $\sigma_w$ (above 0.05 S/m), in which $\sigma_{el}$ is much more significant than $\sigma^*_{surf}$ and the Archie’s law is valid, exhibit linear relationship between $\sigma_w$ and $\sigma^*$, whereas the data with low $\sigma_w$ (below 0.05 S/m), in which the effect of $\sigma^*_{surf}$ cannot be neglected, present non-linearity. Thus, the modified Archie’s law is suitable to evaluate the data in this study, even though the law is an empirical relation for sands entirely saturated with brine.

The modified Archie’s law is shown once again:

$$\sigma' = \sigma_{el} + \sigma^*_{surf} = \frac{\sigma_w}{F} + \sigma''_{surf},$$

(5.2)

where

- $\sigma'$ = real part of conductivity,
- $\sigma_{el}$ = electrolytic conductivity through pores in sample,
- $\sigma^*_{surf}$ = real part of surface conductivity,
- $\sigma_w$ = fluid conductivity,
- $F = $ formation factor $= a / n^m$,
- $n = $ porosity,
- $m = $ cementation factor and
- $a = $ tortuosity index.

The law is identical to the model suggested by Comas and Slater [2004] when the exponent $b$ of Equation (2.45) is equal to 1 and $\sigma^*_{surf}$ is linearly proportional to $\sigma''_{surf}$.

Since $\sigma'$ and $\sigma_w$ are known parameters, $F$ and $\sigma^*_{surf}$ can be deduced as a slope and a $y$-intercept on a linear scale graph respectively. Combined data from Peat 2 and Peat 3 are used to determine the fitting parameters because the data from Peat 1 do not match the trend of the others as mentioned in 4.2.5. Figure 5.6 compares the C&S model from Figure 4.14 with the modified Archie’s law fitting (mAl) for the same plots as Figure
4.14 at the frequency of 10, 50 and 100 kHz on a bi-log scale. The slope is estimated by
the linear portion of the data in the high water conductivity range (above 0.05 S/m). The
y-intercept is determined to make an average relative error between the plots and the
mAl minimum.

The relative error, calculated for each plot by the equation below, and the averaged
error are given in Table 5.1:

\[ e_r = \frac{\sigma' - \sigma'_{fit}}{\sigma'}, \quad (5.3) \]

where \( e_r \) = relative error,
\( \sigma' \) = real part of conductivity of peat and
\( \sigma'_{fit} \) = fitted real part of conductivity of peat.

At 10 kHz the average relative error of the C&S is smaller than that of the mAl,
while at 50 and 100 kHz the fitting curves of the mAl is closer to the plots than that of
the C&S. Nevertheless, the difference between them is not big. Therefore, it is
considered that the mAl is accurate enough to model the relationship between \( \sigma' \) and \( \sigma_w \)
in this study.

The same procedure is taken to find a slope (reciprocal of \( F \)) and an intercept for
each peat sample. A summary of the parameters is presented in Table 5.2. Since the
relationship between \( F \) and \( n \) of a sample is as the equation below and \( n \) is known for
each sample, the coefficients \( a \) and \( m \) can be obtained from curve fitting on \( F – n \)
diagrams for each frequency as shown in Figure 5.7.

\[ F = a n^m \quad (5.4) \]

where \( a \) = tortuosity index,
\( n \) = porosity and
\( m \) = cementation index.

As can be seen in Figure 5.7, there are big variances in \( a \) and \( m \) for each frequency
because there are only two variations in the sample porosity, namely Peat 2 \( (n = 0.922) \)
and Peat 3 \( (n = 0.926) \). Therefore, the data sets in this study are not sufficient to
determine the indexes. In addition, the indexes for peat have not been reported in
literature [Quinton et al. 2008] but for sand, sandstone and carbonate rock [e.g.
Worthington, 1993; Bryant and Pallatt, 1996; Kamel, 2001; Kazemzadeh et al. 2007].
Quinton et al. [2008] employed Archie’s law with \( a = 1 \) to estimate a tortuosity term in
their equation for calculating hydraulic conductivity of peat by pore size and geometry,
and found the best-fit value of \( m \) was equal to 2.3.
Figure 5.6   Comparison between C&S fitting (left) and mAl fitting (right) for Peat 2 and Peat 3 data at 10 kHz (top), 50 kHz (middle) and 100 kHz (bottom).
### Table 5.1 Average relative errors.

<table>
<thead>
<tr>
<th></th>
<th>C&amp;S</th>
<th>mAl</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kHz</td>
<td>0.066</td>
<td>&lt; 0.084</td>
</tr>
<tr>
<td>50 kHz</td>
<td>0.092</td>
<td>&gt; 0.084</td>
</tr>
<tr>
<td>100 kHz</td>
<td>0.109</td>
<td>&gt; 0.085</td>
</tr>
</tbody>
</table>

### Table 5.2 Summary of curve fitting on $\sigma'$ – $\sigma_w$ relationship.

<table>
<thead>
<tr>
<th></th>
<th>10 kHz</th>
<th>50 kHz</th>
<th>100 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat 2</td>
<td>Slope</td>
<td>0.534</td>
<td>0.528</td>
</tr>
<tr>
<td></td>
<td>y-intercept</td>
<td>$1.93 \times 10^{-3}$</td>
<td>$6.29 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>$F$</td>
<td>1.87</td>
<td>1.89</td>
</tr>
<tr>
<td>Peat 3</td>
<td>Slope</td>
<td>0.528</td>
<td>0.530</td>
</tr>
<tr>
<td></td>
<td>y-intercept</td>
<td>$7.74 \times 10^{-3}$</td>
<td>$1.03 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>$F$</td>
<td>1.89</td>
<td>1.89</td>
</tr>
</tbody>
</table>

#### Figure 5.7 Curve fitting on $F$ – $n$ relationship at 10, 50 and 100 kHz.

5.7 Difference between $\sigma_w$ and $\sigma'$

As mentioned in 4.2.4.2, the relative difference between $\sigma_w$ and $\sigma'$ increases with increasing $\sigma_w$ until $\sigma_w = 0.023$ S/m, while it becomes stable above $\sigma_w = 0.023$ S/m as...
shown in Figure 4.12. This can be explained by the modified Archie’s law.

In high solution conductivity, the law can be applied without the term concerning the real part of surface conductivity (\(\sigma'_{surf}\)) because the effect of \(\sigma_{el}\) is much more relevant than that of \(\sigma'_{surf}\). Since \(\sigma_{el}\) is a quotient of \(\sigma_w\) over \(F\) (\(\cong 1.9\) in this case), \(\sigma'\) is always smaller than \(\sigma_{w}\). In addition, the constant behaviour of the relative difference is attributed to the fact that \(\sigma'\) is predominantly dependent on \(\sigma_w\) in high solution conductivity.

On the other hand, the relative difference between \(\sigma_w\) and \(\sigma'\) shows steep slope with changing \(\sigma_w\) in low solution conductivity as shown in Figure 4.12 because \(\sigma'_{surf}\) plays an important role in \(\sigma'\) due to the fact that \(\sigma_{el}\) becomes much less, i.e. small \(\sigma_{w}\). Thus the relationship between \(\sigma_w\) and \(\sigma'\) reverses at a certain \(\sigma_w\) between 0.01005 and 0.023 S/m.
6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Peat is a soil formed mainly from a plant residue which has been partially subjected to carbonisation out of thorough biochemical humification in acidic and anaerobic condition for thousands of years. It is distributed to an area of about 3 % of the Earth’s land surface (ca. 4 million km²) and has played an important role in the biosphere. It is no exceptions for human beings. It means that humans have also enjoyed its considerable amount of benefits on one hand. On the other hand, peat has brought many problems to anthropogenic processes especially in densely populated areas like in the Netherlands. Geotechnical engineers have learnt a great deal of its peculiar characteristics; however, it is still difficult matter for humans to cope with. Although site investigations, which include both geotechnical and geophysical surveys, are usually performed in order to grasp its conditions, it is still the case that the integration between geophysical and geological data is highly empirical and requires qualitative interpretations.

This study particularly focuses on the calibration and verification of the applicability of the new hybrid cell, and the relationship between the electrical conductivities of bulk peat and pore water which saturates the sample. This chapter reminds and concludes the results of this study.

The electrical conductivity measurements on water made known that the reliable frequency for the measurement was from 10 kHz to 100 kHz until the electrical conductivity of water of 0.1018 S/m; however, the maximum limit will become smaller as the electrical conductivity of water increases. Besides, the complex impedance planes demonstrated that no electrode polarisation occurred in the measurements with the new cell.

The electrical conductivity measurements on the peats suggested that the reliable frequency range for the measurement was from 10 kHz to 100 kHz in the electrical conductivity range of pore water ($\sigma_w$) from 0.00244 to 0.933 S/m. Although the data correction was attempted for the outside of the reliable frequency range by introducing the residual capacitance obtained from the water, it was found that the residual capacitance would vary depending on samples.

The plots of the real part of conductivity ($\sigma'$) as a function of $\sigma_w$ were observed to be well fitted to C&S model, though the parameters were smaller than that suggested by Comas and Slater [2004]. However, it was also presented that the modified Archie’s law, which is rejected by Comas and Slater [2004] due to the alteration of the formation factor $F$ in the law, was still a comparable model to C&S for the data obtained in this
study.

The attempt to estimate the tortuosity index $a$ and the cementation index $m$ of $F$ could not be achieved because there were only two variations in the sample porosity. In addition, it was shown that the modified Archie’s law accounted for the mechanism which led to the change in the difference between $\sigma_w$ and $\sigma'$ with $\sigma_w$.

The new hybrid cell was shown to be suitable set-up for the samples investigated in this study and the comparison with a similar cell developed by Blewett et al. [2003] proved that the new cell successfully prevents the electrode polarisation. Simultaneously, some useful features which can be fitted in the new cell are found as in the recommendation below.

6.2 Recommendations for future work

Several recommendations can be made for the future experiments. Firstly, it is recommended mounting a thermistor inside the cell in order to measure the exact temperature in it. Secondly, it is preferable to use a component analyser or a similar instrument which can regulate an input electric current density in order to avoid non-linear effects. In addition, one can generate lower frequency range ($< 20$ Hz) is desirable to compare the electrical behaviour in the range with previous works. It is also necessary to check whether the apparatus measures true hydraulic conductivity of samples, or clogging of electrodes porous plates and paper filters by fine particles takes place, affecting the measurements. Furthermore, it will be worth that clean sieved sand is used as a reference case to review validity of the cell. Because sand is a well-known material in terms of electrical properties, results from the hybrid cell could be compared with the abundant previous works. It is also very important to extend measurements to peat samples with a bigger variety of pore water conductivities and porosities in order to determine a reliable conductivity range of the cell and the cementation index $m$. Finally, the hybrid cell should be used as the Rowe cell in order to perform hydraulic consolidation tests in parallel with electrical measurements, though it was not possible yet in this study. There is no doubt that this function will make a significant contribution to better understanding of the relationship between the electrical properties and the physical and geo-engineering properties of peat.

This work is a first step but it is believed to provide indispensable results for the future study.
REFERENCES


APPENDIX 1: PHOTOGRAPHS OF PARTS OF NEW CELL

Cell base

Electrodes porous plate at bottom

Assembled cell base and cell wall

Bottom electrodes after assemblage

Electrodes porous plate at top

Top electrodes plate and diaphragm
APPENDIX 2: PRECISION COMPONENT ANALYSER 6440A

Reprint of the brochure by Wayne Kerr Electronics Ltd.

### Measurement Parameters
Any of the following parameters can be measured and displayed:

- **Inductance**, L
- **Impedance**, Z
- **R*** and **Capacitance**, C
- **Series or Parallel Equivalent Circuit**, G, R, L
- **Q**, Q
- **Phase Angle**, ø

### Modes of Operation
- **Selection** of any measurement parameter and test condition.
- **Single level function menu** controlled by keyboard and soft keys.
- **Simple and repetitive measurements** displaying major and minor terms.

### Derivation
As a measurement modus but relative or percentage deviations from median value displayed for major or minor term.

### Multi-Frequency
Measurement parameters and test conditions set using measurement mode.

### Frequency Sweep (6440A only)
Measurement parameters and test conditions set using measurement mode.

### Warnings and Cautions
- Measurement parameters and test conditions set using measurement mode.
- **Graphical warning vs frequency with selection of start, stop, step size, units and labelling**.

### MEASUREMENT SPEEDS
Four selectable speeds for all measurement functions up to 20 measurements per second for input frequencies up to 1kHz.

### Measurement Ranges
- **RE**: 10 MHz (to 20kHz) up to 2.5 kHz
- **AC**: 1 mV to > 2kHz
- **DC**: 0 mV to > 2kHz
- **Input**: 0.01 ns to > 1ns
- **Output**: 0.1 ns to > 1ns

### BASIC ACCURACY
- **Accuracy** varies with component range measurement speed and frequency.

### Mechanical
- **Height**: 150 mm (5.91)
- **Width**: 440 mm (17.32)
- **Depth**: 525 mm (20.63)
- **Weight**: 11.9 kg (25.9 lbs)

### Environmental Conditions
- **Temperature Range**: 10°C to 40°C
- **Humidity**: 85% non-condensing
- **Altitude**: Up to 2000m
- **Pollution Degree**: 2 ‘mainly non conductive’

### Overviews
This equipment is intended for indoor use only in a non-explosive and non-corrosive atmosphere.

### SAFETY
Complies with the requirements of EN61010-1.

### FIRE
Complies with EN611212 for emissions and immunity.

### UL5086
Precision Component Analyser 6440A (2MHz - 5MHz) with User Manual, 2m AC power cable and Kevlar clips 1EVA41000

### 1EVA4100
Precision Component Analyser 6440A (2MHz - 5MHz) with User Manual, 2m AC power cable and Kevlar clips 1EVA41000

### OPTIONS
- **D** Damping

### ACCESSORIES
- **Kleen Clips** 1EVA41000 (tine jaw)
- 1EVA410100 (large jaw)

### Component Tester
1EVA1006

### Barcode Scanner
1EVA200090 (full width)

Wayne Kerr Electronics reserves the right to change specification without notice.
APPENDIX 3: VON POST CLASSIFICATION

Citation: Hobbs, N. B. 1986: Mire morphology and the properties and behaviour of some British and foreign peats, Quarterly Journal of Engineering Geology, 19, 7-80.

Appendix A

The von Post classification

Peats are composed of the partly decomposed remains of plant communities containing varying morphology and texture. It is this structure that affects the retention or expulsion of water in the system, gives it its strength and ultimately differentiates one type of peat from another. The von Post classification attempts to describe peat and the structure in quantitative terms and the extended system set out below provides a means of correlating the types of peat with their physical, chemical and structural properties.

Plant types

- *Bryales* (moss) = B
- *Carex* (sedge) = C

<table>
<thead>
<tr>
<th>Degrees of humification</th>
<th>Decomposition</th>
<th>Plant structure</th>
<th>Content of amorphous material</th>
<th>Material extruded on squeezing (passing between fingers)</th>
<th>Nature of residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$</td>
<td>None</td>
<td>Easily identified</td>
<td>None</td>
<td>Clear, colourless water</td>
<td>No peat</td>
</tr>
<tr>
<td>$H_2$</td>
<td>Insignificant</td>
<td>Easily identified</td>
<td>None</td>
<td>Yellowish water</td>
<td>Not pasty</td>
</tr>
<tr>
<td>$H_3$</td>
<td>Very slight</td>
<td>Still identifiable</td>
<td>None</td>
<td>Brown, muddy water</td>
<td>Somewhat pasty</td>
</tr>
<tr>
<td>$H_4$</td>
<td>Slight</td>
<td>Not easily identified</td>
<td>Some</td>
<td>Dark brown, muddy water; no peat</td>
<td>Strongly pasty</td>
</tr>
<tr>
<td>$H_5$</td>
<td>Moderate</td>
<td>Recognisable, but vague</td>
<td>Considerable</td>
<td>Muddy water and some peat</td>
<td></td>
</tr>
<tr>
<td>$H_6$</td>
<td>Moderately strong</td>
<td>Indistinct (more distinct after squeezing)</td>
<td>Considerable</td>
<td>About one third of peat squeezed out; water dark brown</td>
<td>Fibres and roots more resistant to decomposition</td>
</tr>
<tr>
<td>$H_7$</td>
<td>Strong</td>
<td>Faintly recognizable</td>
<td>High</td>
<td>About one half of peat squeezed out; any water very dark brown</td>
<td></td>
</tr>
<tr>
<td>$H_8$</td>
<td>Very strong</td>
<td>Very indistinct</td>
<td>High</td>
<td>About two thirds of peat squeezed out; also some pasty water</td>
<td></td>
</tr>
<tr>
<td>$H_9$</td>
<td>Nearly complete</td>
<td>Almost unrecognisable</td>
<td>High</td>
<td>Nearly all the peat squeezed out as a fairly uniform paste</td>
<td></td>
</tr>
<tr>
<td>$H_{10}$</td>
<td>Complete</td>
<td>Not discernible</td>
<td>High</td>
<td>All the peat passes between the fingers; no free water visible</td>
<td></td>
</tr>
</tbody>
</table>

Designation

With few exceptions natural peats consist of a mixture of two or more plant types. The designation adopted is to list the plant types in descending order of content, i.e. the first symbol represents the principal component. For example, a peat classified as £CÆS consists mainly of *Eriophorum* remnants, while the content of Carex remnants would be lower and that of *Sphagnum* remnants relatively low. The designation is omitted when plant types cannot be identified.

Humification (H)

The degree of humification is graded on a scale from 1 to 10 and designated $H_1$ to $H_{10}$. The various degrees of humification are recognized as shown in the Table below.

Water content (B)

In the field the water content of the peat is estimated on a scale from 1 (dry) to 5 (very high), designated $B_1$ to $B_5$. In terms of actual water contents the following ranges are suggested: $B_1$ less than 500%; $B_2$ 500 to 1000%; $B_3$ 1000 to 2000%; and $B_5$ greater than 2000%.
Hybrid Rowe Cell for Measurement of Complex Conductivity

Fine fibres (F)

Fine fibres are defined as fibres and stems smaller than 1 mm in diameter or width. They are often of the Epilobium species, but Hyssopus and Sphagnum stems may also be included if properly specified, e.g. F(H) or F(S). Shrub rootlets may also be included, specified as F(N). No special designation is indicated for plant root hairs, rhizoids, or other fibres. The content of fine fibres is graded on a scale from 0 to 3 as follows: F0 nil; F1 low content; F2 moderate content; and F3 high content.

Coarse fibres (R)

Coarse fibres are defined as fibres, stems, and rootlets greater than 1 mm in diameter or width. They are often of the Carex genus, but Hyssopus and Sphagnum stems may also be included if properly specified, e.g. R(H) or R(S). Shrub (N) rootlets are specified as R(N). The content of coarse fibres is graded on a scale from 0 to 3 as follows: R0 nil; R1 low content; R2 moderate content; and R3 high content.

Wood (W) and shrub (N) remnants

Wood and shrub content is graded on a scale from 0 to 3 as follows: W0 nil; W1 low content; W2 moderate content; and W3 high content. The original designation for macroscopic wood (W) and shrub (N) remnants was, collectively, V (from Swedish vedraster = wood remnants, von Post 1922).

Additional information

The above system, which has been taken from Landva & Pheeley (1980), can be easily extended by the addition of symbols for organic content, structural anisotropy, smell, plasticity and acidity, if required.

Organic content (O)

It is not possible to estimate the organic content unless the peat is obviously clayey when the von Post humification test would not be realistic. Following ignition loss determinations the organic content may be graded as follows: O0 nil; O1 less than 5% organic matter; O2 5% to 10%; O3 10% to 20%; O4 20% to 40%; O5 40% to 60%; O6 60% to 80%; O7 80% to 90%; O8 90% to 95%; O9 95% to 100%.

Tensile strength (TV and TH)

The tensile strength in the vertical and horizontal directions may be judged by pulling specimens apart in these directions. The following scale may be used: T0 zero strength; T1 low, say less than 2 kN/m²; T2 moderate, say 2 to 10 kN/m²; and T3 high or greater than 10 kN/m².

Smell (A)

The smell which is an indication of fermentation under anaerobic conditions may be scaled as follows: A0 no smell; A1 slight; A2 moderate; A3 strong. Note, methane, CH₄, the main indicator of anaerobic activity has no smell. If specially detected should be reported.

Plasticity (P)

Plastic limit test possible P1, not possible P0.

Acidity (pH)

Acid pH₄; neutral pH₅; alkaline pH₆.

Example in the use of the extended von Post classification description in the field

Dark brown, oxidizing to black, moderately decomposed H₄, mainly fine fibrous peat with some coarse fibres and amorphous material. Low vertical tensile strength, moderate horizontally. No smell. Plastic Limit test possible. Genera not identified.

Extended von Post Classification with ignition loss and pH determinations

H₄, B₃, F₂, R₁, W₆, N₁, TV₁, TH₂, A₀, P₁, pH₆

Appendix B

Glossary of terms used in the paper (mainly after Gore 1983)

Acroctelm: the thin aerobic zone at the surface of the mire, underlain by the thick anaerobic zone called the eutolctelm. Literally top of marsh and bottom of marsh, respectively from the Greek.

Allogenic: change or development produced by influences external to the mire itself.

Autogenic: change resulting from processes internal to the mire, such as the accumulation of peat in modifying the water regime.

Carr: fen with scrub or woodland.

Caiotelm: see acroctelm.

Eutrophic: mineral-rich.

Gyttja (Swedish): partly organic bottom deposits, muds, in lakes or the sea containing remains of water life, etc. Often pale-coloured in contrast to the dark dy, dystrophic mud, deposited from colloidal suspensions.

Hagg (Swedish): natural gully in a bog.

Hydrophilous: tolerant of water and very wet conditions.

Hydroser: wetland vegetational succession as distinct from the dryland succession, xerosere.

Lagg (Swedish): wet perfluent fen margin to a raised bog.

Limnic: (peat formation) occurring on or in deep water by free floating or deeply rooted plants.

Marsh: a tract of soft wetland containing mineral soil partly under water. Includes shallow seasonal or periodic flooding.

Mesotrophic: intermediate between eutrophic and oligotrophic.

Minerotrophic: a supply of water to vegetation) originally derived from mineral soils or rocks but sometimes via lakes or rivers as intermediates; it may be eutrophic, mesotrophic or oligotrophic.

Muskeg: Canadian Indian word for organic terrain, mire and peat.

Oligotrophic: mineral-poor.

Ombrogenous: (peat or vegetation) formed under ombrotrophic conditions.

Ombrophilous: (vegetation) tolerating a predominantly rainwater influence.
APPENDIX 4: SUMMARY OF TEST RESULT ON WATER 1

Test on water 1 ($\varepsilon_r = 0.9 - 1.0 \text{ mS/m}, \text{distance-control}$)

<table>
<thead>
<tr>
<th>Water 6.0 cm</th>
<th>Water 6.0 cm</th>
<th>Water 7.0 cm</th>
<th>Water 7.0 cm</th>
<th>Water 8.0 cm</th>
<th>Water 8.0 cm</th>
<th>Water 9.0 cm</th>
<th>Water 9.0 cm</th>
<th>Water 10.0 cm</th>
<th>Water 10.0 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured capacitance $C_{mea} [\text{F}]$</td>
<td>Measured resistance $R_{mea} [\text{Ohm}]$</td>
<td>Real part of conductivity $\sigma'$ [S/m]</td>
<td>Phase angle $\theta$ [mrad]</td>
<td>Imaginary part of conductivity $\eta$ [S/m]</td>
<td>Complex impedance plane [Ohm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5E-2</td>
<td>1.6E+3</td>
<td>8.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.0E-2</td>
<td>1.0E+3</td>
<td>6.0E-9</td>
<td>5.0E+3</td>
<td>4.5E+3</td>
<td>1.0E-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 5: SUMMARY OF TEST RESULT ON WATER 2

Test on water 2 (electrode distance = 60 mm, conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance $C_{mea}$ [F]</th>
<th>Measured resistance $R_{mea}$ [Ohm]</th>
<th>Real part of conductivity $\sigma'$ [S/m]</th>
<th>Phase angle $\theta$ (mrad)</th>
<th>Imaginary part of conductivity $\sigma''$ [S/m]</th>
<th>Complex impedance plane [Ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water_0.149 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_0.149 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_0.149 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_1.018 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_1.018 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_1.018 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_9.93 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_9.93 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_9.93 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_48.7 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_48.7 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water_48.7 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 6: SUMMARY OF TEST RESULT ON PEAT 1

Test on Peat 1 (sample thickness = 65 mm, \( \gamma_c = 10.7 \text{kN/m}^3 \), \( w = 9.18 \), \( \gamma_r = 1.05 \text{kN/m}^3 \) conductive-control)

<table>
<thead>
<tr>
<th>Measured capacitance ( C_{mea} ) [F]</th>
<th>Measured resistance ( R_{mea} ) [Ohm]</th>
<th>Real part of conductivity ( \sigma' ) [S/m]</th>
<th>Phase angle ( \theta ) [mrad]</th>
<th>Imaginary part of conductivity ( \sigma'' ) [S/m]</th>
<th>Complex impedance plane [Ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat_0.18 mS/cm</td>
<td>Peat_0.18 mS/cm</td>
<td>1.0E-1</td>
<td>2.5E-2</td>
<td>1.0E-1</td>
<td>5.0E+2</td>
</tr>
<tr>
<td>Peat_0.51 mS/cm</td>
<td>Peat_0.51 mS/cm</td>
<td>1.5E-7</td>
<td>2.0E-7</td>
<td>5.0E-7</td>
<td>1.0E+2</td>
</tr>
<tr>
<td>Peat_0.87 mS/cm</td>
<td>Peat_0.87 mS/cm</td>
<td>2.0E-7</td>
<td>2.5E-7</td>
<td>5.0E-7</td>
<td>1.5E+2</td>
</tr>
<tr>
<td>Peat_1.21 mS/cm</td>
<td>Peat_1.21 mS/cm</td>
<td>2.5E-7</td>
<td>3.0E-7</td>
<td>5.0E-7</td>
<td>2.0E+2</td>
</tr>
<tr>
<td>Peat_1.22 mS/cm</td>
<td>Peat_1.22 mS/cm</td>
<td>3.0E-7</td>
<td>3.5E-7</td>
<td>5.0E-7</td>
<td>2.5E+2</td>
</tr>
<tr>
<td>Peat_1.77 mS/cm</td>
<td>Peat_1.77 mS/cm</td>
<td>3.5E-7</td>
<td>4.0E-7</td>
<td>5.0E-7</td>
<td>3.0E+2</td>
</tr>
</tbody>
</table>

Appendix 6  85
Test on Peat 1 (sample thickness = 65 mm, $\gamma_c = 10.7\ kN/m^3$, $w = 9.18$, $\gamma_2 = 1.05\ kN/m^3$, conductivity-control)
Test on Peat 1 (sample thickness = 65 mm, \( \gamma_w = 10.7 \text{kN/m}^3 \), \( \gamma_p = 9.18 \text{kN/m}^3 \), conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance ( C_{mea} ) [F]</th>
<th>Measured resistance ( R_{mea} ) [( \Omega )]</th>
<th>Real part of conductivity ( \sigma' ) [S/m]</th>
<th>Phase angle ( \theta ) [mrad]</th>
<th>Imaginary part of conductivity ( \sigma'' ) [S/m]</th>
<th>Complex impedance plane (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat_6.52 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_7.66 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_8.57 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_9.70 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_10.20 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX 7: SUMMARY OF TEST RESULT ON PEAT 2

Test on Peat 2 (sample thickness = 65 mm, \( \gamma_c = 10.8 \text{ kN/m}^3 \), \( \gamma_w = 9.02 \text{ kN/m}^3 \), conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance ( C_{mea} [\text{F}] )</th>
<th>Measured resistance ( R_{mea} [\text{Ohm}] )</th>
<th>Real part of conductivity ( \sigma' [\text{S/m}] )</th>
<th>Phase angle ( \theta [\text{mrad}] )</th>
<th>Imaginary part of conductivity ( \sigma'' [\text{S/m}] )</th>
<th>Complex impedance plane (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat_0.86 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_0.86 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_1.17 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_1.17 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_2.18 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_2.18 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_3.14 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_3.14 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_4.08 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_4.08 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peat_5.15 mS/cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Test on Peat 2 (sample thickness = 65 mm, \( \gamma_c = 10.8 \text{ kN/m}^3 \), \( w = 9.02 \), \( \gamma = 1.08 \text{ kN/m}^3 \), conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance ( C_{mea} ) [F]</th>
<th>Measured resistance ( R_{mea} ) [Ohm]</th>
<th>Real part of conductivity ( \sigma_r ) [S/m]</th>
<th>Phase angle ( \delta ) [mrad]</th>
<th>Imaginary part of conductivity ( \sigma_i ) [S/m]</th>
<th>Complex impedance plane [Ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat_2 6.19 mS/cm</td>
<td>Peat_2 7.13 mS/cm</td>
<td>Peat_2 8.08 mS/cm</td>
<td>Peat_2 9.13 mS/cm</td>
<td>Peat_2 10.13 mS/cm</td>
<td>Peat_2 11.13 mS/cm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><img src="image1.png" alt="Graph 1" /></td>
<td><img src="image2.png" alt="Graph 2" /></td>
<td><img src="image3.png" alt="Graph 3" /></td>
<td><img src="image4.png" alt="Graph 4" /></td>
<td><img src="image5.png" alt="Graph 5" /></td>
<td><img src="image6.png" alt="Graph 6" /></td>
</tr>
<tr>
<td><img src="image7.png" alt="Graph 7" /></td>
<td><img src="image8.png" alt="Graph 8" /></td>
<td><img src="image9.png" alt="Graph 9" /></td>
<td><img src="image10.png" alt="Graph 10" /></td>
<td><img src="image11.png" alt="Graph 11" /></td>
<td><img src="image12.png" alt="Graph 12" /></td>
</tr>
<tr>
<td><img src="image13.png" alt="Graph 13" /></td>
<td><img src="image14.png" alt="Graph 14" /></td>
<td><img src="image15.png" alt="Graph 15" /></td>
<td><img src="image16.png" alt="Graph 16" /></td>
<td><img src="image17.png" alt="Graph 17" /></td>
<td><img src="image18.png" alt="Graph 18" /></td>
</tr>
<tr>
<td><img src="image19.png" alt="Graph 19" /></td>
<td><img src="image20.png" alt="Graph 20" /></td>
<td><img src="image21.png" alt="Graph 21" /></td>
<td><img src="image22.png" alt="Graph 22" /></td>
<td><img src="image23.png" alt="Graph 23" /></td>
<td><img src="image24.png" alt="Graph 24" /></td>
</tr>
</tbody>
</table>
APPENDIX 8: SUMMARY OF TEST RESULT ON PEAT 3

Test on Peat 3 (sample thickness = 65 mm, \(\gamma_c = 10.0\) kN/m\(^3\), \(w = 8.75\), \(\gamma_i = 1.02\) kN/m\(^3\), conductivity-control)

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Resistance [Ohm]</th>
<th>Imag. part of conductivity [S/m]</th>
<th>Imaginary part of conductivity [S/m]</th>
<th>Complex impedance plane [Ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Real part of conductivity (\sigma) [S/m]</td>
<td>Phase angle (\theta) [mrad]</td>
<td>Ave</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0E-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0E-2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.0E+2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0E+0</td>
</tr>
</tbody>
</table>

The graphs show the variation of resistance, imaginary part of conductivity, real part of conductivity, and phase angle with frequency for different samples of peat.
Test on Peat 3 (sample thickness = 65 mm, \( \gamma_c = 10.0 \) kN/m\(^2 \), \( \gamma_p = 1.02 \) kN/m\(^3 \), conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance ( C_{mea} ) [F]</th>
<th>Measured resistance ( R_{mea} ) [Ohm]</th>
<th>Real part of conductivity ( \sigma' ) [S/m]</th>
<th>Phase angle ( \theta )</th>
<th>Imaginary part of conductivity ( \sigma'' ) [S/m]</th>
<th>Complex impedance plane (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat_0.0811 mS/cm</td>
<td>Peat_0.0811 mS/cm</td>
<td>Peat_0.0811 mS/cm</td>
<td>Peat_0.0811 mS/cm</td>
<td>Peat_0.0811 mS/cm</td>
<td>Peat_0.0811 mS/cm</td>
</tr>
<tr>
<td>Peat_0.1005 mS/cm</td>
<td>Peat_0.1005 mS/cm</td>
<td>Peat_0.1005 mS/cm</td>
<td>Peat_0.1005 mS/cm</td>
<td>Peat_0.1005 mS/cm</td>
<td>Peat_0.1005 mS/cm</td>
</tr>
<tr>
<td>Peat_0.23 mS/cm</td>
<td>Peat_0.23 mS/cm</td>
<td>Peat_0.23 mS/cm</td>
<td>Peat_0.23 mS/cm</td>
<td>Peat_0.23 mS/cm</td>
<td>Peat_0.23 mS/cm</td>
</tr>
<tr>
<td>Peat_0.35 mS/cm</td>
<td>Peat_0.35 mS/cm</td>
<td>Peat_0.35 mS/cm</td>
<td>Peat_0.35 mS/cm</td>
<td>Peat_0.35 mS/cm</td>
<td>Peat_0.35 mS/cm</td>
</tr>
<tr>
<td>Peat_0.50 mS/cm</td>
<td>Peat_0.50 mS/cm</td>
<td>Peat_0.50 mS/cm</td>
<td>Peat_0.50 mS/cm</td>
<td>Peat_0.50 mS/cm</td>
<td>Peat_0.50 mS/cm</td>
</tr>
<tr>
<td>Peat_0.64 mS/cm</td>
<td>Peat_0.64 mS/cm</td>
<td>Peat_0.64 mS/cm</td>
<td>Peat_0.64 mS/cm</td>
<td>Peat_0.64 mS/cm</td>
<td>Peat_0.64 mS/cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.E+0</td>
<td>1.0E+0</td>
<td>2.0E+0</td>
<td></td>
</tr>
<tr>
<td>1.E+1</td>
<td>1.0E+1</td>
<td>2.0E+1</td>
<td></td>
</tr>
<tr>
<td>1.E+2</td>
<td>1.0E+2</td>
<td>2.0E+2</td>
<td></td>
</tr>
<tr>
<td>1.E+3</td>
<td>1.0E+3</td>
<td>2.0E+3</td>
<td></td>
</tr>
<tr>
<td>1.E+4</td>
<td>1.0E+4</td>
<td>2.0E+4</td>
<td></td>
</tr>
<tr>
<td>1.E+5</td>
<td>1.0E+5</td>
<td>2.0E+5</td>
<td></td>
</tr>
<tr>
<td>1.E+6</td>
<td>1.0E+6</td>
<td>2.0E+6</td>
<td></td>
</tr>
<tr>
<td>1.E+7</td>
<td>1.0E+7</td>
<td>2.0E+7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.E+0</td>
<td>1.0E+0</td>
<td>2.0E+0</td>
<td></td>
</tr>
<tr>
<td>1.E+1</td>
<td>1.0E+1</td>
<td>2.0E+1</td>
<td></td>
</tr>
<tr>
<td>1.E+2</td>
<td>1.0E+2</td>
<td>2.0E+2</td>
<td></td>
</tr>
<tr>
<td>1.E+3</td>
<td>1.0E+3</td>
<td>2.0E+3</td>
<td></td>
</tr>
<tr>
<td>1.E+4</td>
<td>1.0E+4</td>
<td>2.0E+4</td>
<td></td>
</tr>
<tr>
<td>1.E+5</td>
<td>1.0E+5</td>
<td>2.0E+5</td>
<td></td>
</tr>
<tr>
<td>1.E+6</td>
<td>1.0E+6</td>
<td>2.0E+6</td>
<td></td>
</tr>
<tr>
<td>1.E+7</td>
<td>1.0E+7</td>
<td>2.0E+7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.E+0</td>
<td>1.0E+0</td>
<td>2.0E+0</td>
<td></td>
</tr>
<tr>
<td>1.E+1</td>
<td>1.0E+1</td>
<td>2.0E+1</td>
<td></td>
</tr>
<tr>
<td>1.E+2</td>
<td>1.0E+2</td>
<td>2.0E+2</td>
<td></td>
</tr>
<tr>
<td>1.E+3</td>
<td>1.0E+3</td>
<td>2.0E+3</td>
<td></td>
</tr>
<tr>
<td>1.E+4</td>
<td>1.0E+4</td>
<td>2.0E+4</td>
<td></td>
</tr>
<tr>
<td>1.E+5</td>
<td>1.0E+5</td>
<td>2.0E+5</td>
<td></td>
</tr>
<tr>
<td>1.E+6</td>
<td>1.0E+6</td>
<td>2.0E+6</td>
<td></td>
</tr>
<tr>
<td>1.E+7</td>
<td>1.0E+7</td>
<td>2.0E+7</td>
<td></td>
</tr>
</tbody>
</table>
Test on Peat 3 (sample thickness = 65 mm, \( \gamma = 10.0 \text{kN/m}^3 \), \( w = 8.75 \), \( \gamma_w = 1.02 \text{kN/m}^3 \), conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance ( C_{meas} ) [F]</th>
<th>Measured resistance ( R_{meas} ) [Ohm]</th>
<th>Real part of conductivity ( \sigma' ) [S/m]</th>
<th>Phase angle ( \theta ) [mrad]</th>
<th>Imaginary part of conductivity ( \sigma'' ) [S/m]</th>
<th>Complex impedance plane [Ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat_0.70 mS/cm</td>
<td>Peat_0.70 mS/cm</td>
<td>Peat_0.70 mS/cm</td>
<td>Peat_0.70 mS/cm</td>
<td>Peat_0.70 mS/cm</td>
<td>Peat_0.70 mS/cm</td>
</tr>
<tr>
<td>Peat_0.99 mS/cm</td>
<td>Peat_0.99 mS/cm</td>
<td>Peat_0.99 mS/cm</td>
<td>Peat_0.99 mS/cm</td>
<td>Peat_0.99 mS/cm</td>
<td>Peat_0.99 mS/cm</td>
</tr>
<tr>
<td>Peat_1.50 mS/cm</td>
<td>Peat_1.50 mS/cm</td>
<td>Peat_1.50 mS/cm</td>
<td>Peat_1.50 mS/cm</td>
<td>Peat_1.50 mS/cm</td>
<td>Peat_1.50 mS/cm</td>
</tr>
<tr>
<td>Peat_1.98 mS/cm</td>
<td>Peat_1.98 mS/cm</td>
<td>Peat_1.98 mS/cm</td>
<td>Peat_1.98 mS/cm</td>
<td>Peat_1.98 mS/cm</td>
<td>Peat_1.98 mS/cm</td>
</tr>
<tr>
<td>Peat_3.02 mS/cm</td>
<td>Peat_3.02 mS/cm</td>
<td>Peat_3.02 mS/cm</td>
<td>Peat_3.02 mS/cm</td>
<td>Peat_3.02 mS/cm</td>
<td>Peat_3.02 mS/cm</td>
</tr>
<tr>
<td>Peat_4.65 mS/cm</td>
<td>Peat_4.65 mS/cm</td>
<td>Peat_4.65 mS/cm</td>
<td>Peat_4.65 mS/cm</td>
<td>Peat_4.65 mS/cm</td>
<td>Peat_4.65 mS/cm</td>
</tr>
</tbody>
</table>
Test on Peat 3 (sample thickness = 65 mm, $\gamma_w = 10.0$ kN/m$^3$, $w = 8.75$, $\gamma_d = 1.02$ kN/m$^3$, conductivity-control)

<table>
<thead>
<tr>
<th>Measured capacitance $C_{mea}$ [F]</th>
<th>Measured resistance $R_{mea}$ [Ohm]</th>
<th>Real part of conductivity $\sigma'$ [S/m]</th>
<th>Phase angle $\theta$ [mrad]</th>
<th>Imaginary part of conductivity $\sigma''$ [S/m]</th>
<th>Complex impedance plane [Ohm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat 3</td>
<td>Peat 3</td>
<td>Peat 3</td>
<td>Peat 3</td>
<td>Peat 3</td>
<td>Peat 3</td>
</tr>
</tbody>
</table>