

**THE DEVELOPMENT OF FOUR-DIMENSIONAL ELECTRICAL
RESISTIVITY TOMOGRAPHY FOR LABORATORY-SCALE IMAGING
OF SOIL MOISTURE DYNAMICS**

By

Narryn I.J. Thaman

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Abstract

This study considers the combination of a novel geophysical monitoring system and geotechnical point sensors for use in controlled laboratory conditions to visualise soil moisture dynamics in different engineered soils. The geophysical monitoring system, referred to here as PRIME (Proactive Infrastructure Monitoring and Evaluation system), uses electrical resistivity tomography (ERT) technology to non-invasively image subsurface moisture-driven processes. The PRIME system and point sensor arrays have been developed for near real-time data acquisition of transient soil moisture conditions in a suite of soil column experiments. This research aims to provide new tools and approaches to further our understanding of soil moisture movement to better assess shallow geotechnical assets by addressing the challenges associated with designing integrated geophysical-geotechnical laboratory-scale monitoring experiments. A total of nine soil column experiments were carried out in this research. Soil moisture content, grain size and density were changed throughout the study to gauge the proficiency of time-lapse ERT for various soils. Nine soil column experiments were conducted to evaluate the effectiveness of time-lapse ERT in various soil compositions, assessing changes in moisture content, grain size, and density. One of the main challenges associated with integrating ERT in a soil column setup is the prevalence of artefacts in the time-lapse imaging. These artefacts, presenting as high or low electrical resistivity contrasts, can be a common feature in ERT surveys and are known to reduce the accuracy of the inversion. This study takes steps to reduce the tendency of artefacts in the results by systematically identifying the source of such modelling errors and adapting the 4D ERT integrated soil column design accordingly. Alongside plotting the electrical resistivity of transient soil moisture conditions in the column experiments, petrophysical relationships derived from the ERT soil columns focus on understanding the link between soil moisture content, electrical resistivity, and suction. These relationships are crucial for improving the interpretation of time-lapse ERT data and enhancing the accuracy of soil moisture monitoring in laboratory and field applications. Findings demonstrate the potential of integrating ERT with geotechnical monitoring systems to advance understanding of soil moisture movement, with applications in geotechnical asset management and environmental engineering.

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List of Abbreviations

BAT: Bourne Amenity Topsoil

BGS: British Geological Survey

CBS: Capillary Barrier Systems

CAT 5: Category 5

CR: Contact Resistance

CT: Clay Topsoil

ERT: Electrical Resistivity Tomography

EC: Electrical Conductivity

EPD: Error Probability Distribution

FDR: Frequency Domain Reflectometry

GMC: Gravimetric Moisture Content

NGIF: National Green Infrastructure Facility

PRIME: Proactive Infrastructure Monitoring and Evaluation system

RE: Reciprocal Error

RMS: Root Mean Square

SNR: Signal-to-Noise Ratio

SMS: Soil Moisture Sensor

TDR: Time Domain Reflectometry

VMC: Volumetric Moisture Content

List of Technical Terms and Definitions

1. **Apparent Resistivity:** The resistivity value calculated from the raw measurements obtained in an ERT survey, which includes influences from the surrounding subsurface materials and is not a direct measure of any specific material's resistivity.
2. **Artefacts:** In the context of ERT data, artefacts refer to distortions or anomalies in the resulting images that do not correspond to actual subsurface features. These can be caused by various factors including equipment limitations, incorrect settings, or external interference.
3. **Batch Inversions:** A method in ERT data processing where multiple data sets are inverted simultaneously to improve efficiency and consistency in the interpretation.
4. **Compaction Experiments:** Laboratory tests designed to study the effects of compaction on soil properties, including density and permeability. These experiments are crucial for understanding how soils behave under mechanical stress, such as when they are used as engineering fill.
5. **Contact Resistances:** Electrical resistances at the interface between the electrodes used in ERT and the soil. High contact resistances can affect the quality of the data and are typically mitigated through proper electrode installation or conditioning.
6. **Cylindrical Finite Element Modelling Mesh:** A type of mesh used in numerical simulations of cylindrical objects or areas, like boreholes or soil columns, to solve problems involving variations in electrical or mechanical properties.
7. **Dipole-Dipole Array:** An electrode configuration in ERT where current is injected through one pair of electrodes (dipole) and the potential difference is measured by another pair of electrodes (dipole) spaced apart from the first.
8. **Electrical Field:** Refers to a physical field produced by electrically charged objects. It affects the behaviour of charged objects in the vicinity of the field.
9. **Electrical Resistivity:** A fundamental property of materials that measures how strongly a material opposes the flow of electric current. In geophysical surveys, it helps in determining the composition and condition of the subsurface.
10. **Electrode Array:** A configuration of electrodes used in ERT to inject current into the ground and measure the resulting potentials. Different configurations (such as Wenner, Schlumberger, Dipole-Dipole) are used depending on the survey requirements.
11. **Error Modelling:** The technique of estimating the impact of measurement and procedural errors on the results of a geophysical survey. This helps in enhancing the accuracy and reliability of the data interpretation.
12. **Error Probability Distribution (EPD):** A statistical analysis tool used to estimate the probability and distribution of errors within geophysical survey data, helping to identify and mitigate potential inaccuracies.
13. **Finite Element Modelling:** A numerical technique used in geophysics for solving complex problems involving variations in subsurface properties by dividing the region of interest into smaller, manageable parts (elements).

14. **Forward Measurements:** In the context of ERT, these are direct measurements obtained by applying a known electrical current through electrodes and measuring the resulting potential differences directly along the survey line.
15. **Forward Modelling:** A process in geophysical surveying where theoretical data is generated from a presumed model of the subsurface to predict the expected survey results, helping to plan and interpret actual survey data.
16. **Goelectrical Modelling:** The process of creating mathematical models that simulate the electrical properties of the subsurface for the purpose of interpreting resistivity data.
17. **Geometric Factor (K):** A constant used in the calculation of resistivity based on the geometry of the electrode array in an ERT survey. It affects how the resistivity is calculated from the measured resistance.
18. **Geophysical Monitoring System:** A system designed to continuously measure and record physical properties of the earth, such as electrical resistivity, to monitor changes in subsurface structures and conditions.
19. **Geotechnical Point Sensors:** Instruments used to measure specific physical properties directly at a point within a geological or soil sample, such as moisture content and temperature.
20. **Inversion:** A computational process used in ERT to convert the measured electrical data (apparent resistivity) into a model that represents the true resistivity distribution of the subsurface. This process helps to interpret the electrical measurements by creating a more accurate representation of the subsurface features.
21. **Inversion Modelling:** The process of converting the apparent resistivity data from geophysical surveys into a model that represents the true distribution of resistive properties in the subsurface.
22. **Mesh Generation:** In the context of ERT, this refers to creating a digital model of the survey area divided into discrete elements, which is used in numerical simulations to solve physical equations related to electrical flow.
23. **Modelling Errors:** These are inaccuracies or mistakes in the geophysical models used in ERT, which can arise from assumptions, limited data, or computational limitations. Identifying and minimizing these errors is crucial for enhancing the reliability of the monitoring system.
24. **Particle Size Distributions:** A measure of the range and size of particles within a soil sample. This distribution affects the soil's physical properties, including porosity, permeability, and strength.
25. **Petrophysical Relationships:** Relationships that describe how rock or soil properties affect the physical measurements obtained by geophysical methods. In the context of this document specifically refers to the relationship between soil moisture content and electrical resistivity.
26. **PRIME System:** An acronym for Proactive Infrastructure Monitoring and Evaluation system, it refers to the specific setup used for real-time monitoring in geotechnical and environmental engineering applications, utilizing ERT technology.

27. **Reciprocal Filtering:** A data processing technique in ERT where measurements are cross-checked by reversing the current and potential electrode pairs to filter out inconsistent data and reduce noise.
28. **Reciprocal Measurements:** These measurements are obtained by reversing the roles of current and potential electrodes in an ERT setup. The reciprocal measurements help to check the quality and consistency of the forward measurements by providing a means of error checking and data validation.
29. **Resistivity Profiling:** A method in ERT involving the measurement of electrical resistivity along a line across the surface to map the lateral variations in subsurface resistivity.
30. **Signal-to-Noise Ratio (SNR):** A measure used in data processing to compare the level of a desired signal to the level of background noise. High SNR values indicate cleaner data with less noise interference.
31. **Soil Column Experiments:** Controlled laboratory tests that simulate soil conditions to study phenomena such as water and solute transport through soils. These experiments are important for validating models and techniques used in field applications.
32. **Soil Suction:** The measure of the tendency of water to move from the soil pore to the atmosphere, an important factor in soil mechanics and hydrology as it influences moisture retention and movement in soils.
33. **Time-lapse ERT:** A method that involves taking multiple ERT measurements over a period to monitor changes in the subsurface resistivity, which may indicate changes in moisture, contaminant levels, or other factors.
34. **Time-lapse Inversion:** A method in ERT where multiple surveys over time are inverted to track changes in resistivity, revealing dynamic processes such as moisture movement or contaminant spread.
35. **Transient Soil Moisture Conditions:** These refer to the temporary, changing states of soil moisture, which can vary due to factors like precipitation, irrigation, or evaporation. These conditions are particularly important in studies involving time-lapse ERT to monitor how moisture content in soil changes over time.
36. **True Resistivity:** The actual resistivity of the subsurface material, derived from correcting apparent resistivity values to remove the effects of surrounding materials and survey geometry.
37. **Vertical Electrical Sounding (VES):** A technique in geophysical surveying where the arrangement of electrodes is expanded radially around a central point to investigate subsurface properties at varying depths.

List of Appendices

Appendix A	Forward – Reciprocal Merging Python Code
Appendix B	Sample of Point Sensor Measurements ¹
Appendix C	Additional Results (Series 1 Soil Column Experiments)
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Note that, given the large volume of data associated with this research, a full account of the data used to produce results presented in this thesis are provided in the Newcastle Data repository (<https://data.ncl.ac.uk/>). Therefore, the data presented in the Appendices at the end of this document provide a snapshot of the outputs from the experiments and do not reflect the entire dataset.

Comprehensive datasets for each experiment can be found for the following subjects:

Clay Topsoil Experiments:	https://figshare.com/s/1819a2e2b72d3c7714d6
Forward Modelling Data:	https://figshare.com/s/83d46ed5f795218f95d2
Gravel filled CBS Soil Column Experiments:	https://figshare.com/s/ee6cd026b4db91288a75
Soil Column Petrophysical Relationships:	https://figshare.com/s/f1476cd2e66420a627a3
Sand Filled CBS Soil Column Experiments:	https://figshare.com/s/e1112721b82240cb86aa
Sand Soil Column Experiments:	https://figshare.com/s/7667773c9260b3495836
Soil Transfer Resistances:	https://figshare.com/s/9517bd8372ecbfea5e3e
Topsoil Column Experiments:	https://figshare.com/s/b05457332bdbc9f7cb8a
Water-based Soil Column Experiments:	https://figshare.com/s/389bbe6dddabe77701c
Soil Column Electrode Geometries:	https://figshare.com/s/37b753445761252fec85

¹ Given the large volume of data attached to this information, full records of change in moisture content during soil column experiments can be found in the data repository.

² Given the large volume of data attached to this information, full records of the processes of calculating petrophysical parameters from soil column-derived electrical resistivity are given in the data repository.

Chapter 1. Introduction

1.1 Context and Rationale

Intrinsic factors affect slope stability and soil hydrology, including slope geometry, soil properties, groundwater, and vegetation-driven matric suction. Field evidence shows that geotechnical infrastructure is susceptible to hydrometeorological-driven instability mechanisms and poses a potential failure hazard to asset operation and public safety. Various methods exist for managing soil hydrology and slope stability, such as implementing capillary barrier systems (CBSs) or deploying ecological engineering strategies to help manage shallow geotechnical assets.

Conventional approaches for assessing the vulnerability of assets to hydrometeorological hazards often rely on intrusive investigations, which can only directly sample a small proportion of the subsurface, or surface observations, which do not reveal the subsurface precursors to failure events attributed to rainfall infiltration. In addition, these approaches are often observed at low temporal and spatial resolutions, limiting opportunities to characterise, for example, processes driving slope failure or CBS soil water recharge rates. To complement conventional approaches, geophysical imaging is being developed for asset monitoring to enable non-invasive, high spatiotemporal resolution monitoring of the subsurface.

In this study, time-lapse electrical resistivity tomography (ERT) is developed for laboratory scale monitoring using the PRIME (Proactive Infrastructure Monitoring and Evaluation) system. Traditionally, when ERT is deployed, one-off snapshots of subsurface conditions are acquired through manual surveys – an approach widely used for environmental and engineering investigation (Loke et al., 2013). However, the PRIME system uses ERT technology to provide near-real-time automated remote monitoring and visualisation of subsurface conditions - allowing for changing ground conditions to be accurately modelled and displayed in four dimensions. This advancement in the capabilities of ERT technology is highly novel, providing researchers with new insight into subsurface processes driving slope failure (e.g., Holmes et al., 2020). Since the PRIME system was developed, it has been typically deployed in regions of slope instability, including for monitoring engineered slopes (e.g., Holmes et al., 2022). However, the PRIME system has not been applied in small-scale laboratory experiments, such as soil column experiments.

Soil column experiments aid in understanding the mobility of water and solutes (e.g., contaminants) through different materials (Ikoyi & Schmalenberger, 2021) and provide an

effective method to scale from a laboratory to a field setting (Sun et al., 2022). Column experiments also allow for detailed studies on how soil properties (e.g., structure, porosity, density, etc.) affect slope stability and hydrological characteristics. Applying time-lapse ERT technology to soil column experiments provides an enhanced geophysical monitoring system that can produce high-resolution near real-time data to continuously monitor and assess soil-moisture dynamics. With potential applications not only in soil hydrology and slope stability but also in the study of contaminant and nutrient transport, which are standard research focuses involving soil columns (e.g., Magga et al., 2008; Banzhaf & Hebig, 2016).

1.2 Research Aims

This study aims to address the technical challenges (e.g., electrode materials and dimensions, measurement settings, geophysical modelling of columnar geometries, etc.) associated with small-scale column experimental design to visualise soil moisture dynamics in different engineered fills (clayey fill, sand, and topsoil) and asset management regimes (CBSs). Due to the limited research on ERT-integrated soil column experiments (e.g., Binley et al., 1996; Olsen et al., 1999; Wehrer et al., 2016) and even fewer papers examining the more advanced 4-D ERT system performance in column experiments, the research put forward in this study applies experimental techniques to derive best practice for conducting such experiments.

1.3 Objectives

To address the research aims outlined in Section 1.2, the following objectives are established:

- To develop a method for incorporating PRIME technology and column practices, thereby providing novel methods for examining soil properties and their hydrological characteristics in a controlled laboratory setting.
- To apply ERT-soil column integration to monitor soil moisture dynamics in different soils under storm conditions in a controlled environment to better assess the applications of ERT in simulated extreme environments.
- To present an opportunity for broader use of the PRIME system in small-scale laboratory experiments, yet unexplored beyond traditional applications in the field (e.g., monitoring of slopes).
- To inform urban planning and development by providing a unique insight into transient changes in moisture conditions in different soils through near real-time data telemetry.

- To establish and evaluate a method for examining soil volumetric moisture content and suction using time-lapse imaging in column experiments to enable future potential uses of ERT in a laboratory setting.

1.4 Thesis Structure

Chapter 1 of this research, the Introduction, provides the context and rationale outlined in this thesis, highlighting the potential uses of ERT soil column experiments to monitor transient soil moisture conditions in near real time. The research aims and objectives have also been addressed, and the various technical challenges associated with designing and building ERT-integrated soil column experiments have been presented, which are discussed in greater detail throughout this research.

Chapter 2 presents a review of the literature that introduces the geophysical and technical nature of ERT by providing a background on electrical resistivity theory and assessing ERT/soil column investigations, which helped inform the methodology, design, and discussion of this work.

Chapter 3, the Methodology, provides insight into design processes informed by preliminary soil testing and the subsequent inspection of electrical resistivity data. Owing to the novel application of time-lapse ERT in this research, the quality of data from the inversion process informed components of the experiment (e.g., electrode material and placement). It is, therefore, necessary to provide the reader with preliminary results of early time-lapse surveys in this chapter to explain why specific columns and ERT equipment features were altered throughout this research.

A 1 in 100 storm event is simulated in the soil column experiments and on different engineered fills and asset management regimes. A 1 in 100 event was selected to simulate the extreme side of rainfall events, which, in recent years, due to the influences of climate change, have become ever more frequent. Additionally, by simulating such events in the confines of a soil column instrumented with ERT, it is possible to test the limits of what can be achieved with such a setup and formulate methods of refining the column and experimental design, thereby making it more robust for future research.

In Chapter 4, the results of the experiments pertaining to changes in the electrical resistivity of the soils in the columns is presented. These experiments tested the capabilities of the ERT setup on materials with different soil properties and under extreme climatic conditions (storm

simulations). The breadth of analysis was crucial in informing the design of the ERT-soil column, the shortcomings of the experiment, and how these can be resolved.

In Chapter 5, the Discussion, the reader is informed as to why changes were made to the design of the equipment used throughout this research, in particular, the ERT soil column set-up.

Lastly, Chapter 6, the Conclusion, summarises the key findings of the research within the context of the research objectives and proposes the advice of the researcher for future work on time-lapse ERT-soil column design and experiments.

Chapter 2. Literature Review

2.1 Introduction

This chapter provides an overview of literature relevant to time-lapse electrical resistivity tomography (ERT) monitoring in soil column experiments and the theoretical concepts drawn upon throughout this research. It explores the purpose and uses of column experiments and the various challenges associated with successful investigations. A basic summary of ERT is provided that explores the fundamentals of electrical surveys, considering topics such as electrical resistivity theory, electrode array types, and the inversion process. A section of the literature review is assigned to the occurrence of artefacts in time-lapse surveys, as such artefacts were observed in the results chapter of this thesis. Although time-lapse ERT is more prominently applied in field investigations, some research on integrating ERT in column experiments is available. These have been examined in this review of the literature. The application of 4-D ERT in this research is possible because of the PRIME (Proactive Infrastructure Monitoring and Evaluation) system. Therefore, this chapter provides an in-depth analysis of the PRIME system and its various applications. ERT is used in combination with point sensor measurements to capture changes in moisture content and suction; as such, the sensors used in the soil column experiments have been researched. Finally, a review of literature specific to the petrophysical relationships between electrical resistivity, moisture content, and suction is given, detailing methods for calibrating ERT to derive suction and moisture content from electrical resistivity.

2.2 Soil Column Experiments

Column experiments are laboratory techniques used to study soil water movement and solute transport in soils (Lewis & Sjöström, 2010; Sun et al., 2022). Experiments can be carried out under controlled conditions, enabling the flow of a solution through a column to be carefully controlled to simulate natural processes in a highly monitored environment. Column experiments are ideal for studying the movement of contaminants (Shu et al., 2023) or soil-water interactions in disturbed or undisturbed soils (Ikoyi & Schmalenberger, 2021). Vegetation can also be incorporated into experiments to study soil-moisture-root dynamics (e.g., Lance et al., 1978; Dinu et al., 2022). Conducting soil column experiments under controlled conditions (e.g., flow rate, solute concentration, and boundary conditions) leads to highly reproducible results (Lewis & Sjöström, 2010). By using undisturbed soil monoliths, column experiments

can simulate closer-to-natural conditions more precisely while maintaining the advantages of a laboratory study (highly monitored and controlled environment).

Despite the various applications of soil column tests, the researcher must consider a number of factors in soil column design and execution. Ikoyi and Schmalenberger (2021) present a detailed protocol for designing and constructing soil columns and outline the challenges associated with testing. Typically, PVC pipes (cut to size) and silicon sealant are used to contain a soil monolith in a column and drilled base caps, or nylon mesh is used at one end of the column to prevent material loss (see Figure 2.0). Although soil column construction appears relatively simple, many technical issues can arise that, if not adequately addressed, can seriously affect experimental outcomes (Bromly et al., 2007; Lewis & Sjöstrom, 2010). Roughening the internal part of the column with sandpaper is often necessary to prevent preferential flow. However, the length and width of a column can make it difficult to achieve uniform coverage of the entire interior of the pipe, resulting in unrealistic hydraulic and solute transport that do not accurately portray natural soil environments (Nakhli et al., 2021). Achieving a realistic bulk density is also difficult. Ikoyi and Schmalenberger (2021) explain that the soil should be wetted and drained to achieve field capacity and compressed at intervals to achieve the intended bulk density. Different soils will have different field capacities and variable bulk density with depth (Mande et al., 2018). Given this, it is likely that the bulk density of the packed soil will change, as filling the column incrementally will result in the compaction of the deeper material over time, emphasising the difficulties of achieving a realistic bulk density. Therefore, undisturbed soil monoliths can be tested under conditions as close to actual field conditions as possible (Demeau, 2013).

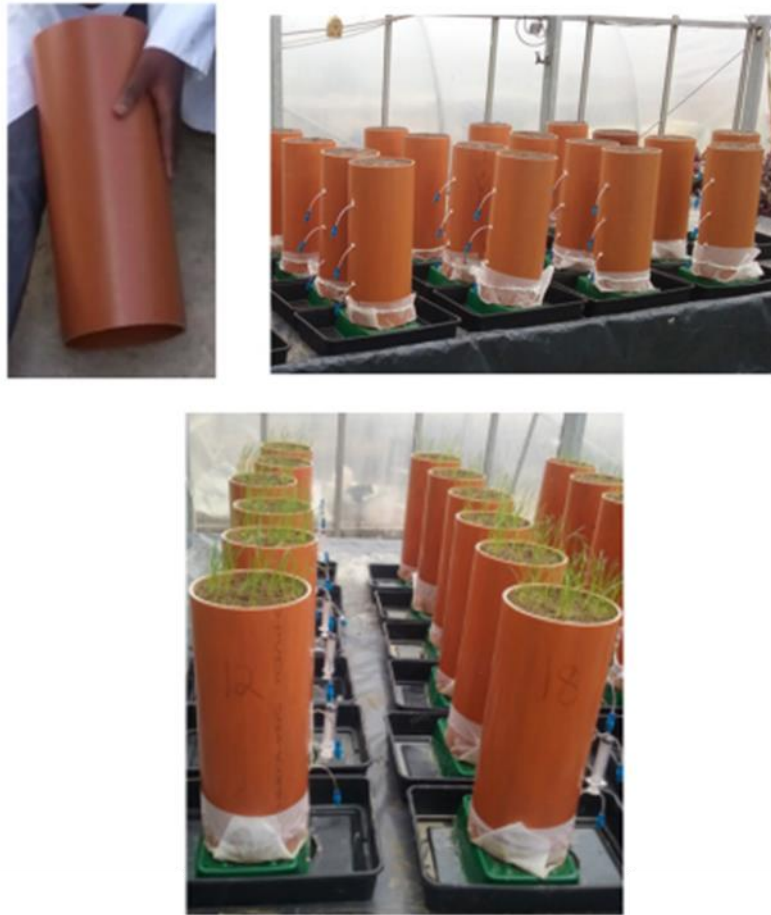


Figure 2.0 Photos of soil columns constructed from PVC pipe and secured with micron mesh at the base. Columns were vegetated with ryegrass and attached with water collection samplers to analyse soil-water-root dynamics under controlled environmental conditions (Ikoyi & Schmalenberger, 2021).

The presence or absence of macropores, unrealistic moisture regimes and inaccurate infiltrate injection can significantly impact soil column experimental outcomes (Lewis & Sjöström, 2010). Packed soil columns using homogenised soils likely have fewer macropores than monolithic soil columns. This will result in greater reproducibility of results but at the expense of real-world conditions, and the opposite can be said for intact monoliths (Lewis & Sjöström, 2010). It is exceptionally challenging to simulate moisture regimes identical to field tests, such as obtaining pore water samples that were not altered by the sampling process (Weihermüller et al., 2007). Identifying potential sources of bias (e.g., preferential flow paths and unrealistic soil bulk densities) and designing experiments that reduce these biases is important in any soil column experiment (Lewis & Sjöström, 2010).

In soil column testing, standards exist for handling hazardous materials or chemicals (e.g., ISO 21268-3:2019 and The OECD Guidelines for the Testing of Chemicals: Test No.312: Leaching in soil columns). However, no standardisation for experimental methods for soil scientists exists (Lewis & Sjöström, 2010), such as British Standards. Often, the experimental techniques applied are unique to the research objectives, making direct comparisons between different studies challenging. However, the challenges of carrying out soil column tests similar to real-world scenarios are recognised and can be mitigated to reduce inaccuracies in the results.

2.3 Resistivity Theory

Loke (2004) explains that the fundamental law used in resistivity surveys is Ohm's Law, which describes the relationship between voltage, current and resistance. The equation for Ohm's Law is given by:

$$R = V/I \quad [1]$$

Where I denote current (Amps), V is voltage (Volts), and R is resistance (Ohms).

Electrical resistance depends on the resistivity of the ground and the geometry of the electrodes. For a flat and homogeneous ground model, resistance can be written as:

$$\rho = R \cdot K \quad [2]$$

Where ρ is resistivity (ohm-meter), and K is the geometric factor (meters).

Almost all electrical surveys generate the current from point sources (Loke, 2004). In this research, a four-point electrode array is deployed per set of measurements. Figure 2.1 provides a schematic diagram of a four-point electrode array. There are different ways of setting up the current and potential electrode configurations for an ERT survey (Loke, 2004). Figure 2.1 shows a setup known as the Wenner array. A current is injected into the ground via a pair of electrodes ($C1$ and $C2$), and the resulting potential difference is measured by a corresponding pair of potential electrodes ($P1$ and $P2$). Electrodes are regularly spaced and connected to the ERT resistivity meter via multicore cables, similar to the ERT setup depicted in Figure 2.2. Many electrodes comprise an ERT survey setup. Resistivity data is collected from a complex combination of current and potential electrode pairs to map the apparent resistivity of near-surface soil conditions (Binley, 2015). The distance between a pair of electrodes in a

measurement sequence dictates the depth the current reaches and data quality. This further highlights the importance of electrode geometry and spacing in resistivity surveyance, as expressed in equation [2].

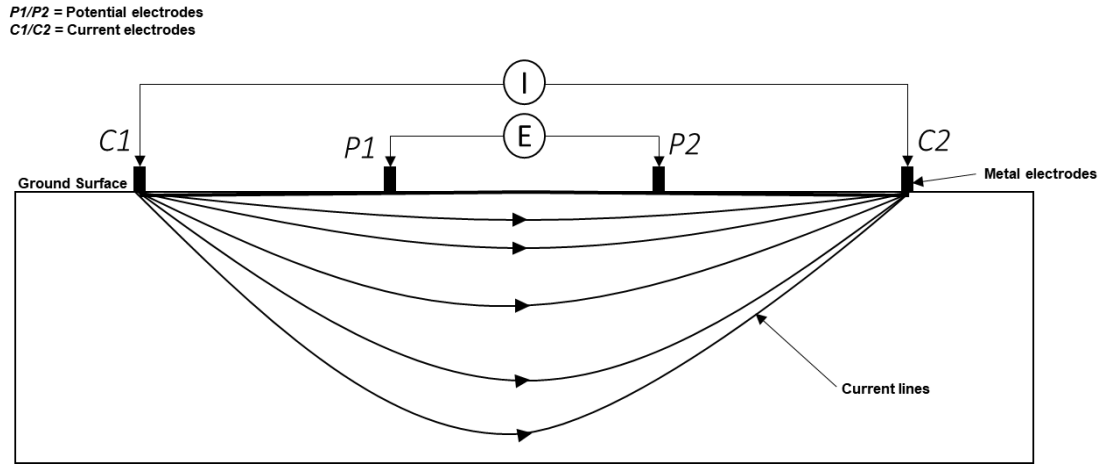


Figure 2. 1 Schematic diagram indicating the general resistivity principles of a Wenner four-point electrode array (Modified version from Benson et al., 1984).



Figure 2. 2 ERT setup demonstrates an electrode array consisting of an electrical meter with cables and electrodes (Wiekenkamp, 2012).

The measured potential difference in Figure 2.1 is:

$$\Delta V = \frac{\rho I}{2\pi} \left[\frac{1}{C1P1} - \frac{1}{C2P1} - \frac{1}{C1P2} + \frac{1}{C2P2} \right]$$

[3]

Where C1P1, C2P1, C1P2 and C2P2 represent the distance between the electrodes. Using equation [3], electrical resistivity can be calculated by considering the geometric coefficient, which is dependent on the spacing of the four electrodes:

$$p = \left[\frac{2\pi}{\frac{1}{C1P1} - \frac{1}{C2P1} - \frac{1}{C1P2} + \frac{1}{C2P2}} \right] \frac{\Delta V}{I} = K \frac{\Delta V}{I}$$

[4]

In an ERT survey, the measured resistivity is known as the apparent resistivity (p_a) and equates to:

$$p_a = KV/I$$

[5]

Array styles, or formats, refer to positioning the potential and current electrodes in an electrode sequence. Many different array styles exist. The most common examples include the Wenner Array, the Schlumberger Array, and the Dipole-dipole Array (Martorana et al., 2017). Figure 2.3 depicts these three conventional arrays. In a Wenner Array, the distance between the potential electrodes will always be the same as between C1 and P1 and C2 and P2. A Schlumberger Array also has a nested arrangement with the potential electrodes between the current electrodes. During an electrical survey, C1 and C2 remain stationary, and P1 and P2 are moved along the distance between the current electrodes. α remains fixed, but the distance between the central point of the potential electrodes and C1/C2 changes as P1 and P2 migrate between them. Dipole-dipole Arrays remove the nested arrangement, separating the current and potential electrodes. Here, α remains constant, and $n\alpha$ changes depending on the distance between the pairs of current and potential electrodes.

Different array styles are deployed situationally; each configuration has advantages and disadvantages. For example, Dipole-dipole Arrays have greater depth penetration than Wenner Arrays. However, the vertical resolution of Wenner Arrays is higher than that of a Dipole-dipole Array. For example, a Dipole-dipole Array was used for the soil column experiments in this investigation.

P1/P2 = Potential electrodes
C1/C2 = Current electrodes
 $a/S/n\alpha$ = Separation between electrodes

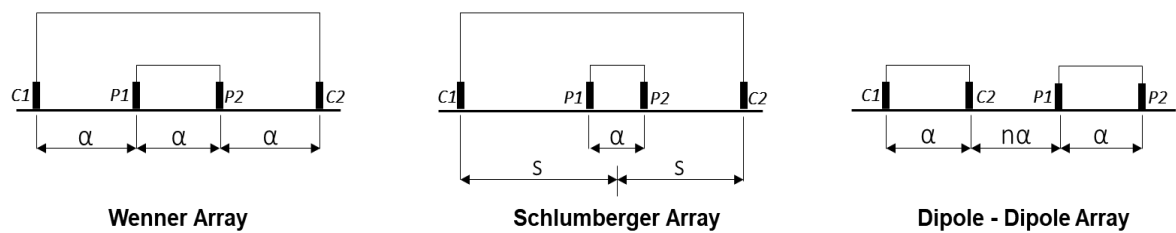


Figure 2. 3 Schematic configuration of conventional electrode array styles in resistivity surveys (Modified version from Hemeda, 2013).

Within soil moisture movement, when an electric current, transmitted via a series of electrodes, passes through the soil, the profile of measured apparent resistivity will deviate depending on the contrast between the soil and water in the void spaces. Apparent resistivity is the weighted average of all resistivity values measured in an area. True resistance (Ω) is only considered over flat homogeneous ground, rarely observed in the field or a laboratory setting. Therefore, we refer to this measurement as apparent resistivity. Figure 2.4 shows variations in resistivity that can occur in a soil matrix. Air is highly resistive relative to wet soil; hence, the ERT equipment would capture a high apparent resistivity at the air void site. On the other hand, a water-filled cavity surrounded by dry soil would be measured as a decrease in apparent resistivity relative to the soil. If no discernible contrast between water in the voids and the soil is measured, namely if the soil is fully saturated, then no changes in apparent resistivity will be measured by the sensors.

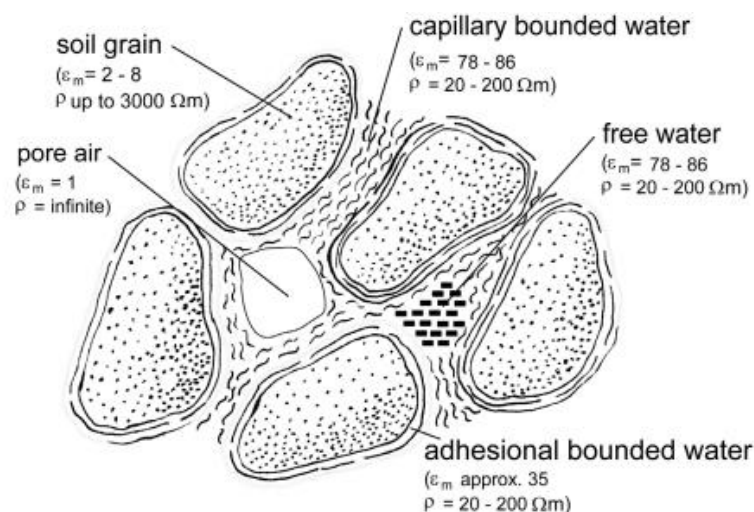


Figure 2. 4 Electric resistivity (ρ [Ωm]) properties of soil phases (Hauk & Scheuermann, 2002).

Early resistivity surveys consisted of one-dimensional surveys where simple four-electrode arrangements (two current and two potential) were moved incrementally along the ground surface (Hemeda, 2013). Apparent resistivity was measured over electrode distance, enabling the user to compare lateral changes in the resistivity of different material layers. Other early 1-D surveys include Vertical Electrical Soundings (VES) (Haldar, 2018), consisting of four electrodes that move away from a fixed central point. Figure 2.5 demonstrates this movement of electrode pairs (AB and MN) from the middle point of the survey area outwards towards the site's boundaries. This survey starts with small spacings between the electrodes that expand as they move away from the first surveyed position. Expanding array distances increases current flow, resulting in greater sensitivity to materials at depth.

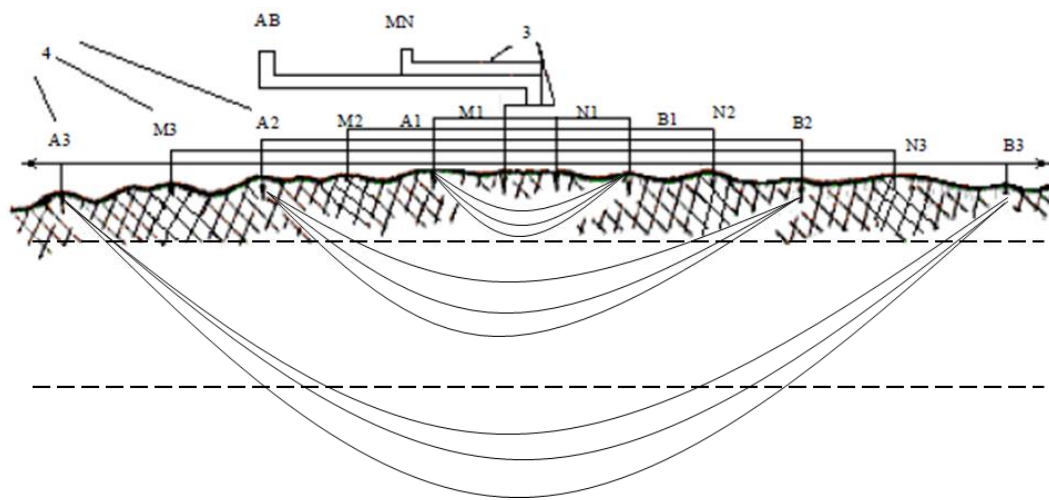


Figure 2. 5 Vertical Electrical Sounding (VES) indicates how the migration of communicator electrodes (AB and MN) influences the depth of current paths in the ground (Akawwi et al., 2014).

Two-dimensional approaches to resistivity imaging consist of a combination of resistivity profiling and VES that deploys multiple electrodes simultaneously (Loke et al., 2013). These strings of electrodes can consist of tens or hundreds of sensors controlled by an ERT instrument. This instrument will select numerous different four-point configurations of electrode pairs to produce a resistivity profile of the subsurface. Typically, this approach adopts multiple array styles, such as Wenner and Dipole-dipole arrays. Using different array styles and, therefore, different electrode configurations will increase the number of resistivity measurements in a survey, improving its quality and efficiency.

Three-dimensional surveys are essential in complex areas where 2-D models suffer from artefacts due to structural displacements outside the two-dimensional space (Chambers et al., 2006). 3-D surveys often consist of a 2-D grid of electrodes at the ground surface. Different line orientations and electrode configurations are used to undertake a 3-D model of the inverted data. Figure 2.6 depicts the grid of electrodes placed at the ground surface in a lysimeter investigation (left) and the results of the 3-D survey (right). A combination of Dipole-dipole and Equatorial Arrays were used. Equatorial Arrays are typical geoelectrical sounding and profiling techniques (Kaufman & Anderson, 2010). In conventional Dipole Arrays, electrode measurements are taken in a line. Equatorial measurements require two parallel lines of electrodes to take measurements perpendicular to the dipole configuration (Chávez et al., 2014).

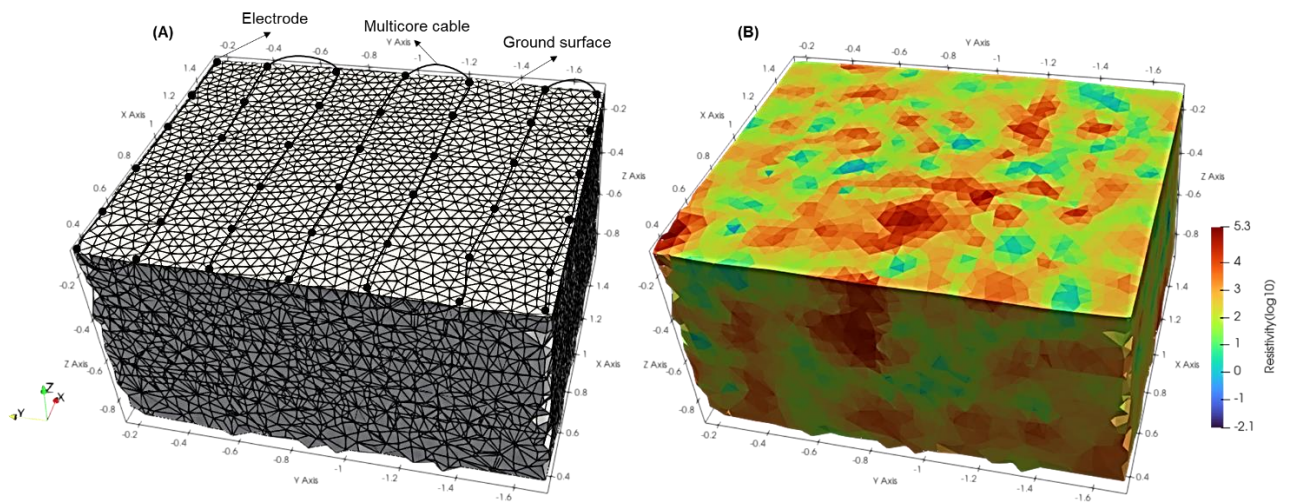


Figure 2. 6 (A) Mesh of electrode positions in lysimeter. (B) Three-dimensional ERT model as a solid volume indicating variations of resistivity.

In four-dimensional surveys, resistivity changes are considered in space and time. Repeat measurements are taken at different times using 2-D or 3-D configurations. 4-D surveys are widely used in regions prone to landslides (Holmes, 2022) and offer a unique insight into the events leading up to slope failure. Resistivity monitoring requires rigorous data quality assessments to ensure accuracy. A common practice in ERT surveyance is to look at reciprocal measurements, whereby the current and potential electrodes are swapped in each configuration. Consistency between what is referred to as the forward measurement and its reciprocal value. Differences in the forward and reciprocal values indicate noise or data quality. Contact resistance (CR) also plays a vital role in data quality. High CRs occur when electrical

conductance is poor between the electrode and soil material. Various methods exist for reducing contact resistances in the field, such as ensuring electrodes are firmly placed in the ground or embedding an electrically conductive material around each electrode.

2.4 Geoelectrical Modelling

Measurements of electrical properties are used to inform upon the distribution of electrical resistivity beneath the soil surface. Mathematical modelling methods are used to evaluate subsurface conditions. These consist of analytical, numerical, and computational techniques. These processes enable geophysicists to simulate physical and chemical Earth responses. This culminates in a quantitative interpretation of the data concerning the distribution of electrical properties, their evolution over time and their uncertainties.

Forward modelling assumes a simplified geoelectrical ground properties model is known. Predicting the data that will be measured using an electrical survey technique is possible. This is useful for assessing the viability of the ERT technique prior to its deployment in the field, allowing for superior survey design. Forward modelling provides a qualitative or semi-quantitative analysis of survey data. In this study, forward modelling was deployed in order to assess the source of artefacts present throughout the column experiments and was therefore instrumental in aiding in the survey design.

This process involves simulating the expected electrical potential distribution within the surface model when subjected to an external current (Hojat et al., 2025). By undertaking forward modelling in ERT, it is possible to compute the theoretical voltage measurements that would be recorded for a specific subsurface resistivity distribution (Day-Lewis, 2008). Forward modelling also serves as the foundation for inverse modelling, where actual field data is used to reconstruct the subsurface resistivity structure.

Day-Lewis et al., (2008) research on the best practices in ERT imaging was used to better understand the data collection, processing and, more specifically, forward modelling techniques in this review of the literature. The process of forward modelling requires a conceptual model of the subsurface is created that includes geological features and assigning resistivity values to different regions. Finite element techniques are deployed to solve equations of electrical flow within the model. ResIPy, the ERT modelling software used in this study, performs these mathematical equations automatically. Defining the model and deployment of numerical simulations yields the synthetic voltage data that corresponds to the specified electrode configurations and injected current.

Inversion modelling uses measured data to predict the geoelectrical properties of the ground. This form of modelling provides a quantitative analysis of the survey data and facilitates the visualisation of property distributions, enabling the assessment of uncertainties and informing survey design. Figure 2.7 depicts an apparent resistivity pseudo section from a 3-D ERT survey of near-surface deposits in a lysimeter. Figure 2.7 (B) provides an image of the distribution of resistivities within a section of the lysimeter acquired through inversion modelling. From the point data depicted in (A), modelling software can predict the resistivity of the ground based on the measured data. This pseudo section highlights concentrated regions of high resistivity, indicative of possible root pathways through a highly vegetated soil medium.

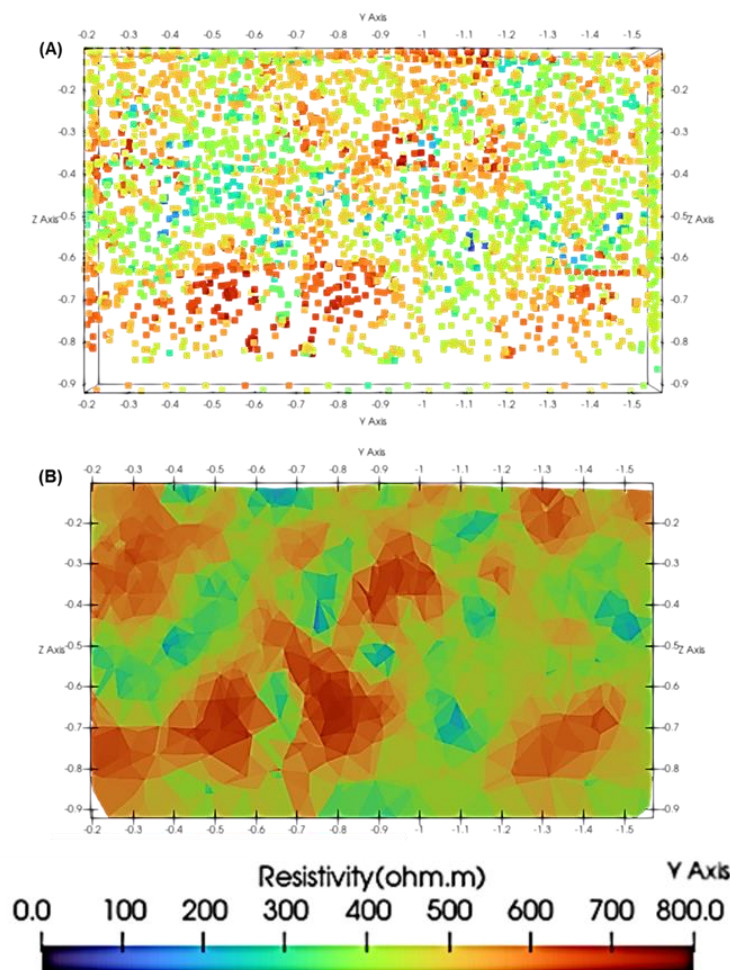


Figure 2. 7 Pseudo section of resistivities derived from a 3-D ERT soil survey in a lysimeter at Newcastle University. (A) indicates the apparent resistivities as point values and (B) the inversion model.

Working out the true resistivity distribution of the ground is possible; however, it requires a model of the electrical properties of the ground that is consistent with the data. Frequently, multiple electrical property models will appear to fit a data set. To find a unique solution to a resistivity survey, the voltage distribution across the boundary of the entire region being surveyed must be established with infinite accuracy and for every possible set of current electrodes at any location. In practice, it is only possible to cover part of the boundary by looking at only a limited number of electrodes. Other factors, including instrument limitations and noise ratios, will also reduce the accuracy of the survey, thereby reducing the probability of finding a unique solution to the inverse model.

Inverting data sets requires knowledge of the sensitivity of measurements to features at different locations and depths. A set of measurements can be developed with different sensitivities to produce an image of resistivity distributions. For each measurement, the amount of signal per current injected into the ground is required to compare noise levels. This is the signal-to-noise ratio (SNR), which informs about the reliability of the data. The signal-to-noise ratio (SNR) compares the desired signal level to the background noise level (Al-Janabi et al., 2023). It dictates the reliability of the geoelectrical data.

2.4.1 ResIPy – Inversion and Modelling Software

Various open software resources exist that provide algorithms for geoelectrical data inversion (Loke, 2004), e.g., pyGIMLi (Python Library for Inversion and Modelling in Geophysics) (Lapenna & Perrone, 2022) and pyres (Python wrapper for electrical resistivity modelling) (Doyoro et al., 2022). This study utilises ResIPy for the inversion process, as the software includes an integrated column mesh builder providing a simple method of constructing a cylindrical mesh (see Figure 2.8).

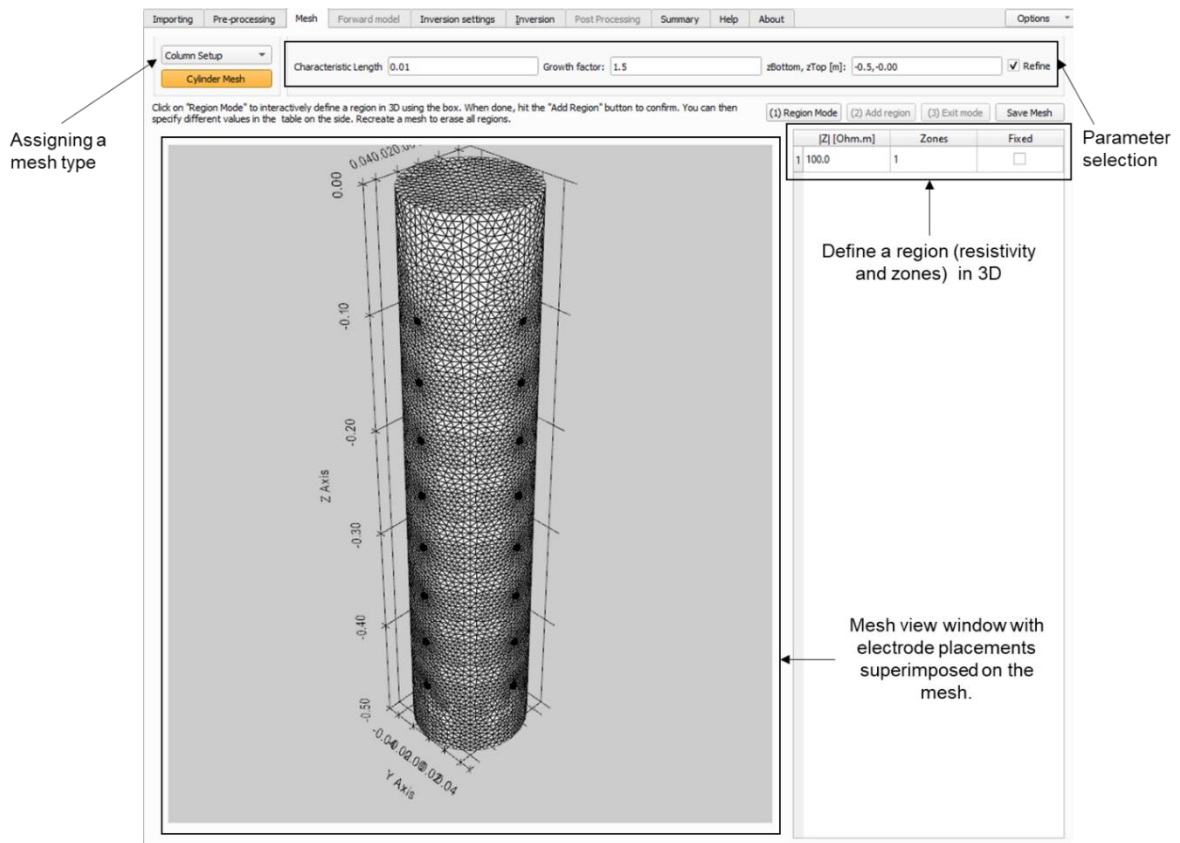


Figure 2. 8 ResIPy project showcasing the mesh tab and features available in mesh construction.

ResIPy was developed to provide an intuitive approach to inversion processes, utilising R2/cR2 inversion codes for ERT and IP (induced polarisation) (Blanchy et al., 2020). Blanchy et al. (2020), who developed the software, provide a detailed analysis of the inner workings of ResIPy. Data can be imported in 12 preselected formats, and a custom format option is available. Automatic and manual data cleaning methods are provided whereby if no reciprocal measurements are forthcoming, ResIPy will calculate and assign reverse measurements, removing invalid or duplicate measurements. ResIPy can fit linear, power-law and parabolic error models to resistivity data and uses a multi-bin analysis to categorise and fit errors. Mesh generation (Figure 2.8) allows for four types of mesh, including field surveys, column setups, tank experiments and a custom mesh import option. The mesh considers the positions of the electrodes (imported) and mesh parameters and uses Gmsh (a meshing code developed by Geuzaine and Remacle, 2009) for complex mesh construction. The inversion process centres around converting the apparent resistivities derived from the imported forward and reciprocal data to true resistivity by minimising the misfit between the observed measurements and predicted response from the electric model (Blanchy et al., 2020). Visualisation tools for inspecting the inversion results are provided alongside the inversion log. ResIPy has features for forward modelling, batch inversions, unconventional surveys, and time-lapse surveys.

2.5 Time-lapse ERT

Electrical Resistivity Tomography, or ERT, is a non-invasive tool for measuring and imaging subsurface soil moisture dynamics volumetrically (Nielson et al., 2021). Variations in electrical resistivity are associated with geological variations and changes in soil saturation and temperature. For decades, electrical resistivity surveys have been used in mining, hydrogeological, geotechnical, and environmental surveys. When using ERT, soil property contrasts influence the detectability of these changes in resistivity (Terradat, 2023). For ERT to be applied successfully, it is necessary to create a contrast in the target location between the feature and the background material.

Time-lapse ERT is used to monitor subsurface changes over time (Trento et al., 2021) and involves collecting resistivity images at different intervals to analyse temporal variations in the subsurface (Musgrave & Binley, 2011). Time-lapse ERT has various applications, including environmental monitoring to track changes in soil moisture content, contaminant migration and remediation processes (Trento et al., 2021); investigating unstable slopes and their internal hydrogeological processes (Boyle et al., 2018); and monitoring of root water uptake dynamics (Carlo et al., 2020). This research uses time-lapse ERT in soil column experiments to investigate soil moisture dynamics in different engineered fills (e.g., compacted clay topsoil and capillary barrier systems). Column experiments that utilise ERT technology are limited in the literature (see Section 2.7), e.g., Binley et al. (1996), Olsen et al. (1999), Koestel et al. (2008) and Thaman et al. (2023). 3-D ERT studies that utilise large experimental tanks or lysimeters are also seen in the literature (Slater et al., 2002). However, field investigations are more common when discussing the applications of time-lapse ERT.

Image quality highly depends on data-error estimates (Lesparre et al., 2017). Parameters such as resolution and accuracy can be improved with higher data density and comprehensive spatial coverage (Wilkinson et al., 2015). Data inversion techniques and the associated algorithms (e.g., the difference inversion algorithm) play a crucial role in the inversion process. Higher image quality is achieved by effectively handling noise and producing stable solutions (Lesparre et al., 2017).

2.6 Resistivity Imaging Artefacts

Survey design (e.g., array type) must be carefully considered, and it is often determined by environmental conditions (e.g., topography, space, soil properties, etc.) (Miller et al., 2008; Wilkinson et al., 2015). Measurement configurations and electrode locations are known to control image resolution (Uhlemann et al., 2018). However, electrode movement or incorrect electrode placement concerning the assumed model can lead to significant artefacts in the resistivity imaging (Boyle et al., 2017). Boyle et al. (2017) analyse the effects of electrode movement on image reconstruction (Figure 2.9).

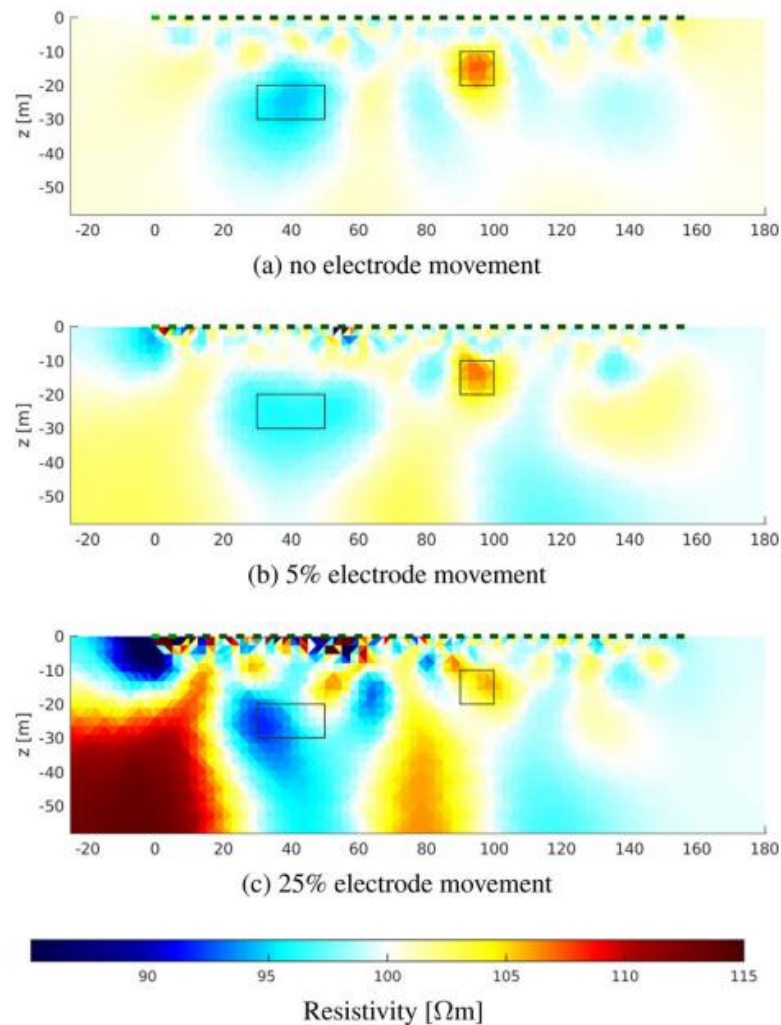


Figure 2. 9 Inversion artefacts in spatial resistivity distribution models where electrodes have been displaced. (a) 0% movements, (b) 5% and (c) 25% (Boyle et al., 2017).

The time-lapse imagery (Figure 2.9) demonstrates the impact electrode displacement has on the appearance of modelling errors. As the percentage of displacement increases, so does the prevalence of these artefacts in the inversion, with artefacts identified between -15m and -30m

depths and in the near-surface close to the electrode array. A joint reconstruction algorithm is used to reduce resistivity artefacts caused by electrode movement significantly (Boyle et al., 2017), emphasising the aforementioned statement regarding the importance of data inversion techniques in improving image data quality. Artefacts of ERT imaging were discussed in several papers during literature review research. They held particular relevance in this study owing to the appearance of artefacts in the soil column resistivity imaging. Clément et al. (2009) observed strong artefacts in their time-lapse inversions when using ERT to monitor leachate infiltration. Figure 2.10 shows the percentage variation in resistivity derived from ERT surveys using different array types. The results of the time-lapse inversion show a considerable difference in artefact prevalence using different array styles, noting that artefacts can occur when using symmetrical electrode arrays (Wenner-Schlumberger and dipole-dipole) and that using an asymmetric array (e.g., pole-dipole) could significantly reduce the appearance of artefacts to produce more reliable ERT imaging.

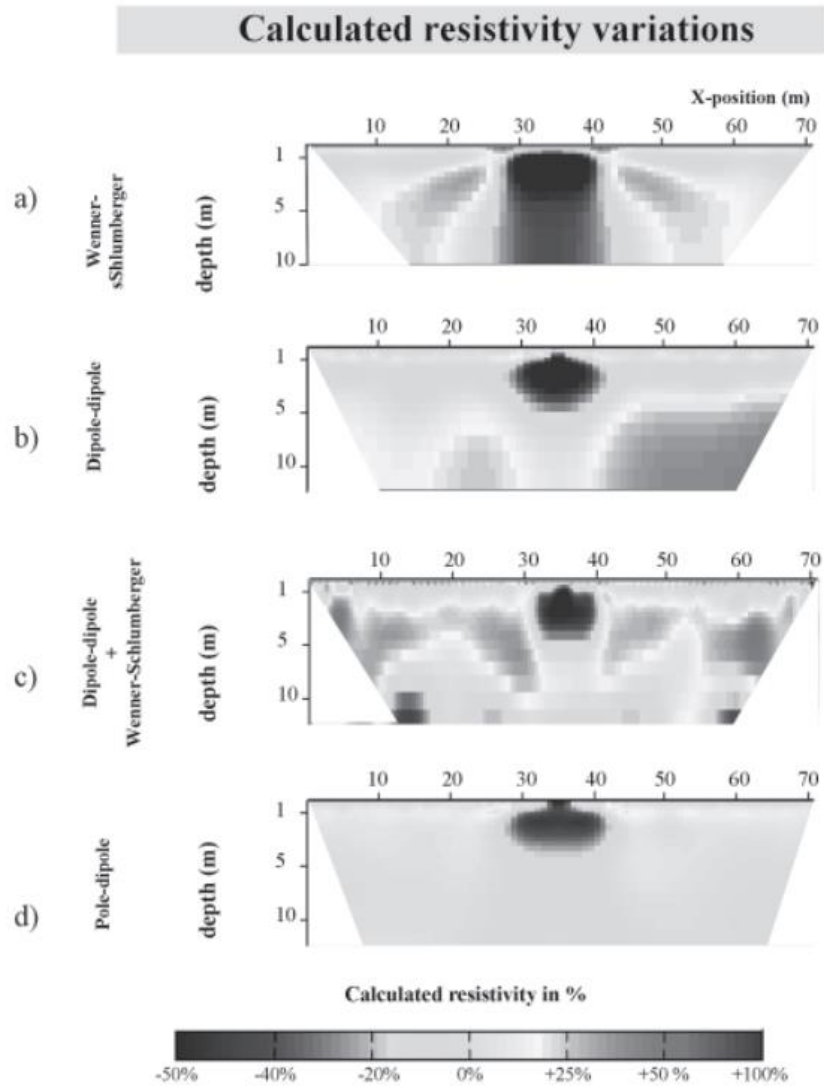


Figure 2. 10 Time-lapse inversion depicting resistivity variations using different array styles to monitor leachate infiltration. (a) Wenner-Schlumberger; (b) Dipole-dipole; (c) dipole-dipole & Wenner-Schlumberger and (d) pole-dipole (Clément et al., 2009).

Similarly, later work by Carey et al. (2017) investigated inversion artefacts using forward modelling. After conducting a non-invasive infiltration processes study in 2014, researchers found artefacts throughout the ERT survey images. Three synthetic models were created with soil layers assigned to different resistivities in each scenario before a time-lapse was simulated (Figure 2.11).

Distance (m) ▶

Depth (m)

0 3 6 9 12

-0.5

-1.5

-2.5

0 3 6 9 12

-0.5

-1.5

-2.5

3000 Ω -m 1100 Ω -m 250 Ω -m

0 1.5 3 4.5 6 7.5 9 10.5 12 13.5

Depth (m)

0

-0.5

-1

-1.5

-2

-2.5

Iteration = 3, RMS = 2.25%, L2 = 0.87

Synthetic Models

Time-lapse Inversion

Distance (m) ►

Depth (m)

0 3 6 9 12

0 3 6 9 12

0.5 1.5 2.5

0.5 1.5 2.5

2000 Ω -m 1100 Ω -m 250 Ω -m

0 1.5 3 4.5 6 7.5 9 10.5 12 13.5

0.5 1.5 2.5

Iteration = 3, RMS = 2.25%, L2 = 0.60

Similar results were found in Clément et al. (2009), where symmetrical electrode arrays produced more artefacts in the inversion than asymmetric arrays (see Figure 2.12). Prior field testing, where artefacts were first noticed during rainfall simulations, identified that artefacts

could arise in the inversion due to significant soil moisture contrasts at different soil depths (Carey et al., 2017), which were exacerbated when deploying a symmetrical electrode array style.

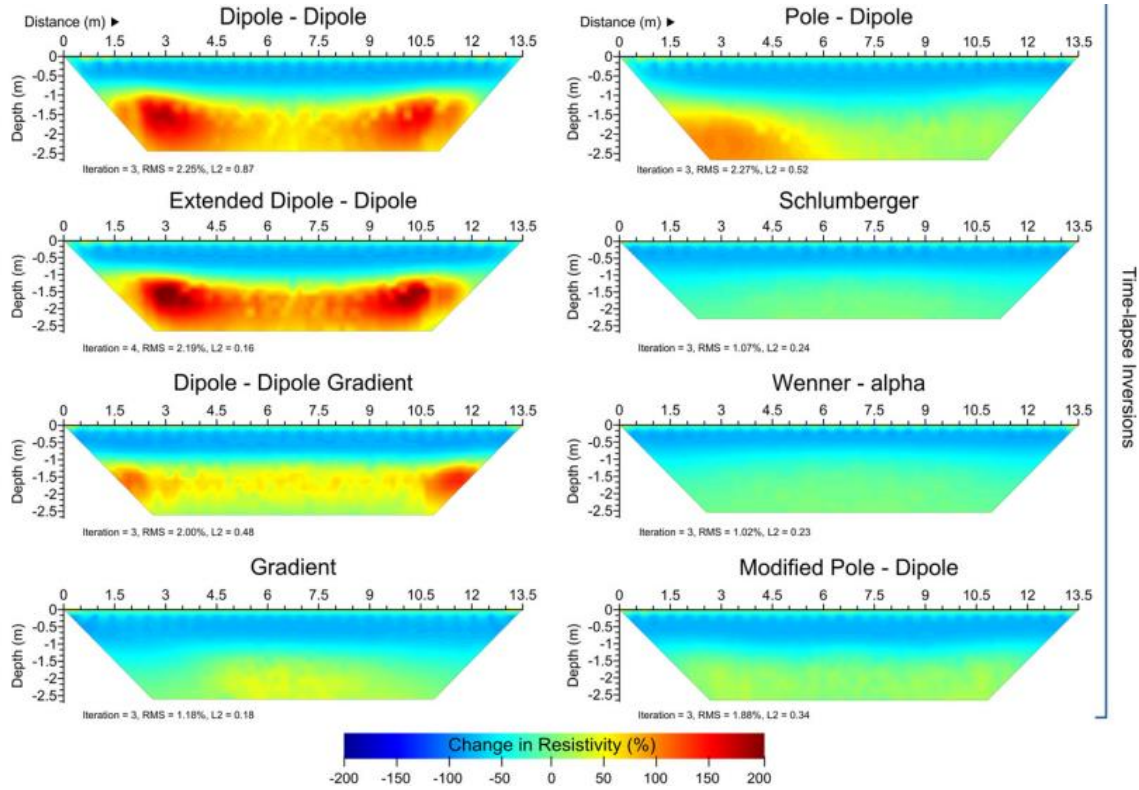


Figure 2. 12 The results of the time-lapse inversion showcasing the seven different array types tested using a synthetic model (Carey et al., 2017).

Batlle-Aguilar et al. (2009) observed incorrect resistivity values (high resistivity zones) in their inversions when using ERT to monitor water infiltration rates during field experiments (see figure 2.13). The study used a 2-D dataset and inversion to interpret 3-D infiltration. This led to incorrect resistivity values for the deepest blocks and a flattened appearance (image b) of the infiltration bulb in the 2-D inversion results (as seen in image b compared to image a). Complex infiltration bulb geometries (due to the heterogeneous nature of the soil) and local variations in soil properties likely contributed to the artefacts seen in Figure 2.13. Batlle-Aguilar et al. (2009) also explain that the application of time-lapse ERT can introduce artefacts if there are significant changes in the geometry of the infiltration bulb over time. This indicates that time-lapse ERT might not always capture rapid or complex changes accurately, leading to artefacts in subsequent time steps.

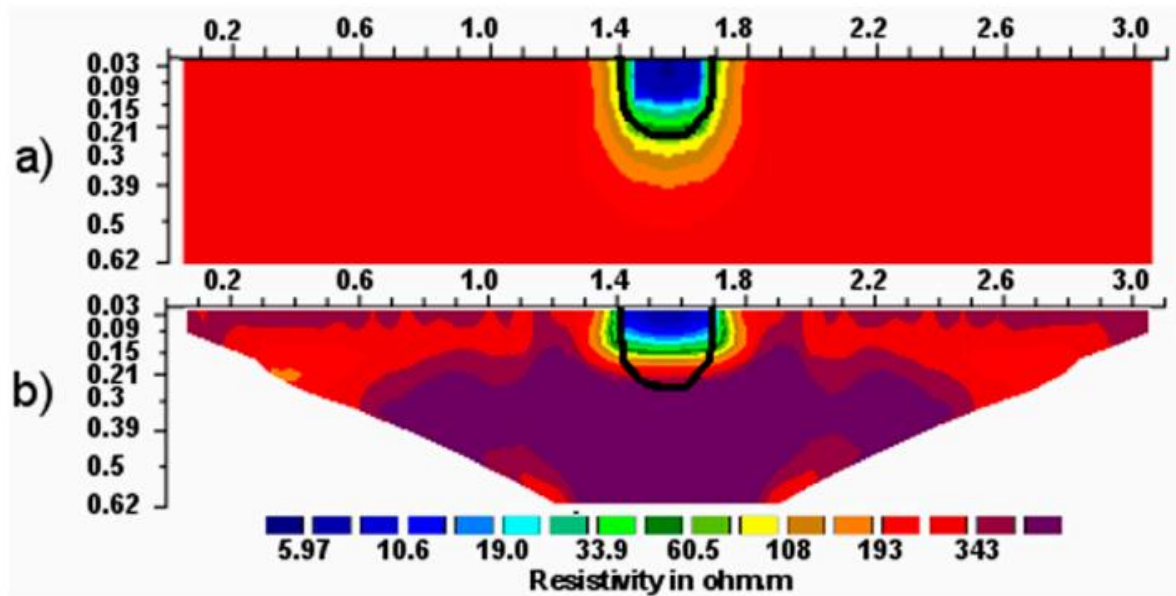


Figure 2. 13 The 2-D and 3-D inversion results show the final step of infiltration with a bulb (black line over imaging), which demonstrates incorrect resistivity features due to the flattening of the infiltration bulb (Batlle-Aguilar et al., 2009).

2.7 The Deployment of ERT in Soil Column Experiments

Previous experimental designs incorporating ERT and soil column setups were examined and used as a foundation for adapting the PRIME system for soil column tests. Notably, electrode deployment and column dimensions were considered. Some studies examining solute transport in soil column experiments using ERT exist (Binley et al., 1996; Olsen et al., 1999; Wehrer et al., 2016). Early research by Binley et al. (1996) used ERT to examine spatial variations in resistivity within a soil core by adopting a four-point electrode array. Figure 2.14 shows the ERT setup used to measure resistance. The method was carried out on an undisturbed soil core containing known distinct zones of preferred solute movement (Binley et al., 1996), suggesting that forward modelling techniques were used to develop images of resistivity distributions. Forward modelling assumes a simplified model of the geoelectrical ground properties is known. The electrode configuration consisted of 16 equally spaced stainless-steel electrodes inserted at different depths – depicted as planes on the diagram.

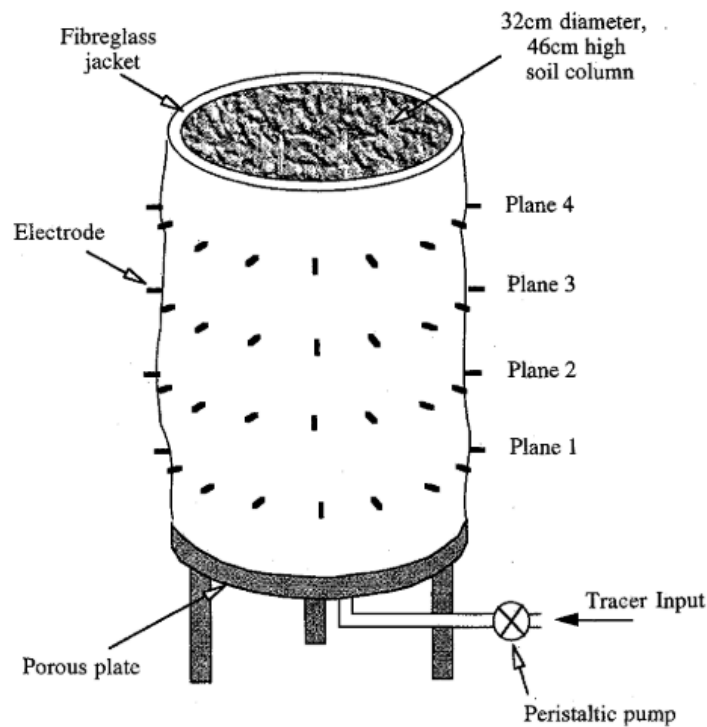


Figure 2. 14 Soil core ERT setup indicating core soil column dimensions and electrode arrangement (Binley et al., 1996).

A tracer solution of sodium chloride (electrical conductivity 2.5 mS cm^{-1}) was injected continuously until steady-state conditions were achieved. A pore volume of sodium chloride was added over 197 hours. ERT measurements were taken at 5-minute intervals at each plane of electrodes, culminating in 300 frames of data collected at each plane (Binley et al., 1996). A measurement interval between planes is required as the current electrodes induce a slight charge in the soil, referred to as induced polarisation (Binley & Slater, 2020). When using a metallic electrode (stainless steel), ions migrate to the oppositely charged electrode in the soil. Even after turning off the current, a measurable voltage will remain. Sufficient time is therefore needed for this induced ground charge to dissipate before the next set of measurements is taken. Data acquisition at each plane took approximately two minutes and consisted of 400 electrode measurements. Surface water was also drained from a small outflow pipe set slightly below the soil surface. This was done to prevent water pooling on the soil surface, which would likely influence the resistivity distributions of the electrical model. In these early adaptations of ERT to small-scale soil column experiments, Binley et al. (1996) found that using 16 electrodes per plane provided a poor resolution compared to preexisting imaging techniques (magnetic resonance or X-ray). It was noted that increasing the number of electrodes to 32 or 64 per plane would improve the resolution.

Binley et al. (1996) provided the first comprehensive method for using ERT in soil column experiments, providing valuable information on the experiment setup and how to achieve image reconstruction of ERT data. The forward and inverse modelling conditions must be considered to model the electrical response of a given resistivity distribution (Binley et al., 1995). The complexity of the model determines the complexity of the forward and inverse problems.

In the forward modelling problem, the subsurface resistivity distributions are specified, and the intention is to calculate the apparent resistivity that would be measured by a survey and over a structure (Loke, 2004). In section 2.4, forward and inverse modelling techniques are introduced as separate methods for imaging resistivity distributions of the ground. However, a forward modelling sequence is also an integral part of any inversion program, as it is necessary to calculate the theoretical apparent resistivity values for the model produced by the inversion to see if it agrees with the measured values (Loke, 2004).

Loke (2004) describes three primary methods for calculating the apparent resistivities for a specific model. (1) analytical methods, (2) boundary element methods and (3) the finite-difference and finite-element methods. Binley et al. (1995) defined parameters such as the current distribution and boundary conditions and deployed the finite element method to reconstruct images from resistivity data. Figure 2.15 shows the finite element model and resistivity parametrisation used (Binley et al., 1996). In the finite element mesh (left), black circles at the mesh boundaries represent the 16 electrodes, and white circles represent node points. Resistivity parameterisation (right) demonstrates using single finite element patches that comprise the finite element mesh. Here, finite elements are used to define the parameter boundaries and group elements to define parameter regions (Binley et al., 1996). The boundary conditions match physical quantities at boundaries between arbitrarily shaped regions. This enables soils with irregular or more complicated regions (containing cavities or complex layering, etc.) to be modelled. The finite element method divides the ground into a mesh of arbitrarily shaped cells, which matches physical quantities at cell boundaries. This allows for a high level of complexity in a model, as each cell can have a difference in resistivity value.

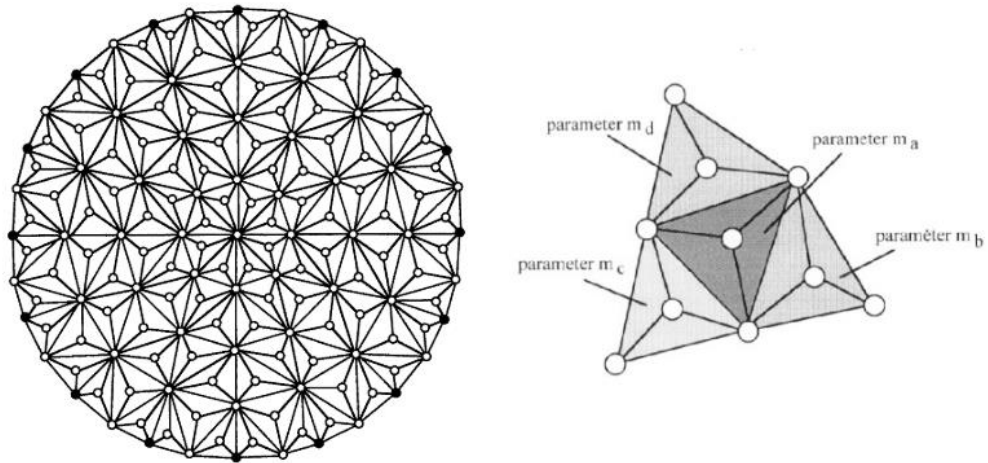


Figure 2. 15 The finite element model (left) is used to calculate the forward solution and the resistivity elements comprising the mesh (right) (Binley et al., 1996).

Similar modelling techniques were deployed by Olsen et al. (1999) in soil column experiments that used ERT. Figure 2.16 shows the electrode positions and finite element mesh adopted to examine solute transport in undisturbed soil cores. Electrodes were placed in four equidistant planes with 16 equally spaced electrodes around the circumference. The soil core was discretised into triangular prism finite elements. Individual elements enable modelling of the spatial distribution of resistivity within the soil column, allowing for computational theoretical measurements of apparent resistivities to be determined (Olsen et al., 1999).

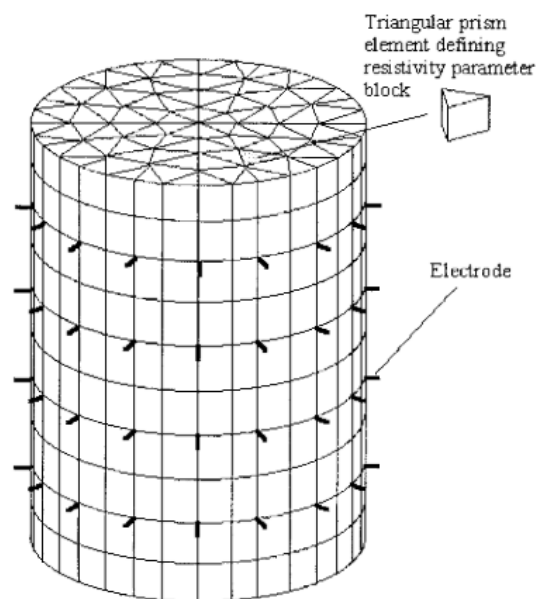


Figure 2. 16 Schematic arrangement of electrodes and finite element mesh of soil column (Olsen et al., 1999).

In a study by Koestel et al. (2008), ERT proved a valuable tool for imaging solute transport processes in the subsurface. ERT was combined with Time Domain Reflectometry (TDR) to provide quantitative information about column-scale solute transport characteristics in natural soils. The study used a large undisturbed soil monolith and applied a two-step tracer test under steady-state unsaturated flow conditions similar to experiments by Binley et al., 1996. The soil monolith was placed in a PVC column (150cm height and 116cm inner diameter), as seen in Figure 2.17. 212 steel electrodes (1.2 cm diameter) were installed, extending 3cm into the soil. The electrodes were placed equidistantly along the circumference of the column with an additional six electrode rings along four vertical lines. 3-D ERT inversions mapped changes in spatial distributions of electrical resistivity inside the monolith using a dipole-dipole array configuration. Each data frame was inverted individually with no applied time-lapse regularisation.

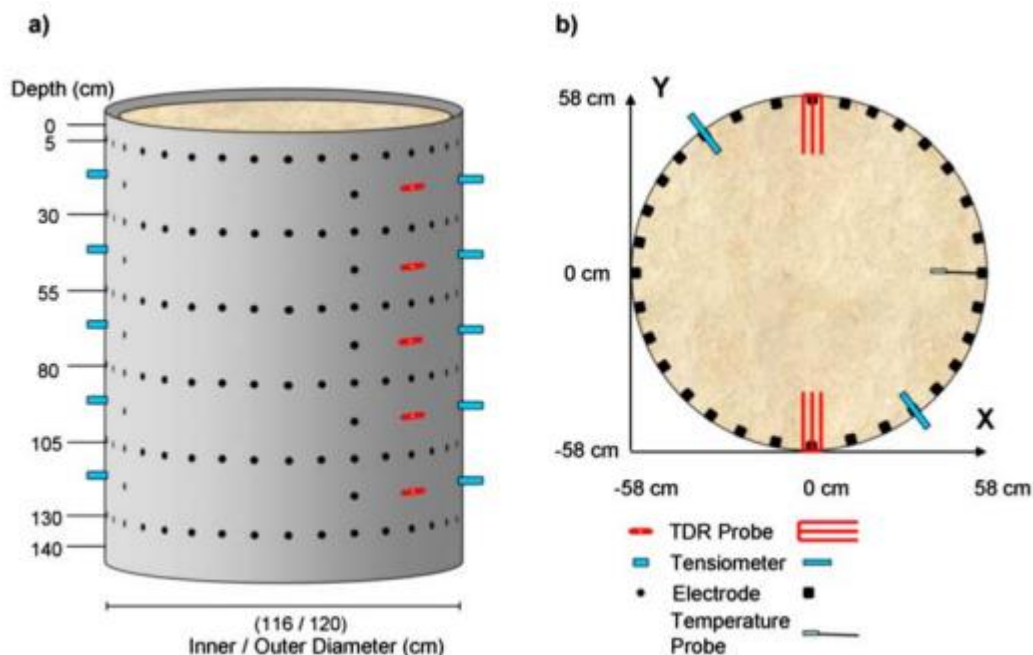


Figure 2. 17 The soil column and instrumentation are used to examine solute transport processes in an undisturbed soil monolith. (a) soil column instrumentation (ERT electrodes, tensiometers and probes) and (b) horizontal cross-section of the soil column (Koestel et al., 2008).

Figure 2.18 shows the spatial distribution of bulk electrical conductivity from the column experiment. The images depict changes in conductivity at 0, 13 and 30 days, respectively, and demonstrate how solute transportation over the experiment timeframe has influenced bulk conductivity in the sandy topsoil monolith. At day 0, bulk conductivity is low, which corresponds to the soil water composition of tap water. As the solution of CaCl_2 percolates through the sample, conductivity increases throughout the soil.

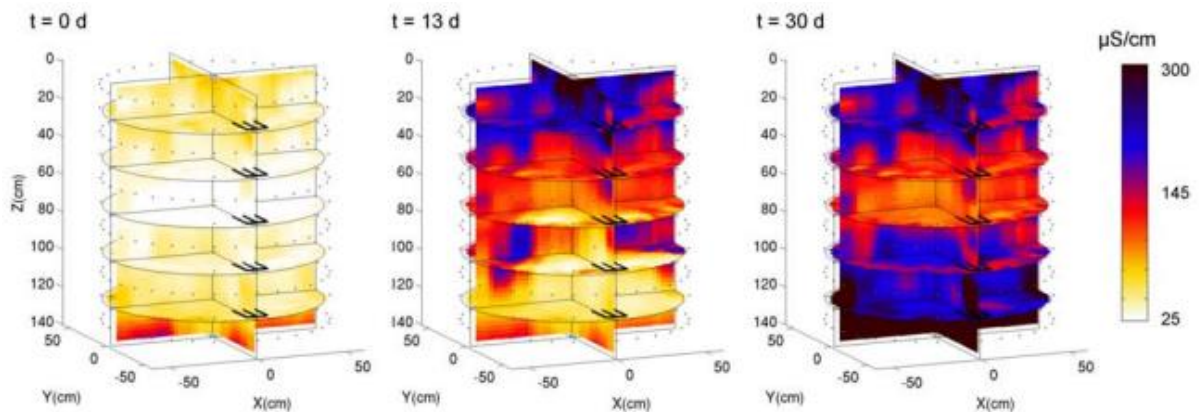


Figure 2. 18 Bulk electrical conductivity of sandy topsoil monolith in soil column experiment at 0, 13 and 30 days (Koestel et al., 2008).

When comparing ERT and TDR to derive bulk electrical conductivity, Koestel et al. (2008) note that the ERT imaging of conductivity was consistently higher than those captured using TDR (Figure 2.19). It was assumed that the mismatch between the two was largely dependent on the error level used in the ERT inversion, but recognised there were likely other contributing factors. The different sampling volumes of ERT and TDR could have led to a mismatch, especially if there were significant variations in bulk electrical conductivity at the TDR measuring scale. Also, for ERT, errors in the ERT data could have been caused by electrode misplacement. Koestel et al., 2008 suggested that by implementing the correct electrode position into the finite element mesh, misfits between the ERT and TDR results could have been reduced. Furthermore, by refining the ERT mesh, there would likely have been improvements. However, this would require more computational power and considerably lengthen the inversion processing time. Koestel et al., 2008 also note that the TDR steel rods could have caused artefacts because of the large electrical conductivity contrasts that the rods provide.

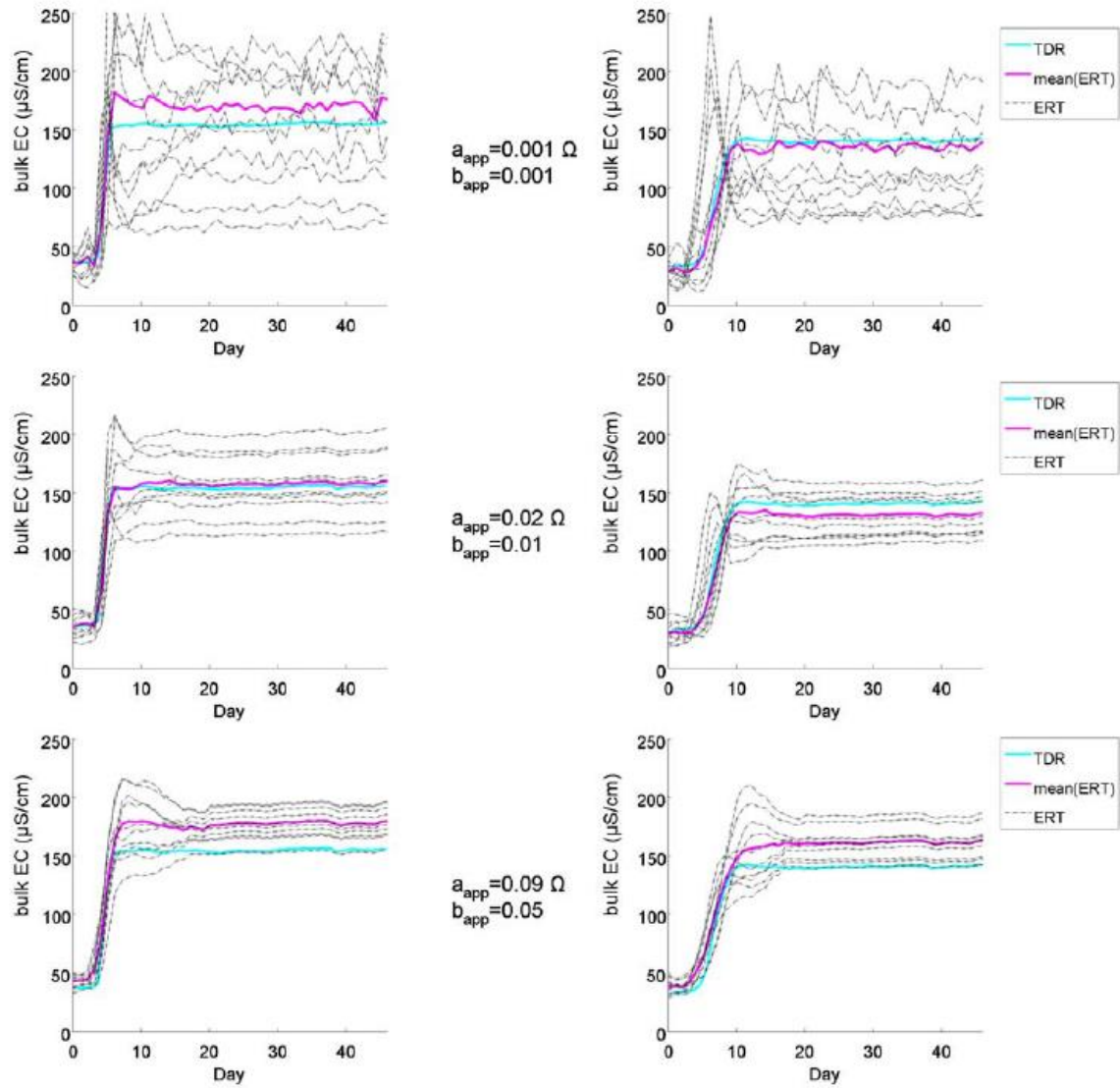


Figure 2. 19 TDR bulk electrical conductivity (EC) compared to the mean ERT element value near the corresponding TDR probe location. The data shows the impact of the ERT inversion error level on results in three examples: top, middle, and bottom (Koestel et al., 2008).

2.8 The PRIME system

The PRIME (Proactive Infrastructure Monitoring and Evaluation) system uses ERT technology to remotely monitor geotechnical assets (e.g., slopes and embankments) to provide early warning of potential failures (UKRI, 2024). Developed by the BGS (British Geological Survey), the hardware consists of a low-power (10 W) resistivity meter, 4G/5G router, solar regulator, and batteries, all housed in a small container (Chambers et al., 2022) (see Figure 2.20). The system uses real-time data telemetry to identify subsurface changes that could indicate instability, thereby providing a proactive approach to mitigating risks associated with

geological hazards. The PRIME system combines emerging ERT technology with server-based processing, wireless telecommunications, and internet portal access (Gunn et al., 2015).

The PRIME System offers significant advantages over conventional ERT systems, particularly in monitoring geotechnical infrastructure. PRIME utilises geophysical methods to visualise the internal structure of earthworks, enabling the detection of moisture content changes and ground movements. This approach identifies potential issues early, allowing for timely interventions. In contrast, traditional ERT systems often rely on surface-level observations and point sensors, which may miss subsurface anomalies (UK Research and Innovation, 2025). Compared to more conventional ERT systems, which often require manual data analysis, PRIME offers automated data processing and interpretation, reducing the need for manual oversight. This continuous monitoring facilitates proactive maintenance decisions (UK Research and Innovation, 2025). Additionally, PRIME has improved accuracy in challenging terrains, addressing limitations in traditional ERT methods, such as sensitivity to terrain-induced anomalies (Zhao et al., 2024).

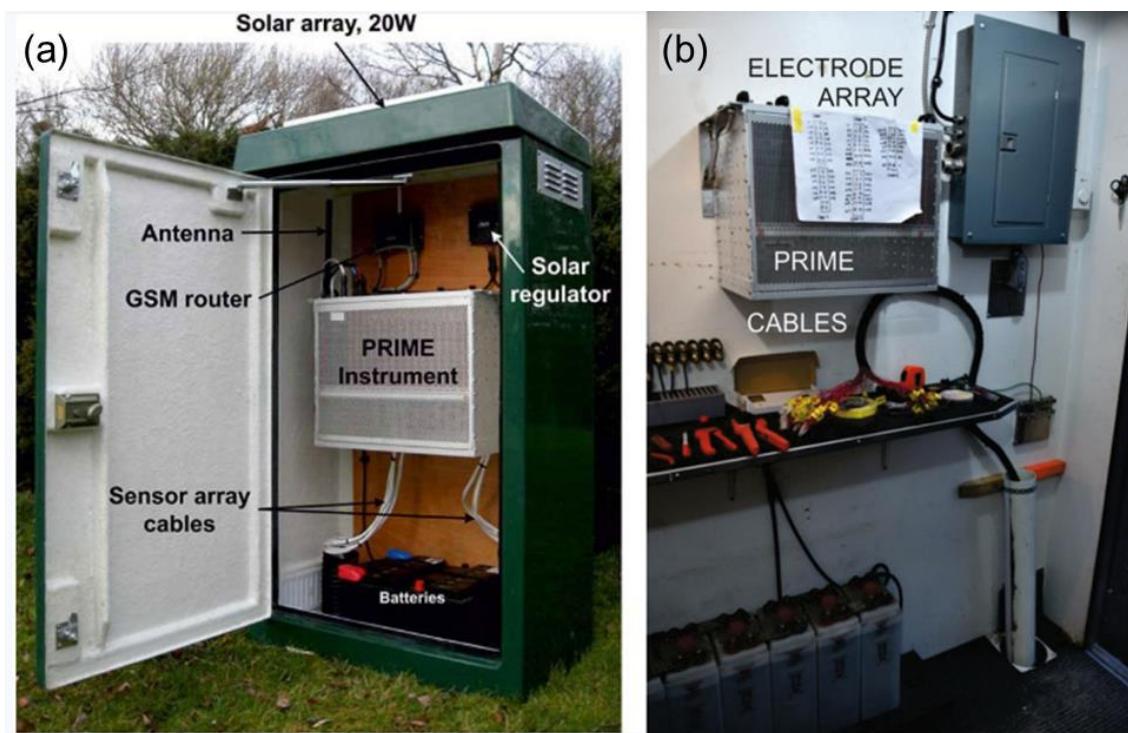


Figure 2. 20 PRIME system installation (a) in the field (Chambers et al., 2022) and (b) housed inside close to the survey area (Huntley et al., 2018).

Chambers et al. (2022) provide an in-depth analysis of the PRIME system and its various applications. Figure 2.21 provides a concept workflow of how the PRIME system operates, which considers the deployment of the instrument and array, data capture and storage, and data processing. The system is designed to address up to 512 electrodes and incorporates seven channels for simultaneous electrical measurements. Once a field/laboratory setup is established,

the operation is fully automatic and dependent on a pre-assigned scheduling system that can be tailored to the desired specifications. Data files from the PRIME instrument are accessed remotely and consist of field measurements (forward and reciprocal), a health log detailing current and voltage output over time, a time series analysis of contact resistances and reciprocal errors (e.g., Figure 2.22) and a summary of error measurements. Diagnostic information (e.g., health logs) and electrical data (transfer resistances, calculated resistivity error, etc.) from the PRIME system can be emailed directly or archived in a data repository. Forward and reciprocal measurements are sent as separate files and are easily merged using Python or input separately into inversion software (e.g., ResIPy). The code, provided by the BGS and developed by Dr Boyde, used to merge the forward and reciprocal measurements are found in Appendix A. Processing and inversion are configured to Res3DInv (Chambers et al., 2022), allowing a simplified workflow from data acquisition, inversion and finally, visualisation with complete control over inversion parameters (Aarhus, 2024).

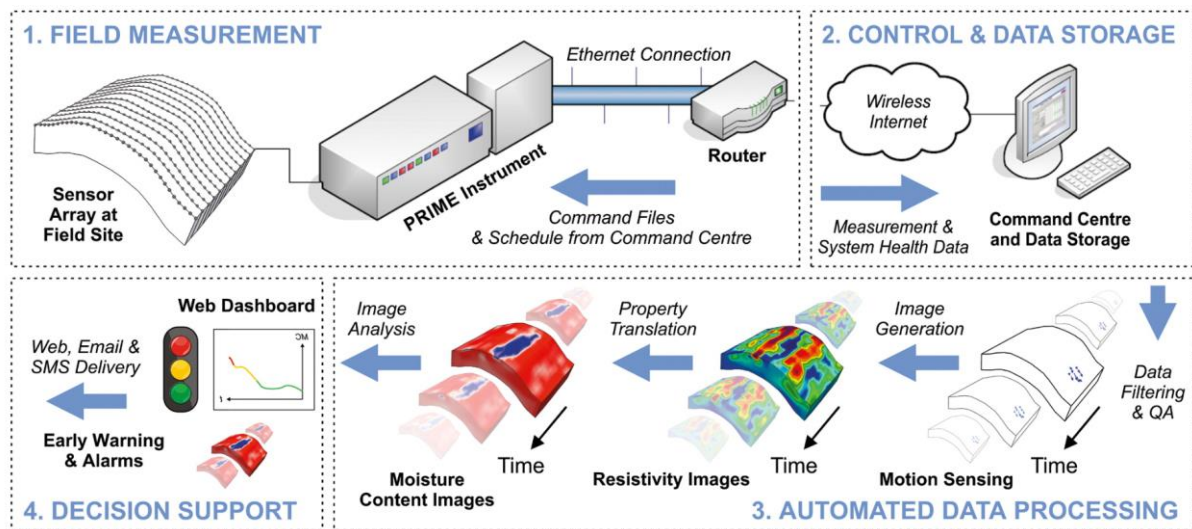


Figure 2. 21 Workflow of the PRIME system (Holmes et al., 2020).

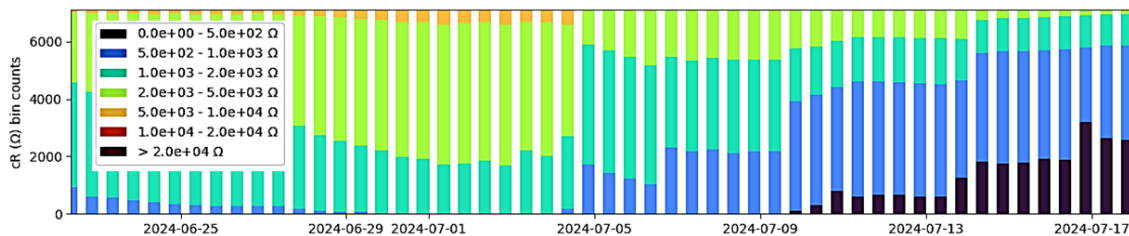


Figure 2. 22 Example of an automatically generated PRIME time series summary of average contact resistances (CR).

The PRIME system has been used to monitor moisture dynamics during landslide reactivation (Uhlemann et al., 2017), investigate slow-moving landslide behaviour (Holmes et al., 2020), monitor ground-water interactions (McLachlan et al., 2020), and soil-water-plant interactions on railway cutting conditions (Holmes et al., 2022). McLachlan et al. (2020) used the PRIME system to extensively monitor river-groundwater interactions in a chalk river adjacent to a wetland. Measurements were taken over one year to capture seasonal variations and hydrological events such as vegetation changes. Time series analysis (Figure 2.23) identified distinct hydrological layers within the peat and gravel, and resistivity patterns constructed from this time series established upwelling of resistive groundwater from the gravel and downwelling of the less resistive peat waters, which were particularly clear during vegetation-cutting events. To ensure accurate resistivity measurements throughout the year, resistivity models were corrected to consider temperature variations throughout the seasons. The PRIME system provided valuable insight into spatial and temporal dynamics of groundwater-surface interactions that furthered understanding of subsurface hydrological processes and their response to environmental changes (McLachlan et al., 2020).

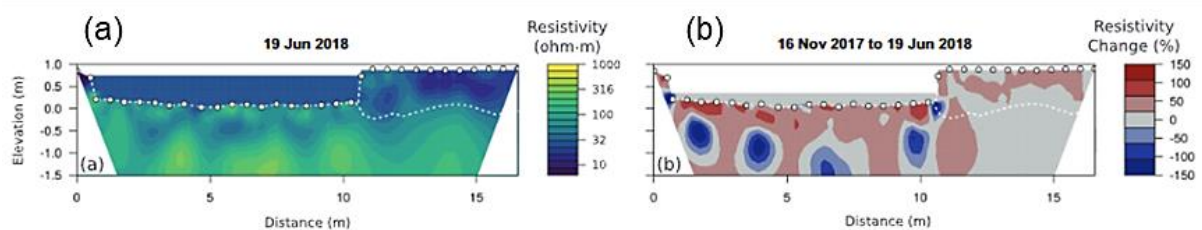


Figure 2. 23 A sample of the time-lapse imaging captured by the PRIME system shows (a) spatial distributions in resistivity and (b) the percentage change in resistivity (McLachlan et al., 2020).

In 2017, a PRIME system was installed at the site of the Ripley Landslide, Canada (Holmes et al., 2020). Sensor arrays took routine measurements twice per day. Field visits were reduced owing to the automated data collection provided by PRIME technology, an advantage over traditional ERT surveys. Results from the experiment (as seen in Figure 2.24) noted that temporal resolutions were far more significant than manual repeat ERT surveys (Holmes et al., 2020). Contact resistances were measured lower in the summer and higher during winter due to localised freezing at the slope surface. This seasonal variability also contributed to complications in interpreting the ERT data due to vegetation activity. The presence of trees led

to significant seasonal changes in moisture content and the shrink-swell behaviour of clays that impact slope instability. The relationship between soil-water-plant interactions and their various influences on the slope were challenging to interpret in the ERT results. Measurements with poor transfer resistances were filtered at $\geq 5\%$ reciprocal errors before inverting to improve image quality (Holmes et al., 2020). The 4-D ERT images collected using PRIME technology provided information on seasonal subsurface hydrological changes at the landslide site. This proved essential for understanding failure characteristics and slope behaviour near critical railway infrastructure.

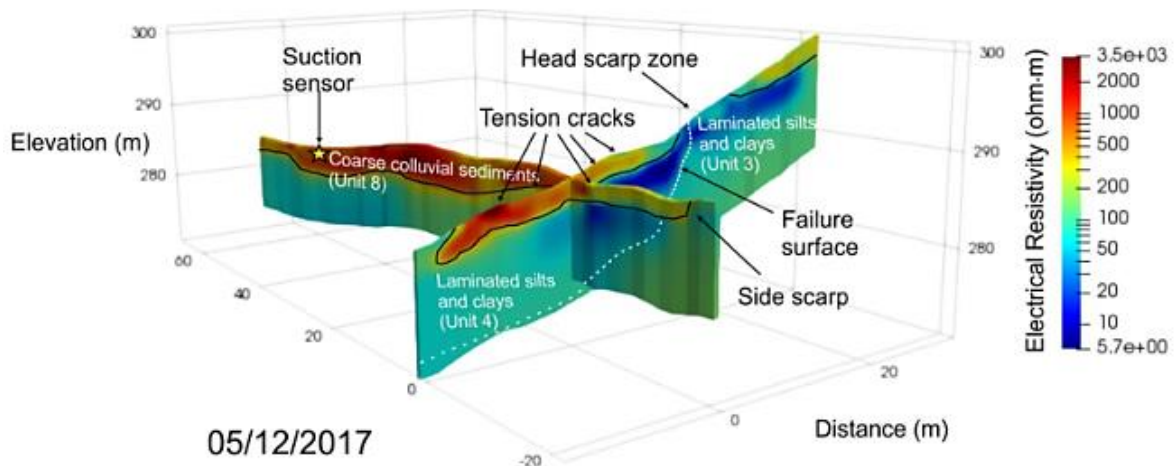


Figure 2. 24 Shows a baseline image used in the time-lapse resistivity survey, distinguishing different lithologies (black lines) and key landslide features. The image shows the spatial distributions in resistivity (Holmes et al., 2020).

2.9 Point sensor measurements

In this research, point sensors are used in combination with ERT technology to monitor soil moisture dynamics in a suite of soil column experiments. Teros 12 and 31 sensors are used throughout this study and compared to the ERT-derived measurements. Both sensors have a robust design, ensuring durability and higher data resolution. They are easy to install and use in a laboratory setting, facilitating efficient and accurate soil moisture monitoring (Meter, 2024).

Teros 12 sensors (Figure 2.25) capture volumetric soil moisture content, temperature, and EC changes. These sensors operate based on capacitance/frequency domain reflectometry (FDR) principles, where an electromagnetic field is generated around the sensor needles (Chan, 2025). The dielectric permittivity (A diagnostic physical property that quantifies the extent of electrical

polarization a material undergoes when subjected to an external electric field) (EM GeoSci, 2025) of the surrounding soil influences the signal, allowing the sensor to determine MC. A factory-calibrated output provides high accuracy for most soil types, though site specific calibration can improve precision (Cominelli et al., 2024). The sensors measure soil temperature via a thermistor located in the middle needle and measures bulk EC by analysing the response of the soil to the applied magnetic field (Fragkos et al., 2024; Nasta et al., 2024).

Teros 12 sensors have been used in various studies (e.g., Jafari et al., 2019; Kimball et al., 2019; Lo et al., 2020). Lo et al. (2020) noted variations in results between repeat experiments measured by the Teros 12 sensors, indicating that hardware consistency and sensitivity to microscale heterogeneity affected their performance. Despite this, studies mention the integral role the sensors had in research, like furthering one's understanding of the temporal changes in soil moisture based on rainfall duration and intensity (Jafari et al., 2019).

Teros 31 laboratory tensiometers (Figure 2.26) are designed to measure soil water potential and temperature and are optimised for soil columns, cores, and sampling rings (Meter, 2024). The sensors are small and well-suited to performing water potential spot measurements in tight spaces. It operates by equilibrating with the water potential of the soil through a porous ceramic tip, allowing for accurate measurements in the range of -85 kPa to +50 kPa and have a five-second measurement response time (Meter, 2024). In this study, Teros 31 sensors are utilised to monitor soil water potential within soil column experiments. These sensors provided high-resolution, real-time data, which was essential for validating electrical resistivity tomography (ERT) measurements and enhancing the understanding of moisture distribution and movement in engineered soils.

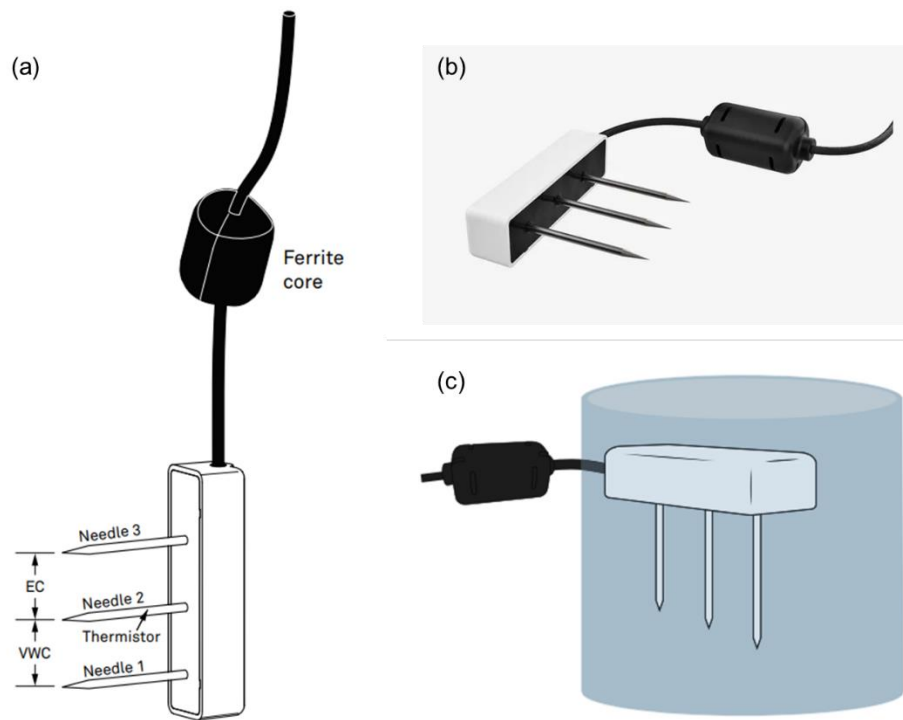


Figure 2. 25 Teros 12 sensor showing (a) an illustration of the sensor and components, (b) a photograph of the sensor and (c) placement of the sensor in a volume of material (Meter, 2024).

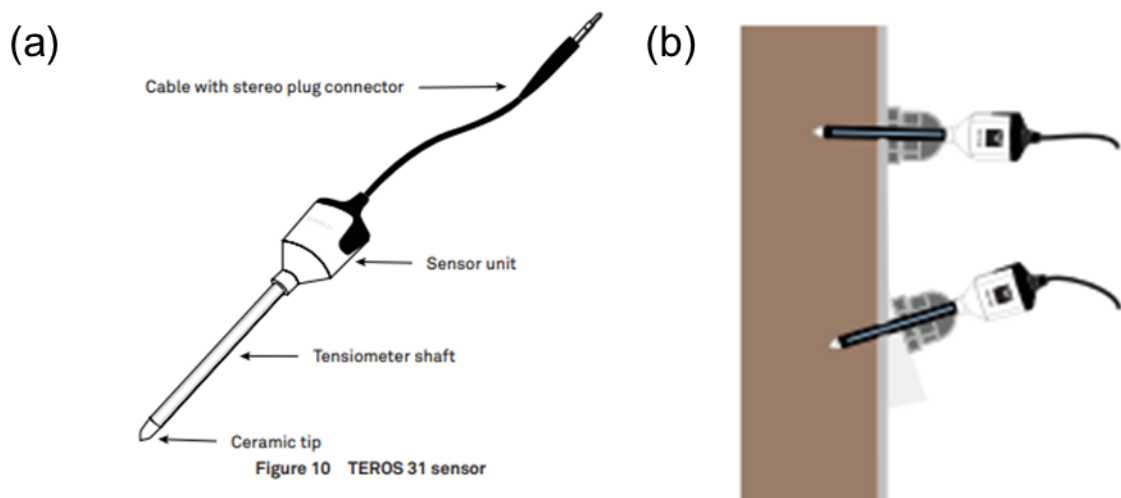


Figure 2. 26 Teros 31 sensors show (a) the sensor and various components and (b) methods of installation in a column/soil core (Meter, 2024).

2.10 Petrophysical Relationships

Soil electrical resistivity is a proxy for temporal and spatial variability of other soil properties like moisture content (Samouelian et al., 2005). Electrical resistivity and moisture content correlate (Holmes et al., 2022). Electrical current in soils depends on the volume of water in pore spaces (Samouelian et al., 2005). Therefore, resistivity decreases as moisture content increases. Both soil suction and electrical resistivity depend on the degree of soil saturation (Liu et al., 2022). Resistivity is also influenced by soil texture and porosity, which can affect soil suction, with fine-textured soils typically having a higher porosity and exhibiting higher suction and lower electrical resistivity measurements when saturated (Liu et al., 2022). This study used a salt tracer during controlled rainfall events to capture a wetting front in the 4-D ERT imaging. Soil salinity can also affect petrophysical relationships whereby higher salt content leads to low resistivity, influencing soil suction (Fang et al., 2019).

4-D ERT can assess variable spatial distributions in moisture content and suction by converting electrical resistivity to gravimetric moisture content (GMC) or suction (e.g., Holmes et al., 2022; Boyd et al., 2024). A calibration model like Waxman-Smits (Waxman & Smits, 1968) is used to fit resistivity and moisture content data, like the modified equation used by Holmes et al., 2022 (Equation 6).

$$p(GMC) = F \left(\frac{(1 - \varphi) D_g GMC}{\varphi D_w} \right)^{-n} \left(\sigma_w + B_{ws} \left[\frac{(1 - \varphi) D_g C}{100 \varphi} \right] \left[\frac{\varphi D_w}{(1 - \varphi) D_g GMC} \right] \right)^{-1} \quad [6]$$

Where, F is a formation factor, φ is porosity, D_g is grain density (g cm^{-3}), D_w is water density (g cm^{-3}), n is a saturation exponent, σ_w is the pore water conductivity (S/m), and C is cation exchange capacity (meq/ 100 g). B_{ws} ($\text{S cm}^3 \text{ m}^{-1} \text{ meq}^{-1}$), the average cation mobility.

Using Equation 6, GMC can be replaced with suction to find the relationship between soil electrical resistivity and suction:

$$p(\psi) = F \left(\frac{(1 - \varphi) \theta_s \gamma(\psi)^{-b}}{\varphi} \right)^{-n} \left(\sigma_w + B_{ws} \left[\frac{(1 - \varphi) D_g C}{100 \varphi} \right] \left[\frac{\varphi \gamma(\psi)^{-b}}{(1 - \varphi) \theta_s} \right] \right)^{-1} \quad [7]$$

Where ψ is soil suction, θ_s is water content at saturation, and b is a fitting parameter.

Numerical models are also used to calibrate ERT data to model moisture content. An inverse power-law distribution has been used to model GMC using Equation 8:

$$R(\theta_g) = \frac{1}{\alpha(\theta_g^b)} + c$$

[8]

Where $R(\theta_g)$ is resistivity as a function of gravimetric moisture content (*GMC*), θ_g is GMC, and α , b , and c are fitting parameters (Boyd et al., 2024).

Deriving soil petrophysical relationships from ERT measurements requires a correlation and translation of electrical resistivity into more generic characterising soil properties like moisture content, porosity and soil suction. This process is crucial for interpreting ERT data as hydrological and geotechnical parameters, ultimately enhancing the understanding of subsurface conditions. This study utilises petrophysical relationships to interpret ERT data collected from soil column experiments. By establishing correlations between electrical resistivity and soil moisture content, it is possible to effectively monitor moisture dynamics within the soil columns. This approach provided a non-invasive means to assess changes in soil moisture over time, thereby validating the effectiveness of ERT in capturing hydrological processes in engineered soils.

Chapter 3 Methodology

3.1 Introduction

A number of studies have used 4-D ERT to examine changes in moisture content over time, with large-scale field investigations being the most prominent (Chambers et al., 2012; Lesparre et al., 2019; Holmes et al., 2022). Deployment of 4-D ERT in a laboratory setting is seldom done, with most controlled experiments carried out using 3-D ERT and with very few studies examining the potential use of ERT in soil column experiments to examine water transport in soils (Binley et al., 1995-96; Slater et al., 2002; Koestel et al., 2008; Kettridge et al., 2011). This chapter provides a narrative of the development of 4-D ERT for column experiments to inform upon design choices and changes to experimental parameters. Due to the limited research on 4D ERT soil column experiments, this study is highly experimental. It relies on the ERT images produced during experiments on different materials (sand, clay, etc.) to develop the methodology and soil column design.

The chapter introduces the different soils and asset management regimes that were tested. The soil column experiments have been separated into two distinct categories referred to throughout this thesis as Series 1 and Series 2. Each series deploys a different methodology, which this chapter explains at length. Traditionally, methodology defines the design and conduct of experiments. This is done at length. However, to inform the reader of the various design choices and subsequent applied conduct, it is necessary to provide some primary results that provide context for the changes made to the soil column experiments throughout this research.

3.2. Deployment of the PRIME system

Electrical measurements using ERT were carried out in a series of soil column experiments and a lysimeter investigation at the National Green Infrastructure Facility (NGIF), Newcastle. The lysimeter study is not detailed in this work. However, the placement of the PRIME system (shown in Figure 3.0) and associated lysimeter electrode cables is relevant to the location of the soil column experiment.

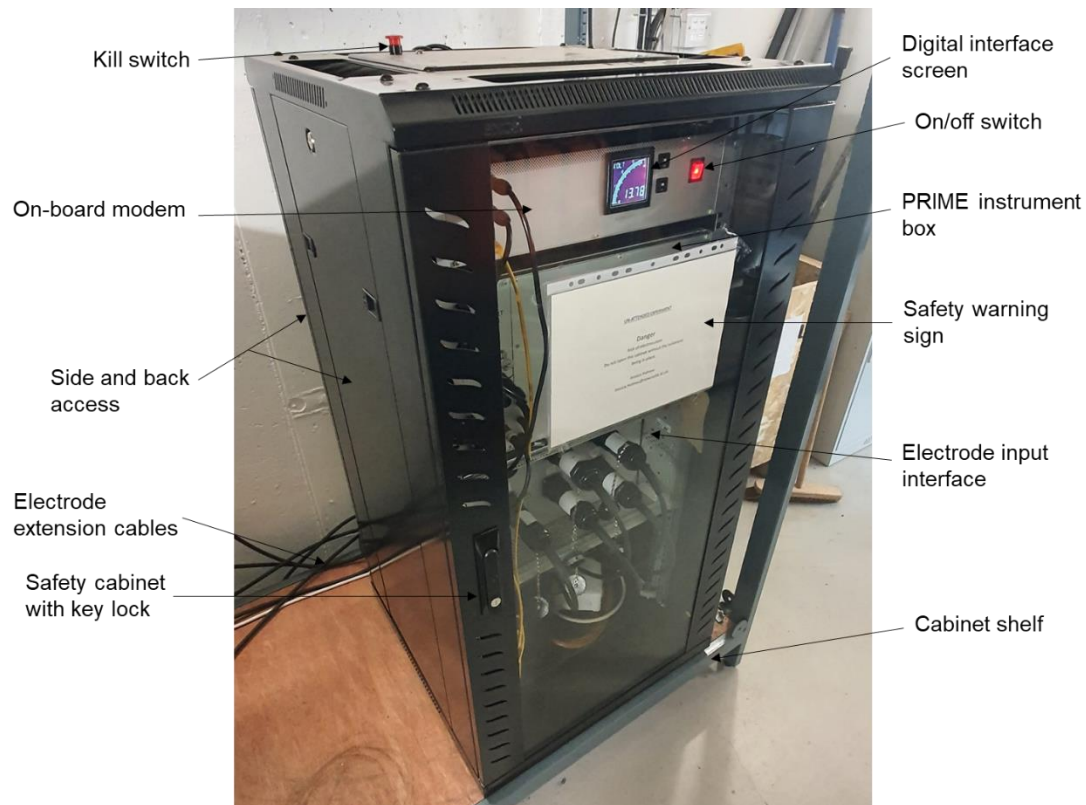


Figure 3. 0 The PRIME system and safety cabinet are housed in the NGIF utility room.

Figure 3.1 shows a deployment map of the PRIME System relative to the position of the lysimeter and environment chamber where the soil columns were housed. The PRIME system was used to conduct electrical surveys on a field and laboratory experiments at different times of the day. Therefore, the system needed to be placed conveniently between the two sites. The site map shows that the electrode arrays were deployed in Lysimeter 2 through underground utility pits beneath the pavement. For the soil column experiments, two multicore cables were also connected to the ERT soil column in the Suds working area (Figure 3.2). These two cables were run through the environment chamber along wall-mounted panels and ceiling cable rails to the PRIME System in the Suds storage room.

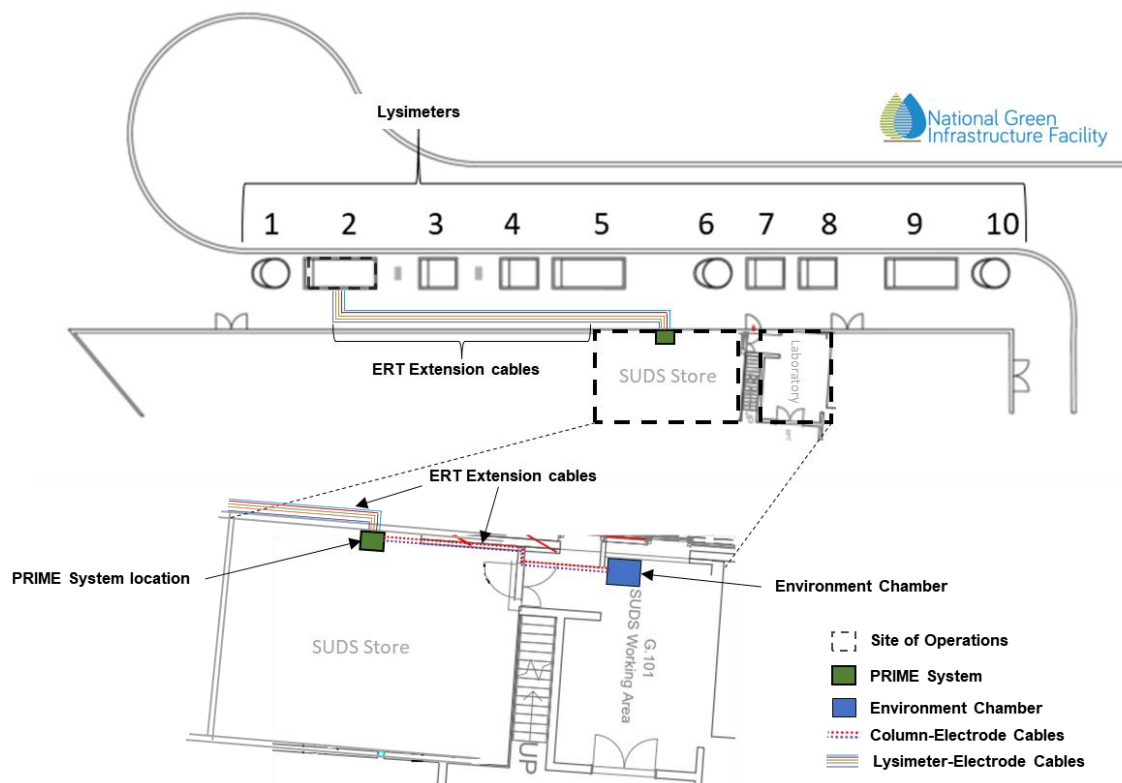


Figure 3. 1 NGIF deployment map indicating the location of the PRIME System relative to the soil columns.

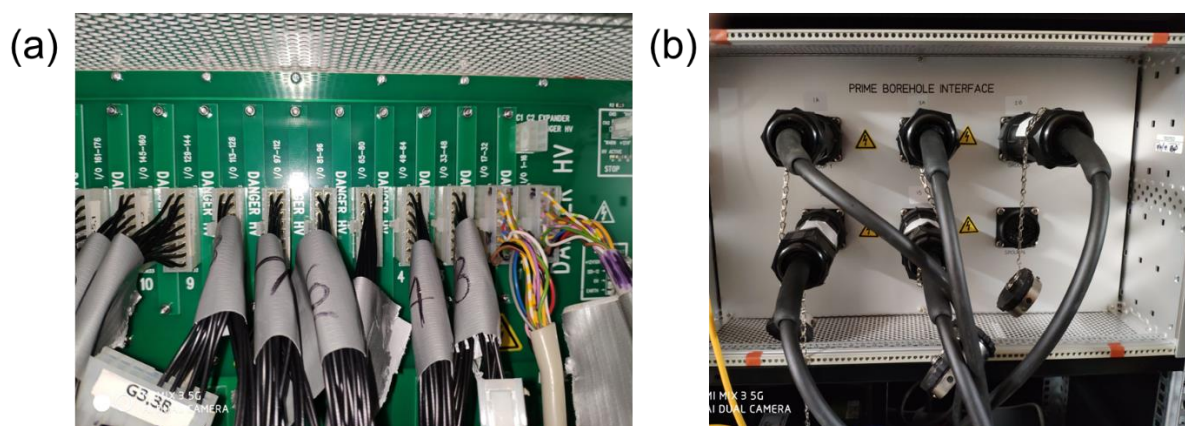


Figure 3. 2 Electrode array cables attached to (a) the back of the PRIME system interface with two multicore cables containing 16 electrode wires each – see coloured cables on the right-hand side of the image and (b) the front of the system with five extension cables.

3.2.1 PRIME System Measurement Schedule

The PRIME system operates on a scheduled measurement system with time allotted for the soil column experiments and the lysimeter project. Figure 3.3 provides a snapshot of the measurement schedule assigned to the PRIME System. Sequenced measurements occur over 24 hours, with gateways opening and closing between 11:00 pm and 1:00 am. Electrical measurements within the lysimeter occur twice daily (morning and evening) for three hours. Sixteen hours are dedicated to electrical measurements of the soil column experiment in a 24-hour window. Forward and reciprocal measurements are taken for each series of measurements. It takes eight minutes for the PRIME system to complete a forward and reciprocal measurement. In four minutes, the PRIME system measures the apparent resistivity between a combination of four electrodes 204 times. The PRIME system takes measurements in the soil column between 01:00 – 06:00 and 09:00-17:00. Simulated storm events took six hours to complete. To ensure that the full extent of the rainfall event was captured by the PRIME system and during the appropriate working hours, rainfall simulations were initiated at 10:00 and concluded at 16:00.

		Command	Forward/Reciprocal	Time	
				Start	Finish
		Gateway Closed		00:55	00:55
Soil column		3001-XH_f SUDS_test	3001	04:00	04:24
		3002-XH_r SUDS_test	3002	04:30	04:54
		3001-XH_f SUDS_test	3001	05:00	05:24
		3002-XH_r SUDS_test	3002	05:30	05:54
Lysimeter		5011-equatorial_measurements_side_A	5011	06:30	07:20
		5012-equatorial_measurements_side_A	5012	07:30	08:20
		6011-equatorial_measurements_side_B	6011	08:30	09:25
Soil column		2001 DD_f SUDS_test	Cmd1	09:00	09:04
		2001-DD_r SUDS_test	Cmd2	09:15	09:19
		2001 DD_f SUDS_test	Cmd1	09:30	09:34
		2001-DD_r SUDS_test	Cmd2	09:45	09:49

Figure 3. 3 Snapshot of the PRIME System measurement schedule indicating the lysimeter measurements taken in the morning and the start of the measurements in the soil columns.

3.3 Soil Column Design

3.3.1 Soil Column Construction

Soil column experiments were conducted at the National Green Infrastructure Facility (NGIF), Newcastle, UK. Figure 3.3 shows a photograph of the soil column experiment setup. Two cylindrical columns (550 mm and 110 mm diameter) were constructed from PVC piping. A

collar was glued to the top of the column to suspend the columns from a stand. The stand was constructed from plywood in the fashion of a chemistry sample tube holder and coated in three layers of black waterproof paint to prevent the wood from swelling after continuous rainfall simulations. The base of the columns was fitted with a base cap to prevent material from falling through. The columns were fitted to tipping buckets, measuring water outflow. The tipping buckets (4ml/tip) were attached to the base of the column via a tube outfitted with a water control gauge, and a mesh was placed at the base of the columns to prevent fines from the soil from washing through the tube and into the tipping buckets. A tube was fitted at the soil surface level (500mm) to prevent ponding. These outflow tubes were connected to tipping buckets to capture surface water drainage. The experiment was conducted in a temperature-controlled environment chamber for the duration of the experiment. Initially, this research aimed to capture soil-moisture-plant dynamics using time-lapse ERT. Therefore, utilising a temperature-controlled environment during experiments was essential. However, the notion of including a vegetation aspect was later dismissed because more time was needed to improve the ERT-soil column design to produce ERT images with fewer modelling artefacts. Column experiments with plants would require time to grow. This was not possible due to project time limitations.



Figure 3. 4 A photograph of the soil column experiment contained in the environment chamber at the NGIF.

3.3.2. Integration of ERT

Figure 3.5 depicts the soil column setup and components. Soil column (a) was instrumented with 32 ERT electrodes in a four-dimensional array. The electrode configuration consisted of four rows of eight, with a 50mm gap between each electrode. A comprehensive combination of geoelectrical measurements ensures that the full extent of soil in the column is captured per measurement cycle. A dipole-dipole array was used to capture spatial distributions in resistivity. Electrodes pairs inject current and read the difference in potential. Corresponding forward and reciprocal measurements utilise the same four electrodes, alternating the electrode pairs that transfer power and current. A dipole-dipole array was used due to the space limitations of the soil column. Other arrays (e.g., pole-dipole) are not well suited as the potential electrodes are typically situated at a distance from the current electrodes, which was not possible in the column experiments.

Alternative electrode configurations, such as Wenner, Schlumberger, or cross-borehole arrays, were considered in the design phase. However, the spatial constraints imposed by the cylindrical column geometry and the need for precise, repeatable measurements in a small-scale environment made these configurations impractical. For example, Wenner and Schlumberger arrays typically require broader spacing between current and potential electrodes, which would have exceeded the physical boundaries of the column or introduced inconsistencies in spatial resolution. Cross-borehole methods were unsuitable due to the absence of paired vertical access points and the desire to minimise structural intrusions. Therefore, a fixed dipole-dipole array was adopted for its compact geometry, compatibility with the PRIME system, and utility in column-scale geoelectrical imaging.

Holes drilled into the column for the electrodes were fitted with a plastic sealant used to support the weight of the electrodes, keeping them level over time and providing a watertight seal. The electrodes were constructed from round carbon graphite rods coated in copper, each 35 mm long, sitting proud of the interior wall of the column, in part contained within glands. The tips of the electrodes were ground to a level blunt end.

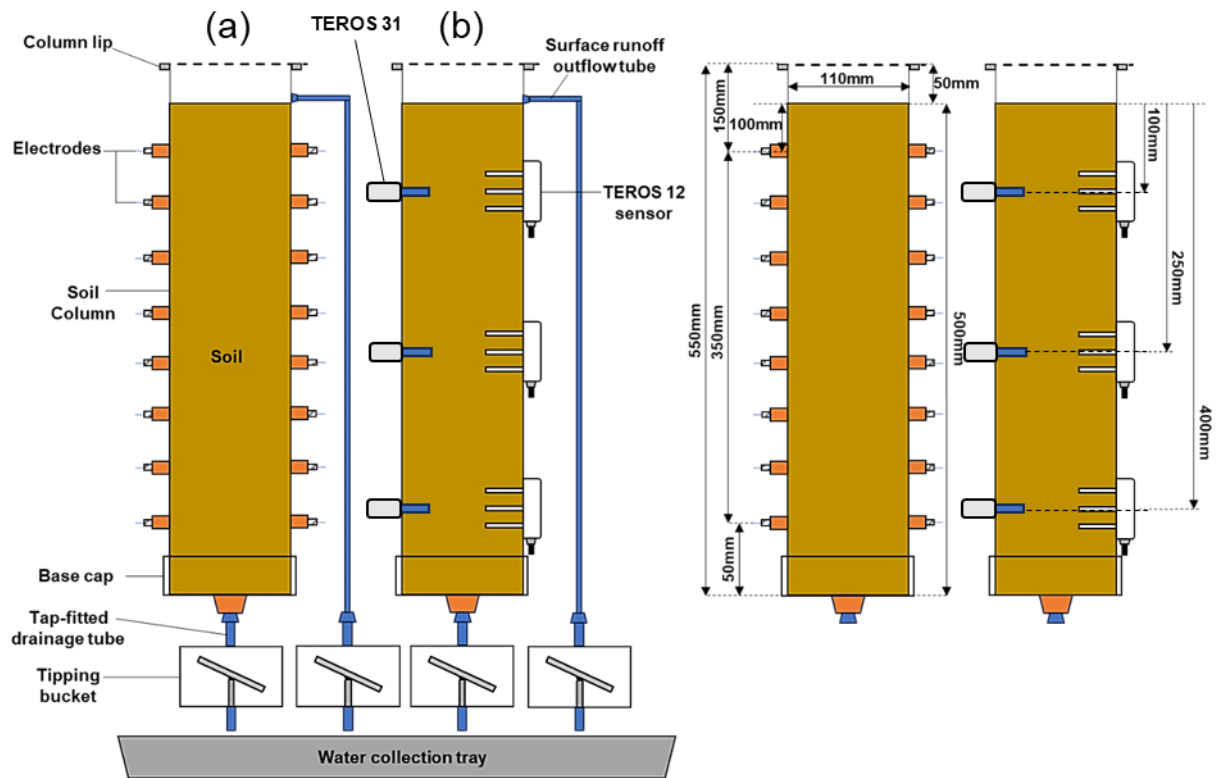


Figure 3. 5 Diagram of soil column experiment with column dimensions on the right and components on the left. The left diagram indicates (a) the ERT-instrumented soil column and (b) the point sensor soil column.

Two iterations of the ERT soil column were developed to adapt the PRIME instrument for column experiments (Figure 3.6). The first design (a) deployed electrodes cut from stainless steel with pointed tips that could protrude into the sample. Glands were fitted to the column so the electrodes could be removed easily between experiments, and the depth that the electrodes extended into the soil could be adjusted. The second column (b) used electrodes cut from carbon graphite coated in copper foil. These electrodes are sealed into a position flush to the inside of the column with blunt tips. Before filling the columns with soil, the ability to model resistivity was evaluated in both designs. Fixing the positions of the electrodes in the column standardised the method for conducting ERT surveys in the column experiments whilst testing different materials. Therefore, specific parameters (e.g., electrode spacing, measurement configurations, and data acquisition sequences) are predetermined and consistently applied throughout the survey, thereby ensuring uniformity and comparability of data between different materials. Measurements with the PRIME system were taken every 30 minutes, allowing 15 minutes for the forward measurement and 15 minutes for the reciprocal. This was the shortest measurement interval allowable due to the number of electrodes.

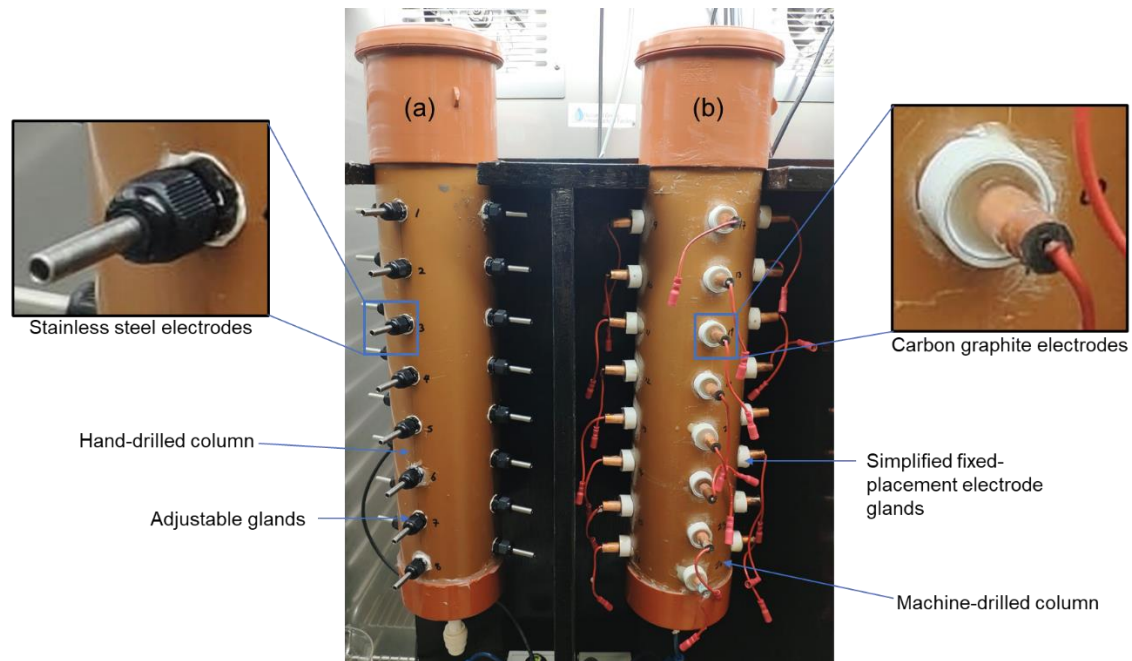


Figure 3. 6 Photograph showing the first iteration of (a) the ERT soil column next to (b) the second soil column design iteration.

A summary table comparing the first and second iteration designs of the ERT soil column is given in Table 1.

Feature	First Iteration	Second Iteration
Column Dimensions	Hand-made column with minor ($\leq 5\text{mm}$) differences in electrode placement	Machine-built column used for precise electrode positions
Electrode Material	Stainless steel with a pointed tip	Carbon graphite coated in copper
Electrode Geometries	Positioned in water-tight glands allowing for adjustable electrode depth through material	Electrodes placed flush to column interior in a fixed position without glands
Point Sensor Instrumentation	x3 soil moisture sensors (TEROS-12) x3 tensiometers (TEROS-31)	x3 soil moisture sensors (TEROS-12) x3 tensiometers (TEROS-31)
Geosynthetic Model	More complex due to modelling of glands and point array deployment	Simple due to electrodes placed flush to column interior and no glands used for adjusting the electrodes
Electrode-Wire Connection	Hollow ended electrode providing a female-male connection for the wire	Wires were soldered onto the blunted ends of the carbon graphite

Table 1 Summary of changes to the ERT soil column design.

The soil columns were filled with Category 5 (CAT 5) water (conductivity = $333.6 \mu\text{S/cm}$), providing a homogenous medium to analyse the water resistivity. CAT 5 water refers to water representing a severe health risk compared to standard drinking water. Diagnostic information supplied by the PRIME system indicated that contact resistances and reciprocal errors were

lower in column (b) than in column (a), suggesting carbon graphite was a more effective electrode design than steel. Early assessments indicated that both columns outputted highly irregular resistivity measurements. Figure 3.7 depicts the resistivity profile of water from columns 1 and 2 produced using ResIPy, a Python wrapper providing a graphical interface to process resistivity data from ERT sources (Blanchy et al., 2020). The inversion of column (a) shows regions of high resistivity surrounding the electrodes. It was assumed that the glands fitted to the column surrounding the electrodes and the length of the electrodes were creating a layer of complexity in the geoelectrical models. A finite element modelling mesh was developed to model the glands and electrodes physically in the 3D volume of the cylinder. This approach helped slightly to achieve a more homogenous resistivity volume as it enabled ResIPy to account for the existence of the glands during processing; however, when column B was filled with water, and the resistivity profile was examined, the same problem persisted for column 2, despite the more simplified geometries.

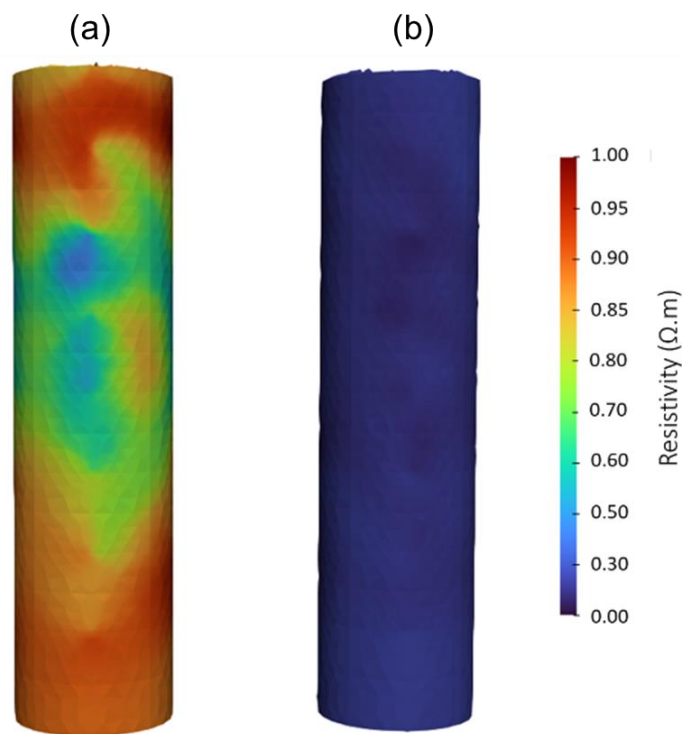


Figure 3. 7 Inversions of (a) Column A and (b) Column B, as seen in Figure 3.6. The columns are filled with water, which demonstrates how changing soil column parameters (electrode material, geometries, etc.) influenced the accuracy of the resistivity models.

Subsequent examination of the ERT-soil column setup revealed that minor inconsistencies in the geometries of the electrodes and voltage clipping were at fault. When modelling the positions of the electrodes in the column, their locations must be as accurate as possible. Research conducted by Wilkinson et al. (2015) highlighted that electrode displacement in the field can lead to errors in the geoelectrical data. The positions of the electrodes were compared to the finite element modelling mesh, and several electrodes were found to be up to 4mm off their modelled location. Such inconsistencies in the field would likely be negligible. However, scaling down an ERT survey to a laboratory scale is likely to increase the sensitivity of the array to factors that can incur artefacts in the ERT imaging. Column (a) was handmade, accounting for these electrode position inaccuracies. The column was remade with machine capabilities (b), removing the risk of human error. Measurements collected by the PRIME instrument with high geometric factors were voltage-clipped, causing inaccuracies in the returned transfer resistances. Geometric factors are physical entities that must be accounted for when modelling ERT resistivity data. The more complex the geometries of the model become, the harder it is to portray the data accurately. Voltage clipping occurs when the PRIME system supplies the electrodes with too much electric pressure, resulting in the voltage transfer between electrodes exceeding its reference voltage level. A reference voltage level was not predetermined before commencing the experiment. Changing the design of the column by using different electrode materials, reducing the complexity of the cylindrical mesh for processing, and reducing the injected current from 20 milliamps (mA) to 2 drastically improved the quality of the ERT imaging, resulting in the bulk resistivity of the column now being within a sensible order of magnitude.

3.3.3. Point Sensor Instrumentation

Soil Column (b), Figure 3.5, features three soil moisture sensors (TEROS-12) and three tensiometers (TEROS-31). 4D ERT captures transient soil moisture conditions over time and point sensor measurements are used to validate the geophysical observations. TEROS 12 sensors measure soil volumetric moisture content (VMC), temperature, and electrical conductivity. TEROS 31 tensiometers measure soil water potential and temperature. A generic calibration was applied as the soils used in the experiments had an electrical conductivity lower than 8000 $\mu\text{S}/\text{cm}$. These sensors are well suited for laboratory work on soil columns, given that the sensor shaft can be installed from outside the column into the material and fitted into place using a gland. This minimises site disturbance levels and can be easily removed during soil refills and maintenance. It would have been advantageous to instrument one column with the

electrode configuration and point sensors (moisture sensors and tensiometers). However, it was likely that the point sensors would interfere with the ERT measurements. Soil column experiments using ERT by Koestel et al., 2008 incorporated electrodes and point sensors into a single column, made possible given the large column size (140cm L x 120cm W). Furthermore, the tensiometers and TDR probes were smaller, reducing the likelihood of significant interference.

3.4 Soil Characterisation Experiments

Soil column experiments were instrumented with 4D ERT electrode arrays and filled with different engineered soils and associated with asset management regimes before being subjected to a simulated storm event. The soils investigated included (1) gravel, (2) sand, (3) clay topsoil, CT (comprised of Ampthill clay, AC, and sandy loam topsoil, SLT), and (4) Bourne Amenity topsoil, BAT. The composition of each column experiment is given in Figure 3.8.

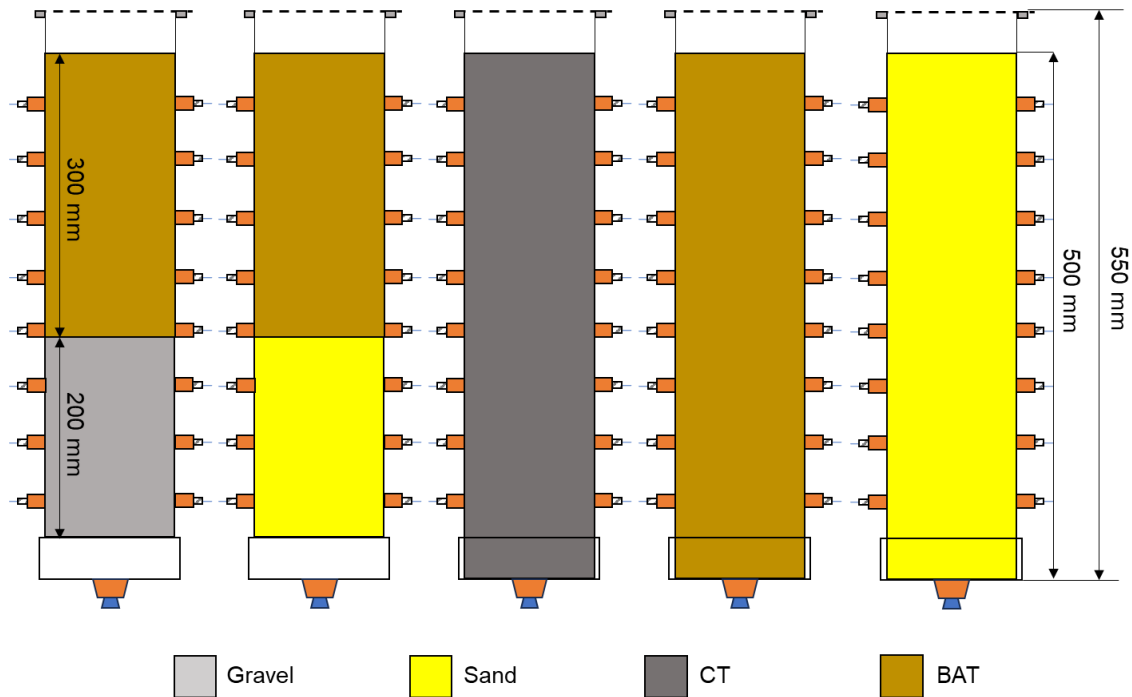


Figure 3. 8 The material compositions of each soil column experiment. (1) Gravel-based capillary barrier system, (2) Sand-based capillary barrier system, (3) Clay topsoil (CT), and (4) Bourne Amenity Topsoil (BAT).

3.4.1 Compaction Experiments

Before starting the soil column experiments, each material underwent several characterisation experiments to establish its physical properties. Compaction tests were performed on each material, except for the sand and gravel, per the British Standards (BS 1377-1-8, 1990-2018). Given that the CT comprises AC and SLT, characterisation tests were also done on these soils. The soils were added to a mould in three layers compacted using a standardised hammer. Here, a Proctor test is used, and each layer receives 25 blows from a 2.5kg hammer dropped from a 30cm height (BS 1377-4-1990). Each layer was compacted evenly to achieve a consistent density. The dry density of each soil was calculated from the bulk density.

$$p = \frac{m_2 - m_1}{V}$$

[9]

Where p is the bulk density, m_1 is the mass of the mould and baseplate (g), m_2 is the mass of the mould, baseplate, and compacted soil (g).

$$Pd = \frac{100p}{100 + w}$$

[10]

Where Pd is the dry density (Mg/m^3) and w is the moisture content of the soil (%), as described in BS1377-4:1990 3.3.5.3. Compaction tests were repeated at different moisture contents to produce a compaction curve (Figure 3.9).

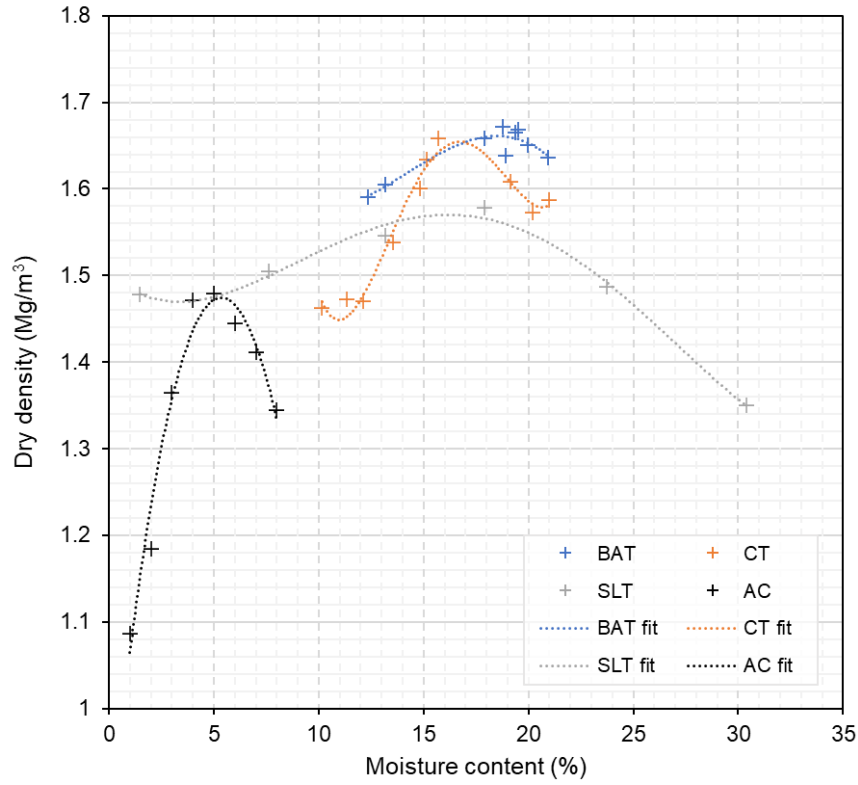


Figure 3. 9 Moisture content versus dry density of soils used in the column experiments. Data was collected through a series of Proctor compaction tests on Bourne Amenity topsoil (BAT), clay topsoil (CT), sandy loam topsoil (SLT) and Amphill clay (AC).

3.4.2. Particle Size Distributions

In line with the British Standards (BS1377-3), particle size distribution (PSD) tests were performed on each soil. A representative sample of each soil is oven-dried and then weighed before passing through a series of stacked sieves arranged in descending order based on soil particle passing size. The stacked sieves are rotationally shaken by hand for 10 minutes. The material retained on each sieve was weighed, and the mass was recorded. The percentage of soil retained on each sieve is calculated:

$$W_{retained} = \left(\frac{W_i}{W_1} \right) 100$$

[11]

Where $W_{retained}$ is the retained soil (%), W_1 is the weight of the dried soil sample (g), and W_i is the mass of retained soil on a given sieve (g). The cumulative percentage passing of the soil (CPP) is then calculated:

$$CPP = 100\% - \sum W_{retained}$$

[12]

Given the high clay content in the AC, a sedimentation test was done due to the high percentage of particles < 0.075 mm. A dispersing agent was used to separate the fine fraction of the soil in a sedimentation cylinder, and a hydrometer was used to measure the density of the suspended particles at various depths over time. Adjustments to the hydrometer were made dependent on the temperature correction factor. Using Stokes' Law, the PSD of the clay was determined:

$$v = \frac{2}{9} \frac{(r^2(p_s - p_w)g)}{\eta}$$

[13]

Where v is the settling velocity, r is the particle radius, p_s is the particle density, p_w is the fluid density, g is the gravitational acceleration, and η is the fluid viscosity (Stokes, 1856). The results from the sieve analysis and sedimentation test were combined, and the results are given alongside the maximum dry density and optimum water content in Table 2.

	Gravel (%)	Sand (%)	Silt & Clay (%)	Maximum Pd (Mg/m ³)	Optimum WC (%)
Gravel	92.00	8.00	0.00	-	-
Sand	0.50	95.00	5.00	-	-
AC	1.60	1.99	96.41	1.48	5.00
CT	0.00	50.00	50.00	1.69	17.00
BAT	1.56	56.28	42.16	1.66	18.70
SLT	15.10	82.67	2.23	1.58	17.90

Table 2 The physical properties of the soils used in the soil column experiments. Where Pd refers to dry density and WC to water content.

3.5 Series 1 Soil Column Experiments

3.5.1 Introduction

Nine soil column experiments took place between December 2022 and August 2023. A 1 in 100 storm event was simulated in each of the experiments. CAT-5 water (tap water) had a conductivity of 333.6 $\mu\text{S}/\text{cm}$. These experiments are grouped into two categories, referred to throughout this research as Series 1 and Series 2. Series 1 refers to soil column experiments conducted on (1) a gravel-topsoil-filled capillary barrier system (CBS), (2) a sand-topsoil-filled CBS, (3) Clay topsoil (CT) at three different dry densities (1.46 Mg/m^3 , 1.57 Mg/m^3 and 1.69

Mg/m³), and (4) Bourne Amenity topsoil (BAT). Series 2 refers to soil column experiments on (1) Sand, (2) CT and (3) BAT. The distinction between the two series is that changes were made to the experiment and methodology to account for several inaccuracies observed in the results of the first series of soil column experiments (Series 1). A summary outlining the difference between Series 1 and Series 2 soil column experiments is provided in Table 3.

Feature	Series 1 Soil Column Experiments	Series 2 Soil Column Experiments
Starting Conditions	Initial conditions were set for a variety of soils with standard protocols	Modified initial conditions with adjusted soil properties and setup details
Watering Schedule	Regular watering schedule based on standard practices (simulation of a 1 in 100 storm event)	Modified watering schedule to add water outside of PRIME scheduled measurements
Use of Salt Tracer	No salt tracer used	Introduction of a salt tracer to trace in storm simulations
Measurement Frequency	Standard frequency for measurements not specified in detail	Likely increased frequency or adjustments for more detailed data collection
Objective and Focus	Focused on establishing baseline measurements and understanding initial soil behaviour	Aimed at refining experimental setup and protocols based on Series 1 findings
Analytical Approaches	Standard analysis of soil properties and water movement	More sophisticated analysis techniques to address specific research questions raised by Series 1 results
Improvements and Adjustments	Basic setup with initial experimental configurations	Adjustments in setup and experimental configurations to improve accuracy and reliability of results
Specific Challenges Addressed	Initial challenges such as data variability and measurement errors	Targeted solutions to challenges identified in Series 1, such as reducing artefacts and improving data quality
Number of column experiments	9	3
Materials tested	Gravel-filled CBS, Sand-filled CBS, CT at three densities, and BAT	Sand, CT, and BAT

Table 3 Summary of differences between Series 1 and 2 ERT soil column experiments.

Due to the scarcity of research on 4D-ERT soil column experiments, this study is highly experimental. Therefore, the results from the ERT imaging were relied on to inform the column design and measurement parameters of the PRIME system. During the Series 1 soil column experiments, time-lapse imaging indicated increased electrical resistivity as water was added to the soil during a storm simulation. Figure 3.10 shows the time-lapse survey derived from a soil column test filled with BAT, where images left and right depict cross sections through the column, and the middle image of each inversion reflects the wall of the column. A baseline-constrained inversion was applied to the data, and reciprocal errors were filtered at 5%. Imaging

shows the percentage difference and spatial distribution of resistivity before and after water was added to the soil column. The data shows that resistivity increased at the soil surface and base, extending towards the middle of the column. Determining why resistivity increased when water was added to the soil columns was challenging. It was uncertain whether the phenomenon was a product of a modelling error in the inversion process or an actual accurate change in resistivity that was occurring. In this Section (3.5), the method of soil column testing is provided for Series 1, and Series 2 is examined in Section 3.6.

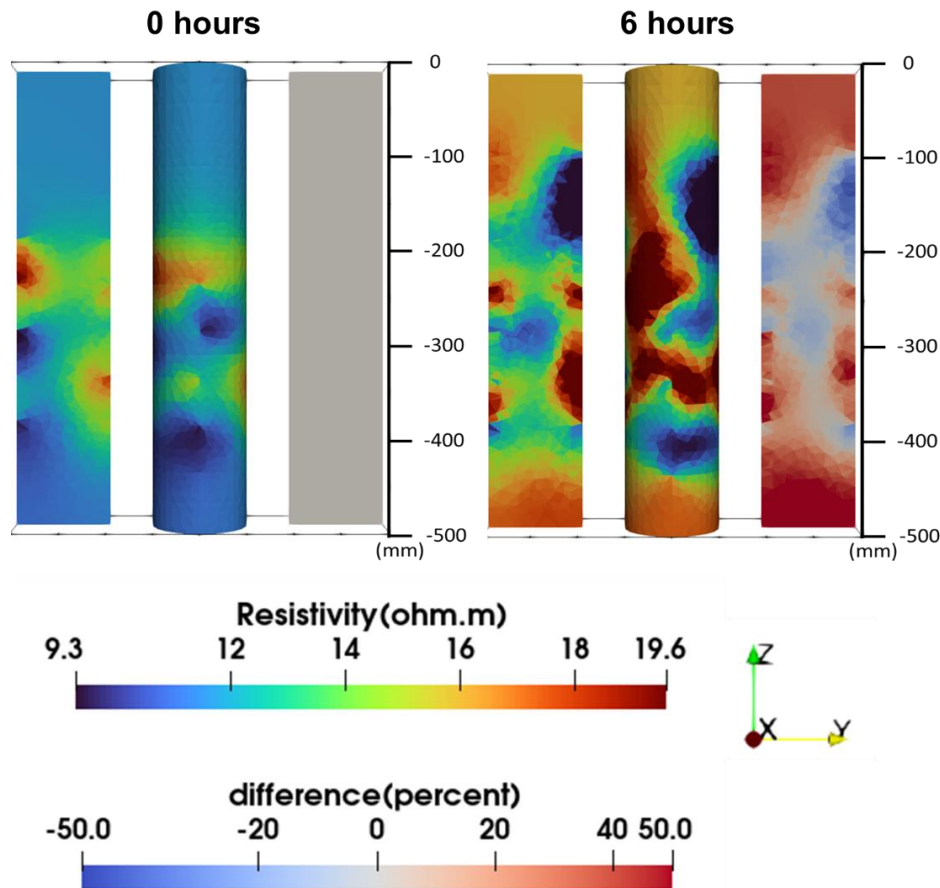


Figure 3. 10 A sample time-lapse survey of a soil column filled with BAT before and after a six-hour simulated storm. ERT images show the spatial distribution of electrical resistivity (left and centre) and the percentage difference in resistivity (right).

3.5.2 Gravel and Sand-Filled CBS

Soil column experiments were carried out on a CBS consisting of topsoil overlying a drainage layer of gravel (approximately 20mm grain size) and a CBS comprised of topsoil overlying sharp sand (2-4mm grain size). The experiment aimed to examine the effectiveness of CBSs during storm events in temperate conditions. Figure 3.11 depicts the soil column setup, indicating the column dimensions, soil heights and positions of the electrodes and point sensors. The materials were dried in an oven before being added to the columns. This was done to ensure

soil moisture content was as close to zero as possible, ensuring that no water would compromise the capillary barrier in effect before a simulated storm event. A geotextile was placed at the boundary between the coarse-grained layer and the fine-grained topsoil to prevent any wash-through of fines into the coarse-grained layer. A second geotextile was placed at the base of the soil column to prevent any material from washing into the tipping buckets. Relative humidity, temperature and lighting in the chamber are kept constant. The environment chamber was set to 16.6 degrees Celsius for all soil column experiments, consistent with mean UK summer temperatures (2017-2021). A 1 in 100 storm event was simulated over six hours (storm event 1). At the end of the storm event, the gravel-filled CBS was left to dry for four weeks before another storm event (storm event 2) was carried out. The drying out period for the sand-filled CBS was adjusted and reduced to 1 week to evaluate the competence of the CBS at effectively reducing water infiltration in wetter conditions after an initial heavy rainfall event. For each soil column experiment in Series 1, to simulate a 1 in 100 storm, 34 ml of water was added to the soil columns every 15 minutes using a syringe.

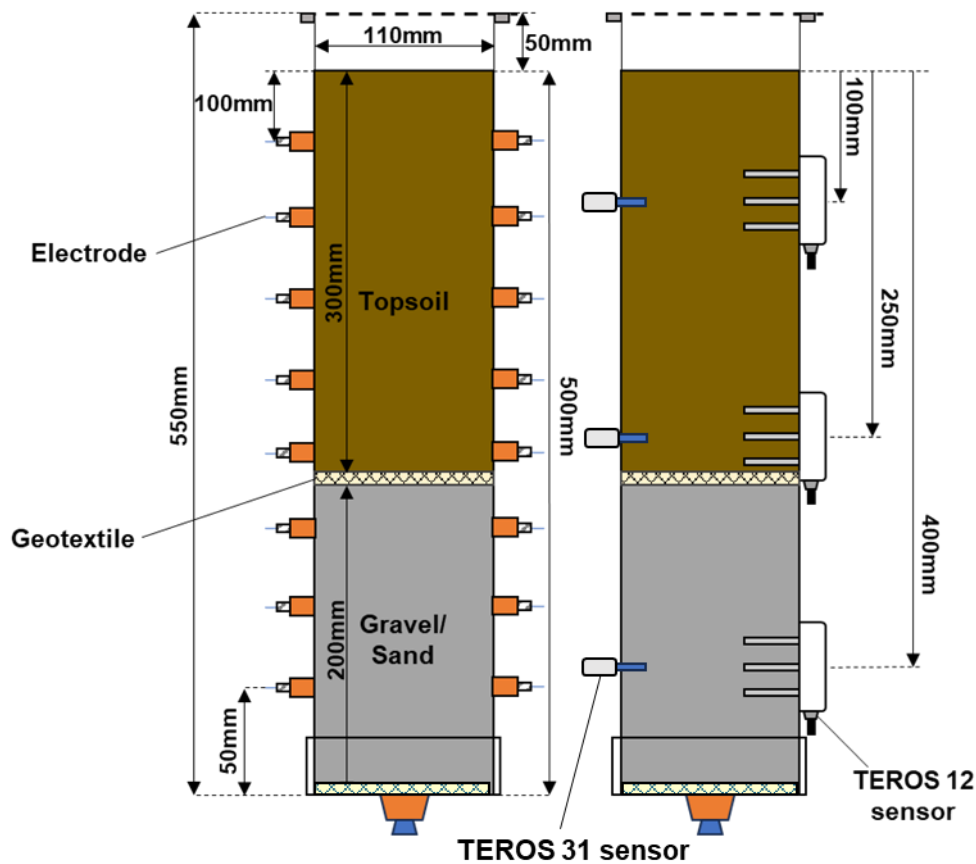


Figure 3. 11 Diagram of the sand and gravel-filled CBS with soil column components and dimensions.

3.5.3 Clay Topsoil Soil Column Experiments

Three soil column experiments were carried out on clay topsoil (CT), which consisted of Amphill clay (AC) and sandy loam topsoil (SLT). AC is used to construct linear infrastructure networks in southern England. The topsoil used consists predominately of medium-coarse sand, and Amphill Clay consists of 95% clay. The subsoil mixture used in the column experiments is a “sandy clay loam” textural class. This mixture consisted of 50% sand, 20% silt, and 30% clay. This mixture sits on the periphery of the area where the subsoil texture is required to fall (BS 8601:2013). However, it has a higher concentration of clay, which would provide results with a closer relatability to clay-based soil.

The soils were tested at three levels of compaction, calculated from the compaction curve depicted in Figure 3.12. (1) the maximum dry density of subsoil is 1.69 mg/m³ at 17% moisture content; (2) the dryer end of the curve at 10.2% moisture content and 1.46 mg/m³; (3) the wetter end of the curve at 20.2% moisture content and 1.57 mg/m³. The soil columns were filled to a height of 500mm. To achieve a uniform density throughout, the soil was added to the columns in five layers of 100mm and compacted accordingly. One 1 in 100 storm event was carried out at each dry density. The column was then left for seven days to allow water to infiltrate the soil.

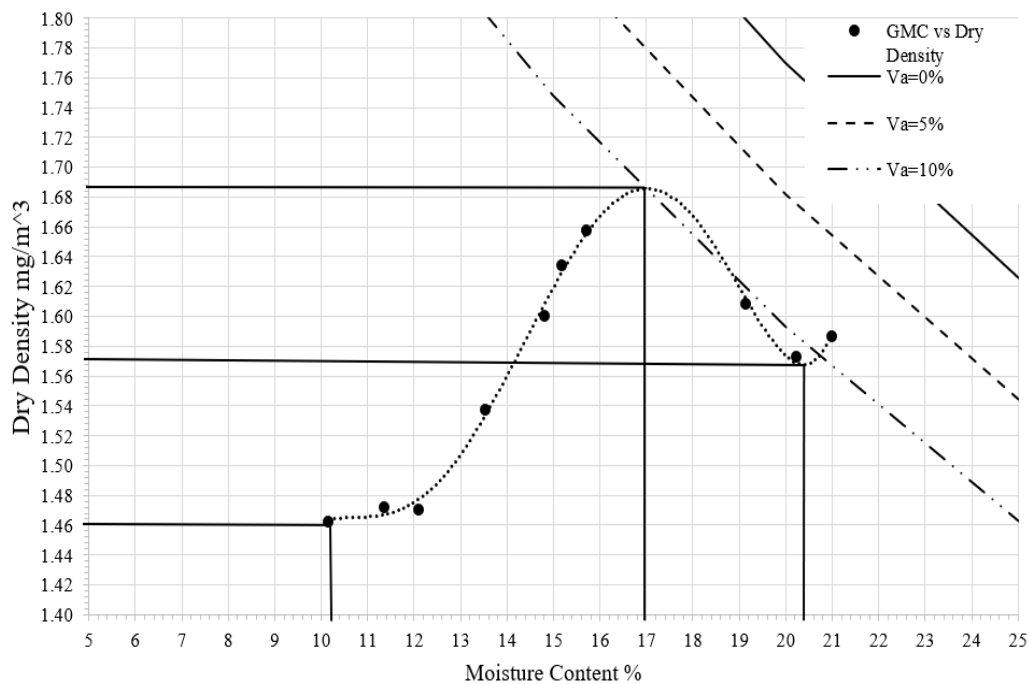


Figure 3. 12 Compaction curve of CT indicating three densities where the material is tested in the soil column experiments.

3.5.4 Bourne Amenity Topsoil Soil Column Experiment

Topsoil with a starting moisture content of 10% was added to the soil column to a height of 500mm. The soil was loosely added to the column and not compacted to a specific dry density. A six-hour, 1 in 100 storm event was simulated using a syringe. Similar to the CT experiment, the soil was left for seven days after the storm to allow the water to percolate through the material. The experiment was repeated due to the high level of settlement that occurred as water was added to the column. This settlement exposed the top electrodes and soil sensors to the air. Therefore, the topsoil was loosely compacted with a compaction hammer in the repeat experiment. The pressure was applied gently and uniformly to 100mm soil layers, similar to the CT experiment. A loosely compacted state ensured that settlement was reduced whilst soil water infiltration remained high and good contact between the electrodes and soil was achieved. A diagram of the soil column experiment for the CT and BAT is shown in Figure 3.13. The image shows the incorporation of surface water runoff tubes into the design.

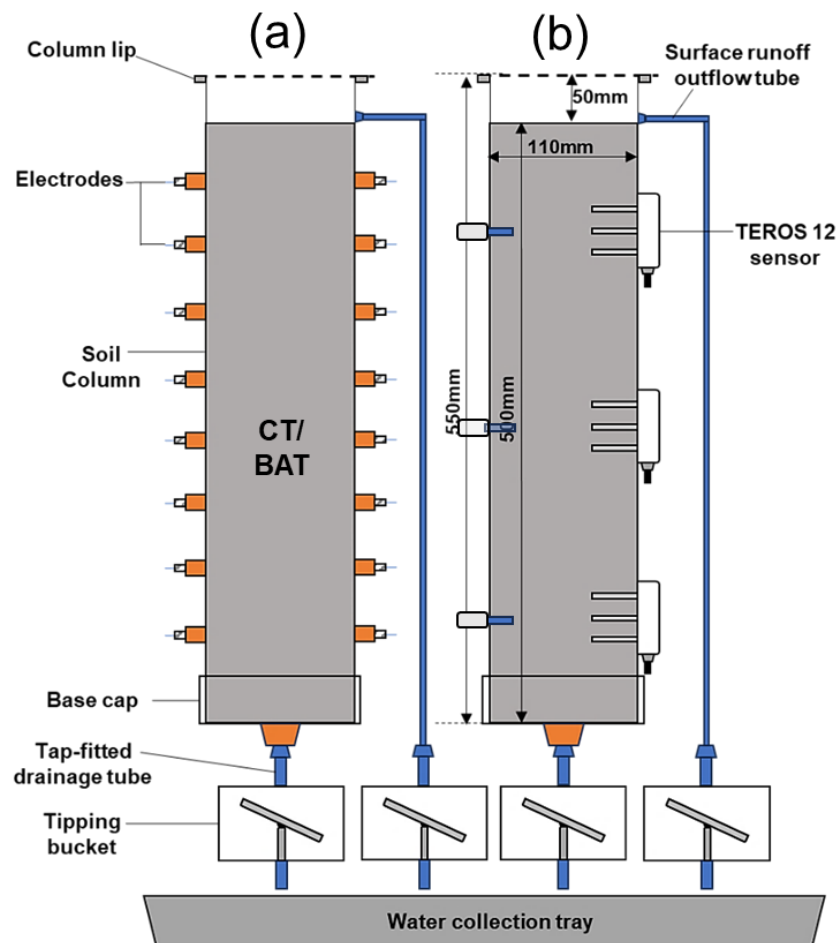


Figure 3. 13 A diagram of the soil column setup used to test clay topsoil (CT) and Bourne Amenity Topsoil (BAT).

3.6 Series 2 Soil Column Experiments

Series 2 of the soil column experiments commenced in August 2023. Processing and examining the ERT imaging from the soils tested in Series 1 indicated that changes to the methodology were necessary to reduce the prevalence of artefacts/modelling anomalies in the results. In Series 2, the same soils were investigated. However, gravel was not tested due to the unavoidable high contact resistances between the large gravel clasts and electrodes. Capillary barrier systems were also not re-examined to avoid overcomplicating the experimental design. Therefore, three soils were re-examined: sand, CT, and BAT.

3.6.1 Soil Starting Conditions

The soil in previous ERT column experiments was oven-dried before simulating a storm event, specifically in the capillary barrier regimes where dry starting conditions are essential to ascertain how successful the CBS is at reducing water infiltration at the boundary between the fine and coarse soil layers. Dry starting conditions lead to high contact resistances between the electrodes and the soil, making the data difficult to invert. The starting moisture conditions for the re-tested materials (sand, CT, and BAT) were approximately 10%. The soils were then slightly compacted to ensure good contact between the electrodes and the material. Data collected from previous ERT column experiments on soil and water indicated that once the columns have been filled with material, they must be left for a suitable period to climatise to the conditions of the environment chamber. Therefore, for each of the materials used in the second iteration of column experiments, soils added to the environment chamber were left for a minimum of 24 hours before a watering event.

3.6.2 Modifications to the Watering Schedule

Initial soil column experiments adhered to simulating a 1 in 100 storm event. This required 34 ml of water to be added to the column every 15 minutes. The PRIME system took four minutes to complete a forward and reciprocal measurement set, respectively. Given the time required to complete a set of measurements and the necessity of adding water every 15 minutes to simulate a realistic storm event, inevitably, there was an overlap between when water was added to the column and when the PRIME system was taking a set of measurements.

Furthermore, the wetting front regularly outpaced the speed of the PRIME system to complete a series of measurements. This would often result in problematic error probability distributions

that made it challenging to filter reciprocal errors at 5%. Given the problems experienced with adding water during a measurement cycle, water was added outside these windows. Ideally, it would have been better to modify the PIRME systems measurement schedule to accommodate simulating a one-in-one-hundred storm event. However, reducing the time to complete a set of measurements was impossible without risking data corruption or system errors. This meant that water was added every 30 minutes instead of 15 minutes. Water was also not added at the start of the measurement window to provide a control timestep during processing. Changes to the original watering schedule reduced the accuracy of simulating a 1 in 100 storm event in a laboratory setting. However, the total volume of water added to the column remained the same. The changes to the watering schedule resulted in 62.8 ml of water being added to the column every 30 minutes for 7 hours.

3.6.3 Addition of a Salt Tracer

In previous ERT soil column experiments, tap water had been used during a simulated storm event (CAT-5 water with a conductivity of 0.33 mS/cm). The intention was to measure this drop in resistivity and generate a timelapse of a wetting front moving through different soils. No wetting front was observed in any soils during the first set of soil column experiments despite point sensor data detecting the material getting wetter throughout each storm. To prevent a repeat of previous difficulties, 8.16g of salt (NaCl) was added to the 816g of water used during the wetting event of the second iteration of soil column experiments (conductivity = 16.3 mS/cm). The saltwater solution behaves similarly to a tracer fluid, often used in geophysics and engineering to help identify, observe, or follow the behaviour of various physical, chemical, or biological processes (e.g. International Atomic Energy Agency, 2020).

3.7 Interpreting Soil Transfer Resistances

Given the prevalence of inversion artefacts in the ERT imaging throughout the soil column experiments, transfer resistances from various column tests were analysed to ascertain if the electrodes accurately measured changes in electrical resistivity when water was added to the soil. This was instrumental in identifying if the changes in electrical resistivity observed in the ERT imaging were a product of modelling errors encountered during the inversion process or actual changes in resistivity occurring throughout simulated storm events.

A complex configuration of electrode measurements (dipole-dipole arrangement) was established to ensure variations in the spatial distribution of resistance were captured throughout

the soil profile. For the PRIME system to measure the calculated resistance, two current and two potential electrodes are needed per measurement. Figure 3.14 depicts the positions of the four-point electrode configuration deployed in the soil column experiments. In total, 32 electrodes were used, totalling 408 forward and reciprocal measurements. Examples of electrode configurations are provided in the diagram where C1 and C2 denote the current electrodes, and P1 and P2 are potential electrodes.

To best illustrate changes in electrical resistivity in response to changes in soil moisture content, point sensor data is plotted alongside the transfer resistances. However, due to the electrode configurations deployed during these experiments, it is not possible to examine resistivity directly at the locations of these soil moisture sensors, as no measurement configurations assess changes in resistivity circumferentially. Since water was added to the soil from the surface, significant moisture content and resistivity changes would occur at the top before percolating towards the base. For example, a series of measurements that isolates electrodes 1, 9, 17 and 25, as seen in Figure 3.14, does not exist. Instead, electrode potential (P) and current (C) combinations across the material occur; for example, $C_{1,2} = 10$ and 1, and $P_{1,2} = 28$ and 5. As a result, isolating the electrodes at the site of the top moisture sensor was not possible.

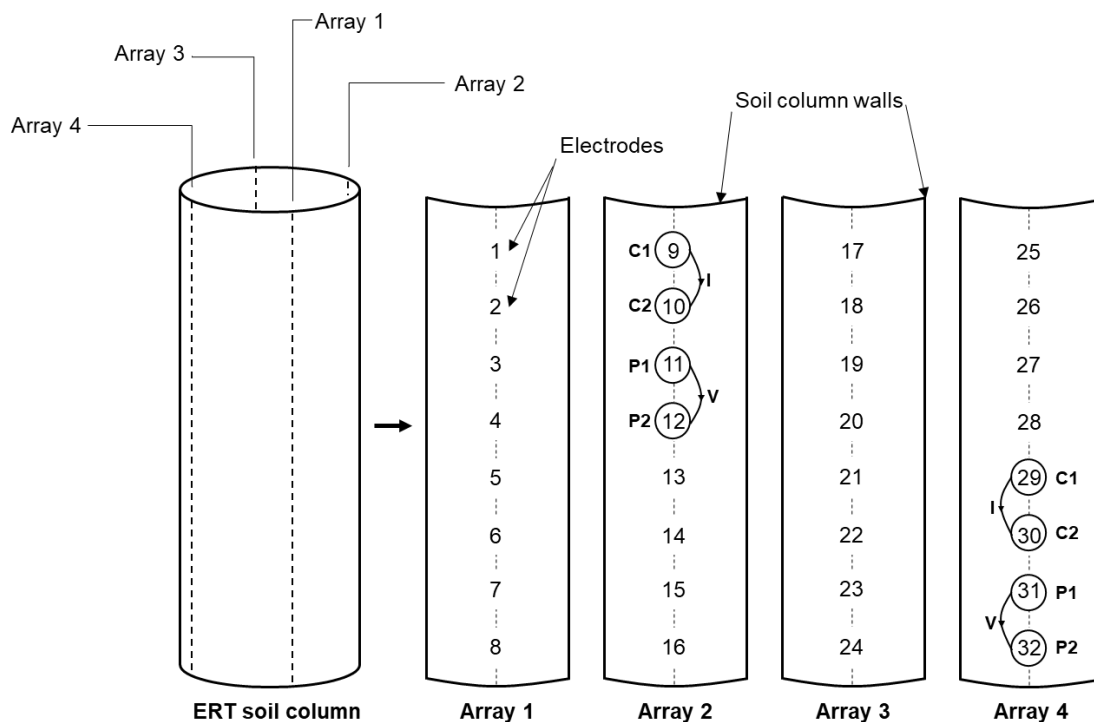


Figure 3. 14 Images of the electrode positions in the four-point array deployed in the soil column experiments. The diagram indicates possible current and potential electrode combinations that are assessed to derive the transfer resistance of the soil at a given depth.

3.8 Geoelectrical Modelling and Inversion

3.8.1 Merging of the Forward and Reciprocal Measurements

The PRIME System was scheduled to measure spatial resistivity distributions in the column for 8 hours of the day. During this window, a one-in-one-hundred storm event was simulated over 6 hours. On the day of a storm event, 30 files measuring the apparent resistivity of the soil are taken. The PRIME system outputs the forward and reciprocal measurements separately and uploads the data to a shared cloud file system. Before data processing, the forward and reciprocal measurements are merged using Python. ResIPy, a software for inversion and modelling geoelectrical data, was used to process time-lapse survey data for the soil column experiments. Merging the forward and reciprocal measurement files allows multiple datasets to be imported to ResIPy and ensures the software correlates the files chronologically. Geometric factors are applied to the measurements, which prompts the program to map the electrical data relative to the position of the electrodes (Figure 3.15).

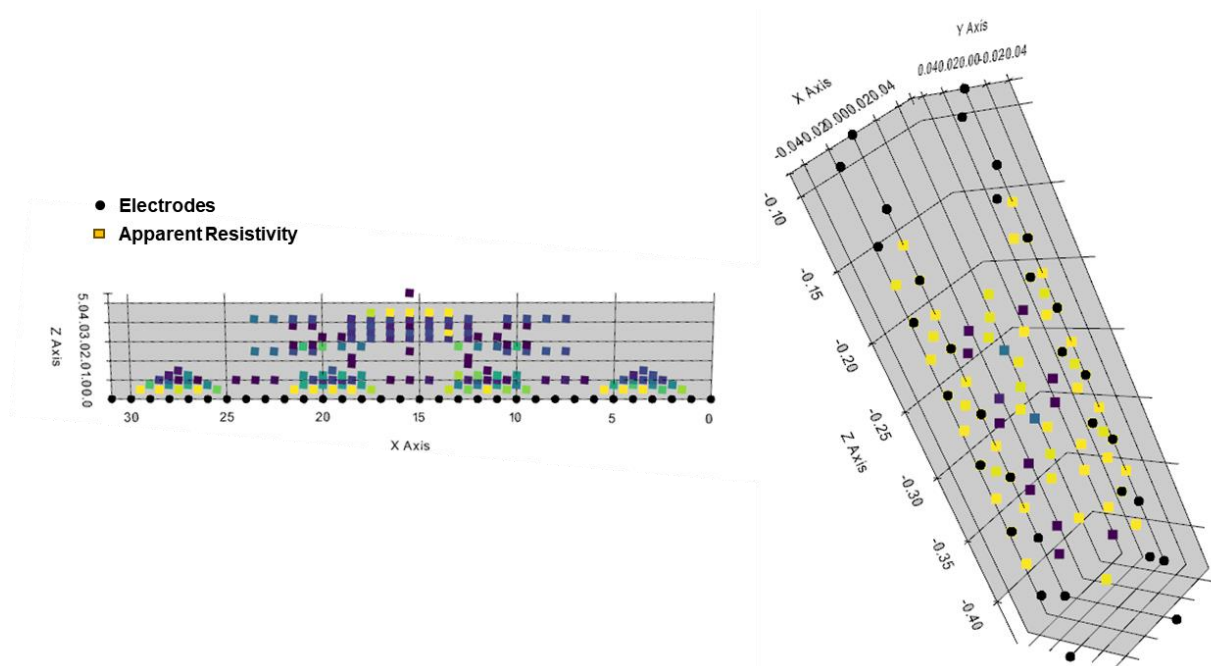


Figure 3. 15 Apparent resistivities of a single timestep of soil column data. (Left) indicates the 2-D format applied to the survey before the electrode geometries are provided. (Right) demonstrates the 3-D electrode array and the transformed locations of the apparent resistivities given as point values.

3.8.2 Reciprocal Filtering and Resistance Error Modelling

Reciprocal filtering is applied to each timestep in the dataset. This enables the removal of data points with reciprocal errors (REs) outside the margins of expectation. A 5% error threshold is

applied to the data. ResIPy can calculate the signal-to-noise ratio (SNR) and provide options for filtering the data to reduce image noise levels. Figure 3.16 shows the signal-to-noise ratio as an error distribution generated by ResIPy. (A) indicates the error distribution for a saturated topsoil used in an ERT column experiment. Several error spikes can be observed up to 90%. These significant error feedback from the electrical survey can be removed using appropriate filters, typically at a threshold of 5% (Zhou & Dahlin, 2003; Ferahtia et al., 2009; Loke et al., 2013). If error values are not filtered, the inverse model can be challenging to fit as it implies subsurface properties are outside a reasonable range.

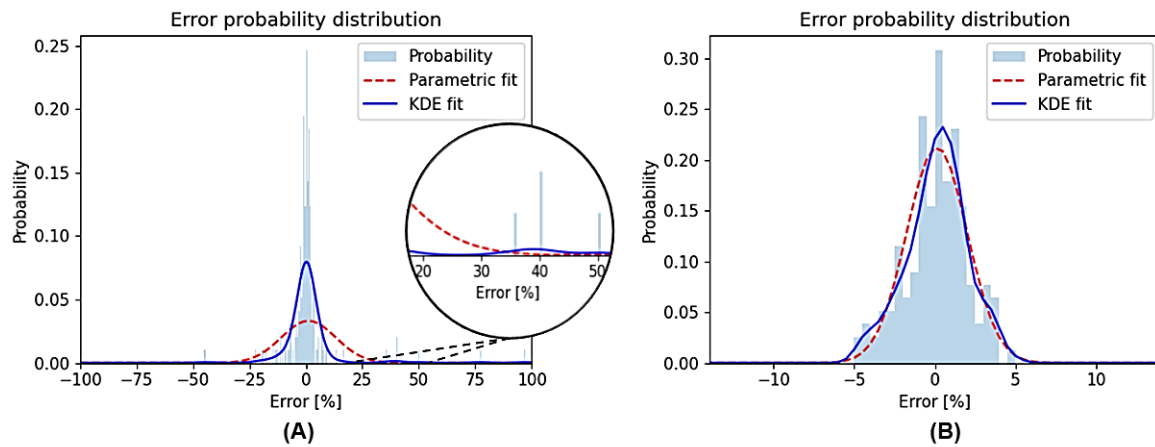


Figure 3. 16 (A) The signal-to-noise ratio is depicted as an error distribution in topsoil used during ERT soil column experiments. (B) ResIPy software filters errors over 5%.

An error model generates an error for each quadrupole (an expression of a sequence of resistance configurations). A Power Law Fit is applied to the combined dataset (Dahlin, 2013). Figure 3.17 shows the fitted error line used to improve the stability of the inversion. The raw data depicted on the graph represents the grouped range of transfer resistances and their corresponding errors.

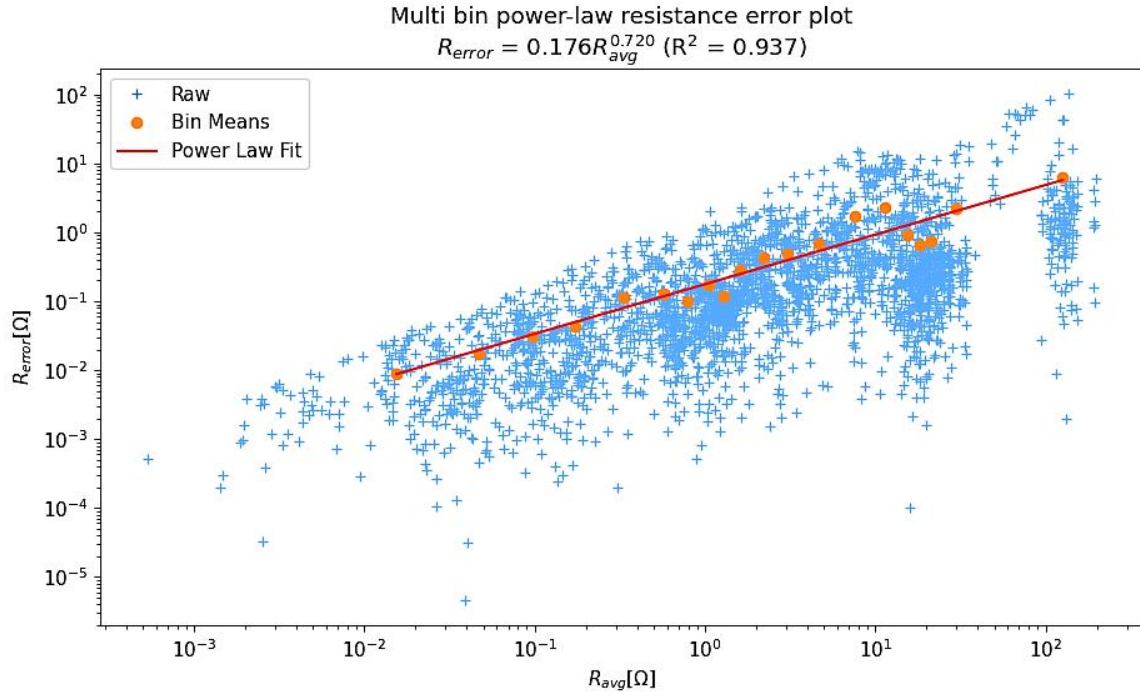


Figure 3. 17 The power-law relationship between the error on phase and the corresponding resistances in topsoil used in soil column experiments.

3.8.3 Development of a Cylindrical Finite Element Modelling Mesh

A finite element modelling mesh was created using ResIPy that incorporated the positions of the electrodes into the dimensions of the soil column. When developing electrical measurement sequences for 3-D data acquisition, the acquisition geometry influences the mesh design. The dimensions of the soil column are small, allowing for a refined mesh with relatively low processing times to be achieved. In the case of these 4-D ERT surveys, processing times are dictated more by the number of timesteps per survey instead of how refined the mesh is and the size of the survey area. Figure 3.18 shows the finite element modelling mesh used for the soil column experiments. ResIPy facilitates the creation of the cylindrical (column) mesh in-program. This allows the characteristic length, growth factor, and top and bottom cylinder boundaries to be assigned.

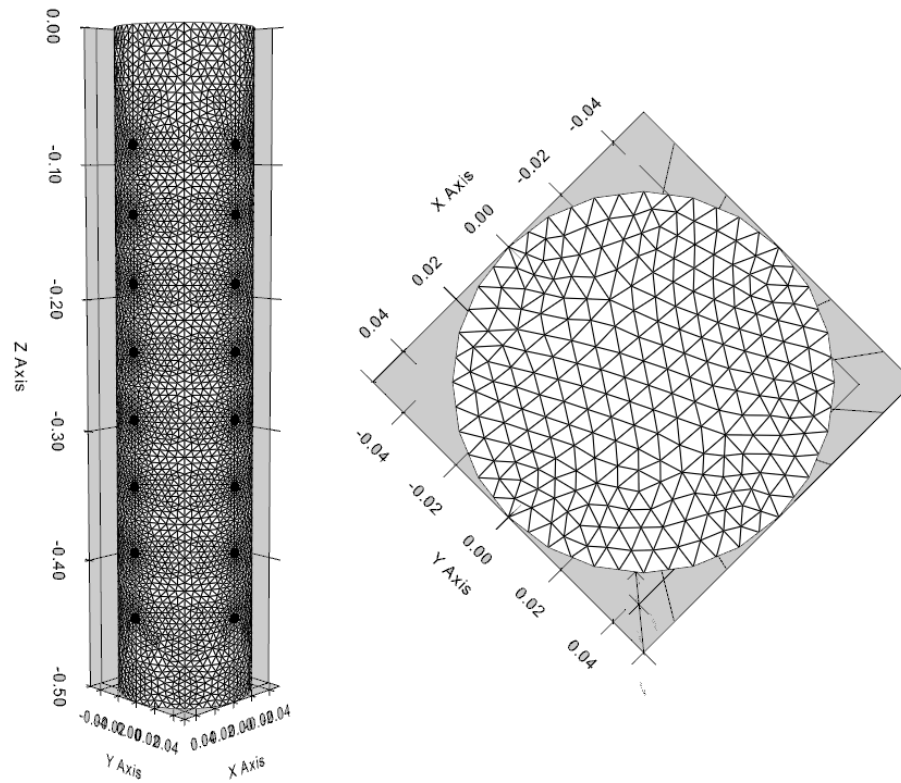


Figure 3. 18 A finite element modelling mesh of the ERT soil column showing electrode positions and column dimensions (left) and a top-down view of the soil column and triangular element mesh (right).

3.8.4 Inversion Parameters

Survey regularisation is applied to the dataset using a baseline-constrained inversion. This means all data in the time-lapse survey is regularised from the first (initial) timestep in the series. The initial model does not necessarily have to be the first inversion in the time series – which is what ResIPy assumes as the initial model – instead, the initial model can be selected based on a desired signal-noise-ratio or error probability distribution displayed by a particular timestep. Figure 3.19 shows the error probability distributions (EPDs) in three timesteps of a 4-D soil column electrical survey. The first EPD (10:30 am) was taken before water was added to the column. This is an ideal initial model for survey regularisation as the curve has a Gaussian distribution, and the number of outliers beyond a 5% error is small. Despite the first timestep being an appropriate initial model, the second EPD (12:30 pm) would also be an adequate initial model as it displays characteristics similar to those of the initial timestep. At 3:00 pm, the EPD is significantly scattered without the Gaussian features desirable in the initial model. This highlights the importance of evaluating all timesteps in the series to decide which is best for the initial model.

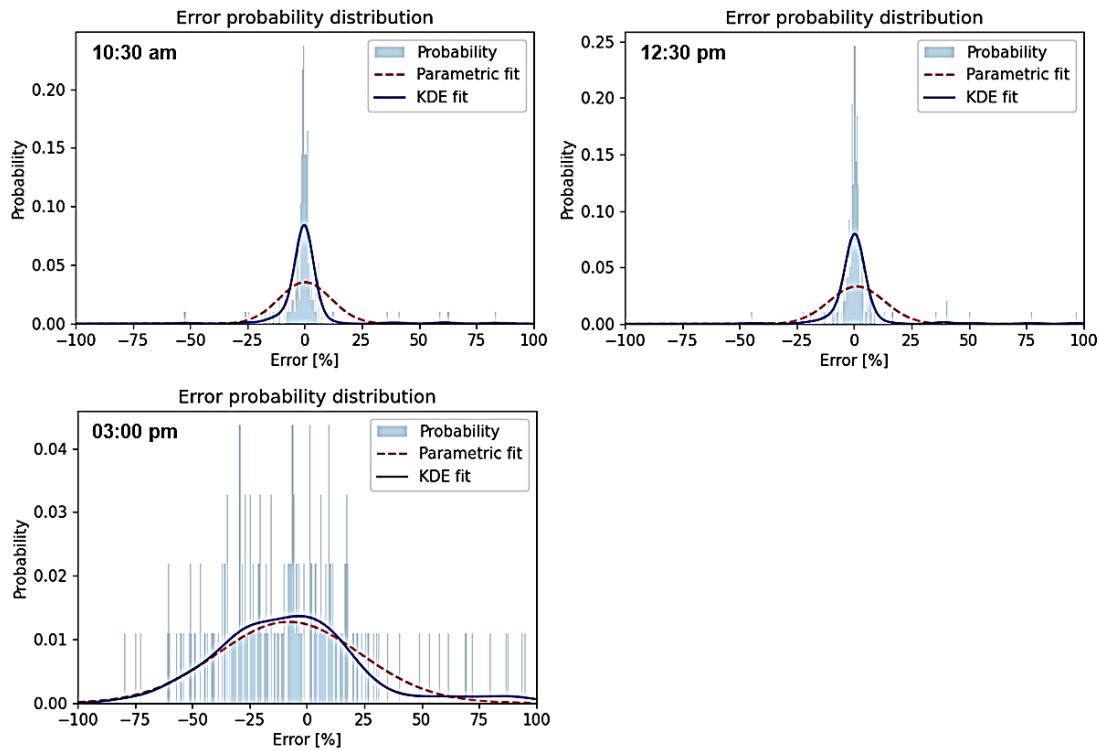


Figure 3. 19 A sample of the error probability distributions (EPD) in 4-D ERT soil column experiments on BAT.

The number of iterations per dataset was set to 20 per survey. Performing many iterations reduces the number of root mean square (RMS) misfits. The more iterations, the fewer misfits. Reducing the number of data misfits ultimately improves the quality of the survey, thus enhancing its reliability. ResIPy also facilitates parallel inversions to be run when conducting a timelapse survey. Parallel inversions can significantly improve the processing time by handling several inversions simultaneously. However, this is computationally demanding, especially for 3-D surveys, as the required RAM level can be significant as multiple 3-D datasets are processed at once (Blanchy et al., 2020).

3.9 Petrophysical Tests

3.9.1 Introduction

Although time-lapse resistivity surveys indicate soil moisture dynamics, to determine the range and extent of soil moisture movement in different materials, a modified HYPROP 2 was used in combination with the soil column experiments (Figure 3.20). The modified HYPROP 2

measures electrical resistivity, soil suction and moisture content. By taking all three measurements simultaneously, it is possible to ensure that these petrophysical measurements are taken under similar environmental conditions to emulate the conditions of the soil column experiments more reliably. Resistivity and suction (soil-water characteristic curve) depend strongly on moisture content (Holmes et al., 2022). Therefore, developing a quantitative relationship between these two parameters is possible using a modified HYPROP 2 system (an instrument used to create soil moisture curves). This method was developed by Holmes et al. (2022), enabling resistivity to be measured in tandem with soil suction and moisture content. In a series of preliminary experiments on various soils using the modified HYPROP setup, tests were performed on Ampthill clay (the clay constituent in the clay topsoil made). The material placed into the sample holder shown in Figure 3.20 was the clay that had visibly shrunk as it had dried, resulting in it detaching from the sides of the container. As a result, the four electrodes placed into the sides of the sample would become detached from the sample, causing errors to appear in the logged electrical data. This shrink/swell behaviour was not observed in the other samples tested, including the clay topsoil samples.

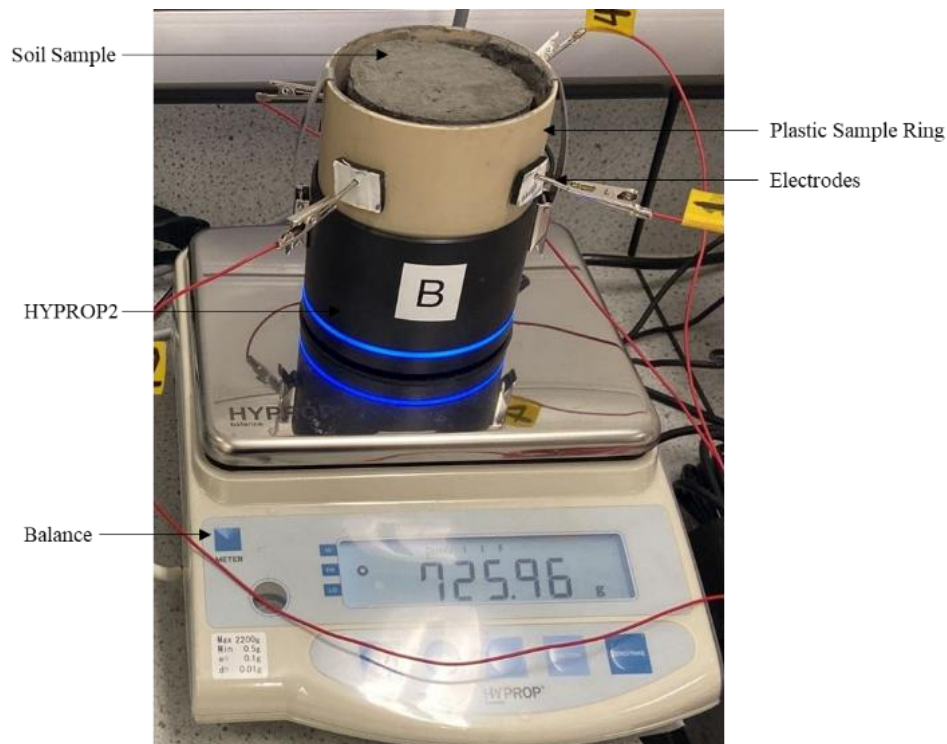


Figure 3. 20 Photograph of modified HYPROP 2 set up at the National Green Infrastructure Facility, Newcastle. The sample ring contained dried Ampthill Clay that had shrunk over time.

Two modified HYPROP 2 instruments were built to measure soil moisture content, suction, and resistivity. The HYPROP 2 consists of two tensiometers that measure suction and soil moisture content, and an ES-2 electrical conductivity and temperature sensor were used to calculate resistivity. Typically, ES-2 sensors measure the electrical conductivity of liquids in pipes or tanks (Meter Group, 2024), where measurements are taken by inserting the sensor head into a solution. However, the sensors were deconstructed and modified by removing the built-in conductivity electrodes and attaching four stainless steel rods to the instrument to create the four-point electrode array seen in Figure 3.20. The HYPROP 2 and ES-2 instruments were connected to a ZL-6 data logger to record and transmit the data for analysis. A high-performance plastic with high heat resistance was necessary to oven-dry the soil after the modified HYPROP 2 experiment had concluded. Therefore, the plastic sample rings were made from Polyether Ether Ketone (PEEK). The plastic rod was cut and cored to the exact dimensions of a typical 250cm^3 steel HYPROP 2 sample ring container (50mm height, 80mm length). The cylindrical sample is placed on a digital balance in a temperature-controlled laboratory.

Modifying the ES-2 electrode array required a calibration model to determine the conductivity measured by the electrodes in the four-point array assigned to the geometry of the sample rings. Different concentrations of salt water were added to the sample containers, and a laboratory conductivity probe was used to measure the solution's conductivity in tandem with the modified HYPROP 2. Figure 3.21 shows the linear relationship of conductivity in the salt solution and different concentrations. The equation of the line was then used to calibrate the transmitted data from the ZL-6 data logger.

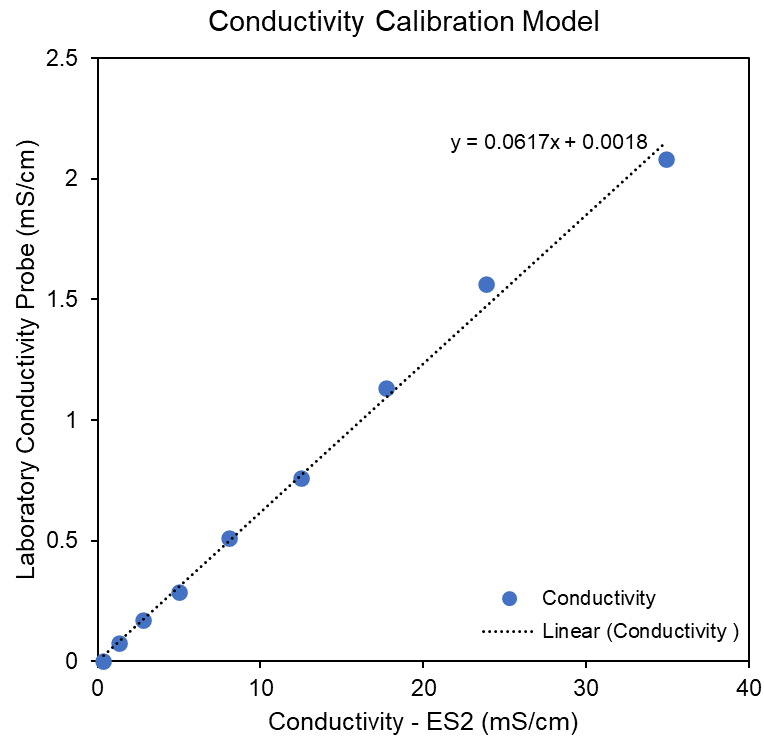


Figure 3. 21 The conductivity calibration model of the modified HYPROP 2 setup. The graph shows the linear relationship of the salt solution tested between the conductivity measured by the ES-2 sensor and the laboratory conductivity probe.

For soils examined in Series 1 soil column experiments, CAT-5 water was used during a simulated storm event. Therefore, the samples were saturated in CAT-5 water in the PEEK soil rings and then transferred to the balance for testing. After the experiment, the two tensiometer measurements (tension top and tension bottom) from the HYPROP 2 device were averaged to determine suction at different sample weights. Gravimetric moisture content (GMC) was calculated from the net weight and dry weight of the material. The dry soil weight was measured after the experiment when the soil sample was oven-dried. When the tensiometers reached cavitation, the HYPROP stopped measuring matric potential. However, the experiments continued until the ES-2 electrodes no longer measured conductivity to estimate resistivity at near-residual saturation (Boyd et al., 2024).

3.9.2 Series 1- Soil Moisture Content – Electrical Resistivity Relationship

Various empirical relationships exist between resistivity and soil moisture content, such as those described by Archie (1947) and Waxman and Smits (1968). A modified Waxman-Smits model was used to fit the resistivity and moisture content data measured using the modified HYPROP 2 (Uhlemann et al., 2017; Holmes et al., 2022):

$$p(GMC) = F \left(\frac{(1 - \varphi) D_g GMC}{\varphi D_w} \right)^{-n} \left(\sigma_w + B_{ws} \left[\frac{(1 - \varphi) D_g C}{100 \varphi} \right] \left[\frac{\varphi D_w}{(1 - \varphi) D_g GMC} \right] \right)^{-1} \quad [14]$$

Where, F is a formation factor, φ is porosity, D_g is grain density (g cm^{-3}), D_w is water density (g cm^{-3}), n is a saturation exponent, σ_w is the pore water conductivity (S/m), and C is cation exchange capacity (meq/ 100 g). B_{ws} ($\text{S cm}^3 \text{ m}^{-1} \text{ meq}^{-1}$), the average cation mobility was calculated using the following:

$$\left(B_{ws} = 4.6 \left(1 - 0.06 \text{Exp} \left[1 \frac{\sigma_w}{1.3} \right] \right) \right) \quad [15]$$

where values were estimated from the empirical fit given by Waxman and Smits (1968) (Holmes et al., 2022). Except for the cation exchange capacity (C), F and n , each parameter was measured in the laboratory. The CEC of each soil was outsourced to the NRM laboratory, and F and n are fitted parameters.

A Waxman-Smits model was used as Archie's Law is typically applied to non-clay, sandy soils and is generally suitable for fully saturated conditions and may not perform well under varying saturation levels (Ewing & Hunt, 2006; Tso et al., 2019). The Waxman-Smits model also includes parameters that account for the cation exchange capacity (CEC) of the soil, which influences the soil's ability to retain and conduct electrical charge (Pope & Nyquist, 2023). This leads to a better representation of the soil's properties and a more precise calibration of the ERT model.

Waxman-Smits models were fitted to data from each soil used in Series 1 of the soil column experiments. The parameters used to convert electrical resistivity to gravimetric moisture content are given in Table 4. Due to changes made to the methodology in Series 2, specifically saltwater use during storm simulations, conducting modified HYPROP 2 experiments on soils used in Series 2 would prove ineffective. A different method was used to measure the electrical resistivity—soil moisture content relationship of soils tested in Series 2 (see Section 3.9.3).

Waxman-Smits Model	F	n	φ	D_g g cm ⁻³	D_w g cm ⁻³	σ_w S/m	C meq/ 100 g
Sand	62.107	1.568	0.404	2.60	1	0.01	4.0
Clay Topsoil	0.442	2.913	0.403	2.60	1	0.02	10.7
Bourne Amenity Topsoil	225.497	1.814	0.445	2.60	1	0.02	10.0

Table 4 Parameters for the soils used during the Series 1 soil column experiments. (Formation factor, F , a fitting parameter, n , porosity, ϕ , grain density, D_g , water density, D_w , pore water conductivity, σ_w , and cation exchange capacity, C).

Attempting to fit the data using a Waxman-Smiths equation proved ineffective in each of the tested soils, given that a Waxman-Smiths model does not account for the change in porosity that occurs as the sample dries and undergoes a shrink-swell behaviour. Different iterations of F and n were applied to the graphs using a generalised reduced gradient nonlinear method. However, no combination of values provided a sufficiently effective fit to the soil moisture content-resistivity data. To mitigate this issue, a numerical approach was adopted to better fit the data by using an inverse power-law distribution (Boyd et al., 2024). A power law is a functional relationship between data sets, where a relative change in one set results in a relative change in the other (Bar-Yam, 2011). It is often used in statistics to model various phenomena (Clauset, 2009).

$$R(\theta_g) = \frac{1}{\alpha(\theta_g^b)} + c$$

[16]

Where $R(\theta_g)$ is resistivity as a function of gravimetric moisture content (GMC), θ_g is GMC , and α , b , and c are fitting parameters (Boyd et al., 2024). Table 5 gives the fitting parameters used to convert electrical resistivity to gravimetric moisture content using a power law.

Power law fit	α	b	c
Sand	130.0	3.70	100.0
Clay Topsoil	2.0	2.216	10.0
Bourne Amenity Topsoil	137.572	2.475	6.742

Table 5 Fitting parameters for the soils used during the Series 1 soil column experiments. The power law equation used three fitting parameters (α , b , and c).

3.9.3 Series 2- Soil Moisture Content – Electrical Resistivity Relationship

For soils tested in Series 2 of the soil column experiments (where changes to the column experiment methodology and design were made to reduce the appearance of artefacts in time-lapse inversions), a different method for deriving the MC-resistivity relationship of the

materials was used. In Series 1, CAT-5 was used during storm simulations. Therefore, HYPROP 2 samples were saturated in CAT-5 water to emulate the conditions applied during the soil column experiments. Since salt water was added to the soil columns used in Series 2, the samples must be saturated in salt water. If a modified HYPROP test were used, as samples dried, the remaining salt would allow the samples to continue to conduct electricity even as the sample neared zero percent moisture content. This would affect the soil moisture content–resistivity relationship derived from the HYPROP tests. To test the resistivity-MC relationship for Series 2 soils (sand, clay topsoil and Bourne Amenity topsoil), a new experiment was devised to measure electrical resistivity and moisture content simultaneously (Figure 3.22). Soil samples were mixed with salt water (10g salt/L) to a range of moisture contents, and the resistivity of the material was measured using the same electrode array used in the modified HYPROP experiments.

Although the Teros12 sensor is not sensitive to variation in soil texture and EC because it operates at a high measurement frequency, using this sensor in soils with a high salinity without applying a substrate-specific calibration can affect the accuracy of the measurements made (Meter, 2024). The sensor has a factory calibration optimised for mineral soils with low EC (≤ 8 dS/m) (Meter, 2024). In saline soils, the dielectric measurements of the sensor can be biased leading to inaccurate VWC readings. In this study, a specific calibration for salt water was not applied when measuring the relationship between soil moisture content and electrical conductivity. Meter Environment (2025) indicates that soil specific calibration can increase accuracy to ± 1 to 2% for all soils. Although this difference is not significant, it is none the less an oversight of the petrophysical experiments that, if repeated, should be rectified by conducting a specific calibration for salt water to ensure accuracy of results. To achieve accurate soil moisture measurements, in saline conditions, the raw readings of the sensor are correlated with known moisture content values from the target soil. Despite this oversight, its implications on the electrical resistivity data presented throughout this research are less significant due to the fact that plotting changes in moisture content for the duration of the column experiments was conducted to inform if the ERT-derived resistivity measurements were capturing a realistic change in resistivity over time. For example, if point sensors measured an increase in moisture content at the base of the column, then a subsequent decrease in resistivity should be measured accordingly. As the precise moisture content measurement at any given stage of the experiment is not a direct representation of a specific level of electrical resistivity, the calibration method that should have been deployed is less pertinent to this work.

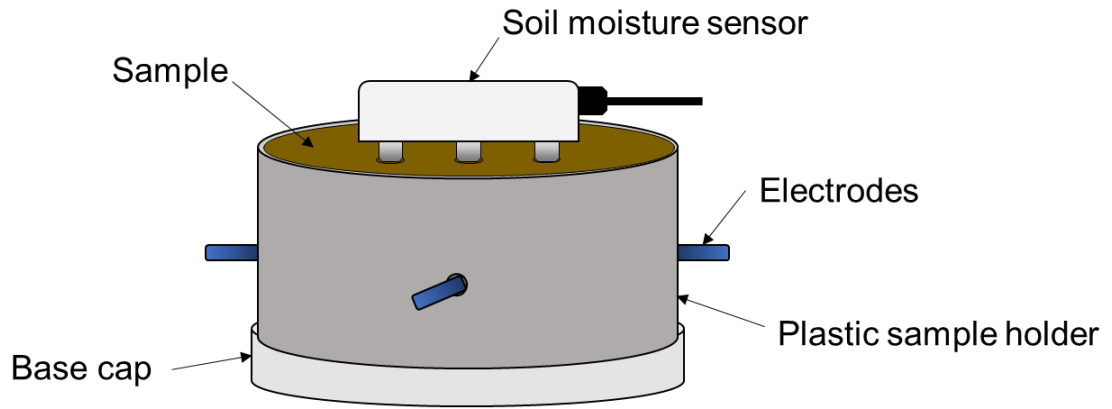


Figure 3. 22 A diagram depicting the experiment used to derive the soil moisture content – resistivity relationship in soils used in Series 2 of the soil column experiments (sand, clay topsoil and Bourne Amenity topsoil).

A PLF was applied to the data from each experiment, and a table of the fitted parameters used for each calibration curve is given in Table 6. Teros 12 soil moisture sensors were used to measure the volumetric moisture content (VMC) of the soils. When calculating the MC-resistivity relationship for Series 1 soils, GMC was measured and applied to the modified Waxman-Smits model. Furthermore, data collected using the modified HYPROP accounted for the net weight/dry weight of the soils. However, given that the Teros sensor measures in VMC, it was appropriate to continue measuring the soils volumetrically to compare the VMC timelapse inversions to the data collected by the soil moisture sensors during a simulated storm.

Power law fit	α	b	c
Sand	2.48	1.40	4.05
Borne Amenity Topsoil (BAT)	1.43	1.45	2.49
Clay Topsoil (CT)	4.12	3.33	0.00

Table 6 Fitting parameters for the soils used during the Series 2 soil column experiments. The power law equation used three fitting parameters (α , b , and c).

3.9.4 Soil Suction – Electrical Resistivity Relationship

Conductivity and suction measurements from the modified HYPROP setup were used to determine the relationship between soil suction and electrical resistivity and derive a suitable calibration curve. This method is similar to that described by Boyd et al. (2024), whereby

electrical conductivity at saturated and residual moisture content is substituted into the van Genuchten model to best fit the data. The van Genuchten equation for soil water retention is:

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + [\alpha h]^n)^m}$$
[17]

Where θ is the water content, h is the suction, θ_r is the residual water content, θ_s is the saturated water content, α , n and m are fitting parameters (van Genuchten, 1980) with:

$$m = 1 - \frac{1}{n}$$
[18]

The modified van Genuchten equation used to relate soil suction and conductivity is:

$$EC(h) = EC_{res} + \frac{(EC_{sat} - EC_{res})}{(1 + [\alpha h]^n)^m}$$
[19]

Where EC_{sat} is conductivity at the saturated water content and EC_{res} is conductivity at the residual water content. Equation [19] was rearranged to make suction, h , the subject:

$$h = \left(\frac{\left(\left(\frac{EC_{sat} - EC_{res}}{EC(h) - EC_{res}} \right)^{\frac{1}{m}} - 1 \right)}{\alpha^n} \right)^{\frac{1}{n}}$$
[20]

Other fitting models were observed in the literature, such as a modified Waxman-Smits equation, whereby GMC is replaced with parameters pertaining to soil suction (Holmes et al., 2022) derived from an equation for relating soil water content with soil suction (Fredlund & Xing, 1994). However, this method of substituting GMC for suction assumes that the Waxman-Smits model used to relate resistivity to GMC was an appropriate model for fitting one's data, which was ineffective for the soil column experiments. Similarly, applying an inverse power-law distribution would not work, as the suction curve is sigmoidal; hence, the application of a modified van Genuchten model, which is arguably more desired as the equation relates to

measured soil parameters, unlike the power-law fit, which is a numerical model. Table 7 indicates the values of the parameters used to fit the data in accordance with Equation [19].

Unit	EC_{sat}	EC_{res}	α	n	m	
BAT	64.048	3.046	0.067	2.000	0.500	
CT	9.596	0.003	0.005	1.900	0.474	

Table 7 Parameters used in the van Genuchten equation to fit the sandy topsoil (ST) and clay topsoil (CT) soil suction and resistivity relationship. Where EC_{sat} and EC_{res} are measured in mS/m.

Derivation of petrophysical relationships through the Waxman Smits model and the RMS approach was necessary to accurately interpret the complex interactions between soil properties (soil moisture content, conductivity and suction) under varying conditions. The use of a modified HYPROP 2 system facilitated high-resolution measurements that were essential for further understanding how moisture, suction, and conductivity/resistivity evolve over time within the soil columns during simulated storm events. The application of these relationships to specific column experiments like sand, CT, and BAT highlighted the adaptability of the model and precision in different substrates and provided insight as to where the model, and therefore the column experiments themselves, could be improved to produce more accurate results. This was particularly valuable in overcoming the challenges posed by persistent artefacts in some experiments, underscoring the importance of tailored petrophysical analysis in hydrogeological applications.

3.10 Summary of the Methodology

The methodology outlined in this thesis explains how the PRIME system was deployed at the NGIF in Newcastle to monitor transient soil moisture conditions in a suite of soil column experiments. Section 3.3 provides information on the various features of the soil columns (e.g., electrode array geometry and material selection) and why design choices were made. A summary of characterisation experiments is given, and tables summarising the physical characteristics of the various materials investigated are supplied in Section 3.4.

When conducting time-lapse ERT surveys in the field, various studies and reports provide crucial information regarding the careful procedure for geoelectrical data collection. However, limited literature on using 4D ERT in soil column experiments is available. Therefore, the methodology was developed over time based on the results of the experiments in order to

improve the quality of ERT images. As such, Sections 3.5 and 3.6 outline two methodologies for investigating soil moisture movement in different soil types/asset management regimes that were informed by the results of this investigation. Soil column experiments in Series 1 mark the first of the soil column tests where artefacts appeared in the ERT images, reducing the reliability of the data. In response, various changes to the method and design (e.g. the measurement schedule and soil starting conditions, etc.) were implemented to improve the quality of the ERT images (Series 2).

Analysing soil transfer resistances in soil column experiments is essential to verify whether the electrodes accurately measured changes in electrical resistivity when water was added to the soil. A method for analysing transfer resistances is provided in Section 3.7.

After establishing the parameters of the experiment (selected soils, soil column design, etc.), the inversion process is defined in Section 3.8. Here, the method for acquiring and merging the data supplied by the PRIME system is provided, and the parameters and procedure for inverting the data using ResIPy are described.

In addition to the physical soil characteristics described in Section 3.4, the petrophysical characteristics of the soils investigated are shown in tables found in Section 3.9. Because of the relationship between soil water content, suction, and electrical resistivity, it is possible to apply a modified HYPROP 2 to calibrate electrical data and model soil moisture content and suction, which ultimately provides greater insight into the soil moisture dynamics in different soils.

Chapter 4 Results

4.1 Introduction

4.1.1 Soil Column Experiments Series 1 and 2

This chapter analyses data collected in Series 1 and 2 of the soil column experiments. Time-lapse surveys of each material are provided. Each experiment took place over one month (for the CBSs) and one week to ten days for all other materials. Every 24 hours, the PRIME system produced 28 soil column-related timesteps. This is a substantial portfolio of resistivity data that can be analysed. Given that column experiments in Series 1 aided in enhancing the design of the soil ERT-soil column for Series 2, a significant proportion of the results (soil moisture content, transfer resistances and 4D ERT plots) can be found in Appendix C. Additionally, timesteps for each survey are provided depending on whether the PRIME system captures a visual change in either the spatial distribution of electrical resistivity or the percentage change in resistivity during periods of wetting and drying. Owing to the simulation of extreme climactic events (1 in 100 storm events) in each soil column experiment, resistivity scales in each ERT tomogram vary because moisture levels, and therefore electrical resistivity, can increase significantly during the experiment. Also, because of the presence of modelling artefacts, tomogram scales are adjusted to visually observe changes in resistivity that would otherwise be obscured by such artefacts.

4.2 Gravel-Filled Capillary Barrier System

The first column experiment was performed on a gravel-filled capillary barrier system (CBS) consisting of 300mm of Bourne Amenity topsoil (BAT) overlaying 200mm of gravel separated by a geotextile. Initially, the experiment aimed to examine the effectiveness of CBSs during storm events in temperate conditions. However, this was not pursued further due to complications observed during the inversion process. The PRIME system was used alongside point sensor data to capture changes in soil resistivity/moisture content over time to evaluate 4D ERT as a means of accurately modelling changes in electrical resistivity and soil moisture. Figure 4.0 depicts the soil column dimensions relative to the positions of the soil moisture sensors, electrodes, and material heights. TEROS 12 and 31 sensors were positioned proximal to the top, middle and bottom of the soil profile to capture changes in soil moisture content and suction during two storm simulations.

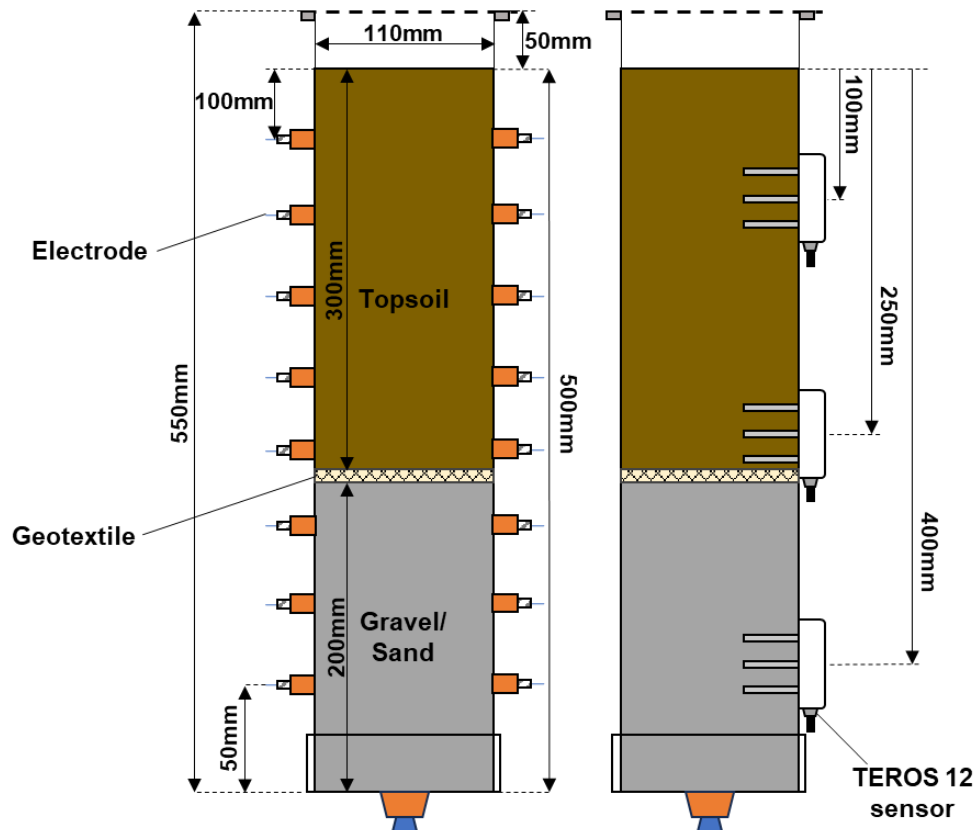


Figure 4.0 Electrode and soil moisture sensor positions relative to material thicknesses in CBS soil column experiments.

Figure 4.1, a graph depicting changes in soil moisture content, shows the two simulated 1 in 100 storm events, indicated by sharp increases in moisture content. Point sensor data describing soil moisture content is separated into three distinct zones dependent on the locations of these moisture sensors. On the graph, data pertaining to the ‘Top’ of the soil column denotes moisture content at 100mm – relative to the soil surface. The ‘Middle’ refers to soil at 250mm halfway through the soil profile, and the ‘Bottom’ refers to soil at a depth of 400mm relative to the soil surface. Throughout this research, references are made to the ‘Top’, ‘Middle’ and ‘Bottom’ sensors. These soil moisture sensors have an approximate zone of influence of 100mm (Meter, 2024). The graph shows that moisture content increased during the two storm simulations (indicated by the graphical peaks) before decreasing days afterwards. Moisture levels at the bottom of the column (below the capillary barrier) increase less than in the overlying material, demonstrating the natural barrier's relative success. A more detailed account of the changes in soil moisture content in the gravel-filled CBS can be found in Appendix C.

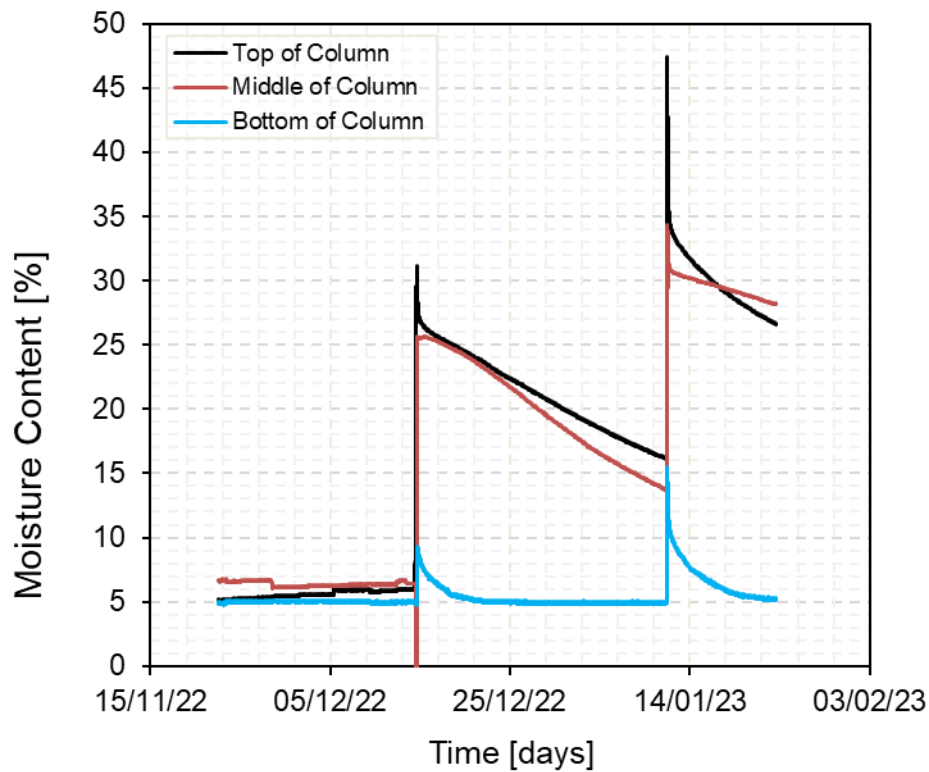


Figure 4. 1 Moisture content data captured by TERSOS 12 sensors in the gravel-filled capillary barrier system column experiment during two simulated storm events.

Electrical resistivity measurements collected from the gravel-filled CBS soil column were exceptionally challenging to model due to the high contact resistances, CRs ($\geq 20,000$ ohms), and percentage of errors throughout the experiment. High CRs can cause inaccurate measurements as the electrical current applied to the survey area (soil columns) may not penetrate deeply enough into the sample or be diverted, resulting in misleading data. This increases the probability of measurement errors, and variations in contact resistances can lead to inconsistencies throughout the soil profile, complicating the interpretation of the results. Before the storm, CRs were $\geq 20,000$ ohms. This is due to the low starting moisture content and poor contact between the coarse-grained gravel and the electrodes. After Storm Event 1, CRs continue to average 20,000 ohms. After Storm Event 2, CRs are between 2,000 and 20,000 ohms.

CRs were reduced as water was added to the soil column. However, due to the high permeability of the gravel layer, water was drained from the columns quickly, resulting in a high percentage of errors ($\geq 50\%$) during the storms. The percentage error references the error probability

distribution (EPD) and measures the similarities between the forward and reciprocal measurements of electrode pairs during a measurement sequence. Figure 4.2 shows the EPDs derived from the gravel CBS before and after the storms and demonstrates the high levels of error recorded by the PRIME system throughout the soil column experiment. EPDs are measured after each six-hour storm when water percolation levels remain in full effect as water migrates through the topsoil and partially through the gravel.

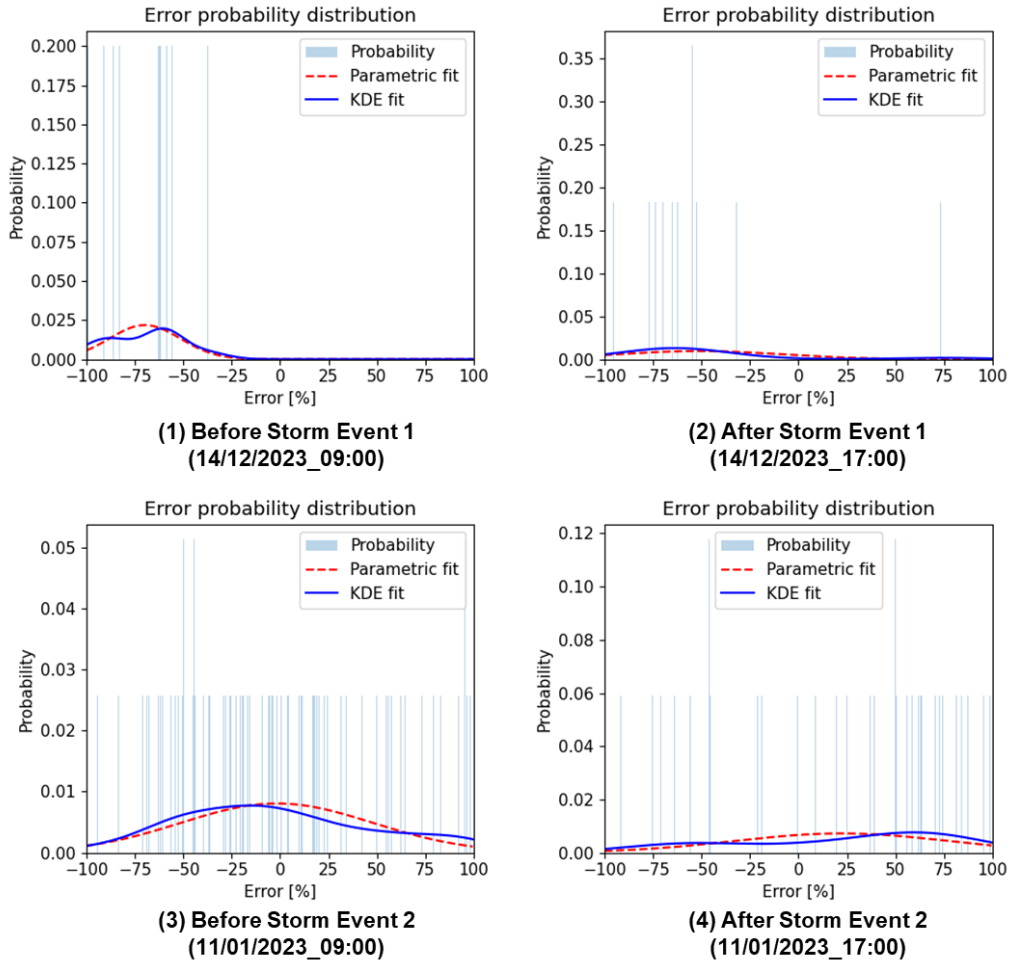


Figure 4. 2 Error probability distributions of gravel-filled capillary barrier system during Storm Events 1 and 2.

Processing a complete time-lapse survey from the gravel-filled CBS experiment was impossible due to the high CRs and reciprocal errors (REs) encountered throughout. Figure 4.3 shows the timesteps that were successfully inverted. No reciprocal error filtering was applied to this data, as any attempts to use an error threshold caused ResIPy (geoelectrical modelling and inversion software) to crash. However, applying a power-law resistance error model to the combined data

was possible before an inversion. The data presents an impression of the spatial distributions in resistivity of the two soil layers (fine-grained topsoil and coarse-grained gravel). The band of high electrical resistivity at the base of the column represents the coarse-grained gravel, and the topsoil is the overlying, less resistive material. Changes in the distribution of resistivity are observed in the modelled data. However, the results cannot be accurately interpreted due to the need for a comprehensive time series and an error threshold – which was not applied.

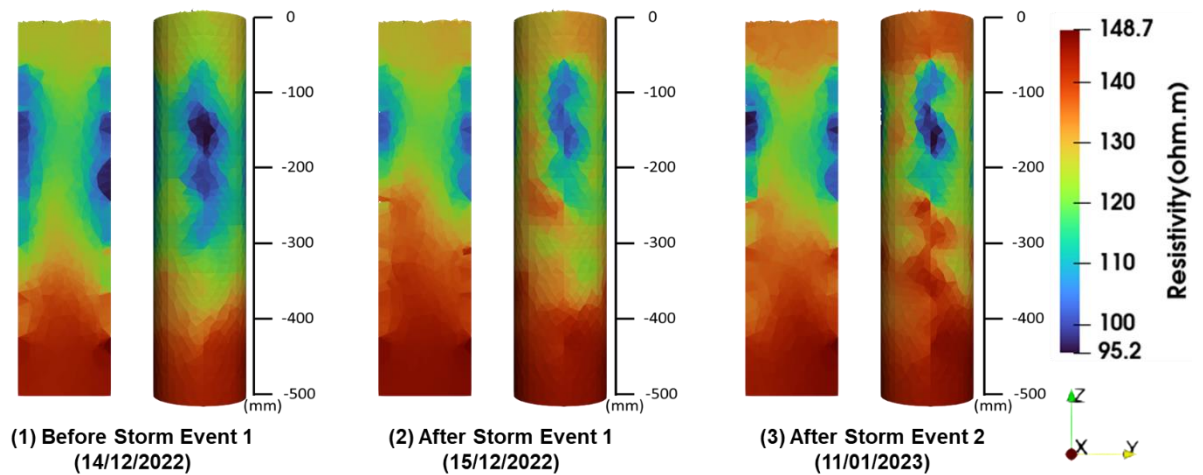


Figure 4. 3 Timelapse survey of gravel-filled capillary barrier system column before and after simulated storm events.

Soil transfer resistances are analysed to determine whether the ERT column can identify changes in electrical resistivity during storms. Given that the gravel-filled CBS column is divided into a coarse-grained and fine-grained layer, the transfer resistances of both materials (topsoil and gravel) are plotted in Figures 4.4 and 4.5.

Figure 4.4 shows the transfer resistances and moisture content in the topsoil during Storm Events 1 and 2. Before water is added to the soil, transfer resistances are between 187.9 and 4509.5 ohm.m. As water is added to the soil during Storm Event 1, moisture content increases from 5.9% to 25.9%. This increase in moisture content is portrayed in the transfer resistances, which fell between 0.09 and 19.8 ohm.m. As moisture content decreases between Storm Events, transfer resistances increase as the topsoil dries.

Figure 4.5 shows the transfer resistances and moisture content in the gravel layer during Storm Events 1 and 2. Due to the high contact resistances in the gravel compared to the topsoil, transfer resistances are significantly higher, with measurements over 200,000 ohm.m before the stormwater has reached the underlying material (gravel). One day after Storm Event 1, moisture

content increased from 5.0% to 8.2%. Simultaneously, transfer resistances decrease by approximately 80%, with the highest recorded measurement of 33,618 ohm.m. As moisture content decreases between Storm Events, a slight increase in resistance is observed. During Storm Event 2, moisture content increases from 4.9% to 10.0%, and transfer resistances decrease accordingly.

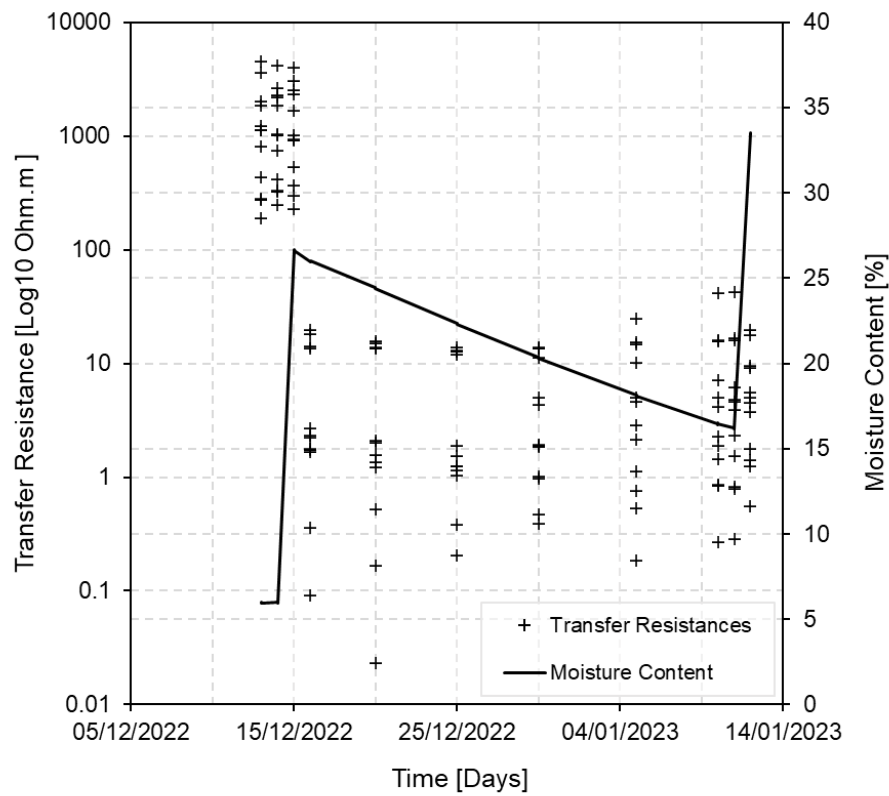


Figure 4. 4 Transfer resistances of the topsoil layer in the gravel-filled capillary barrier system soil column experiment during Storm Events 1 and 2.

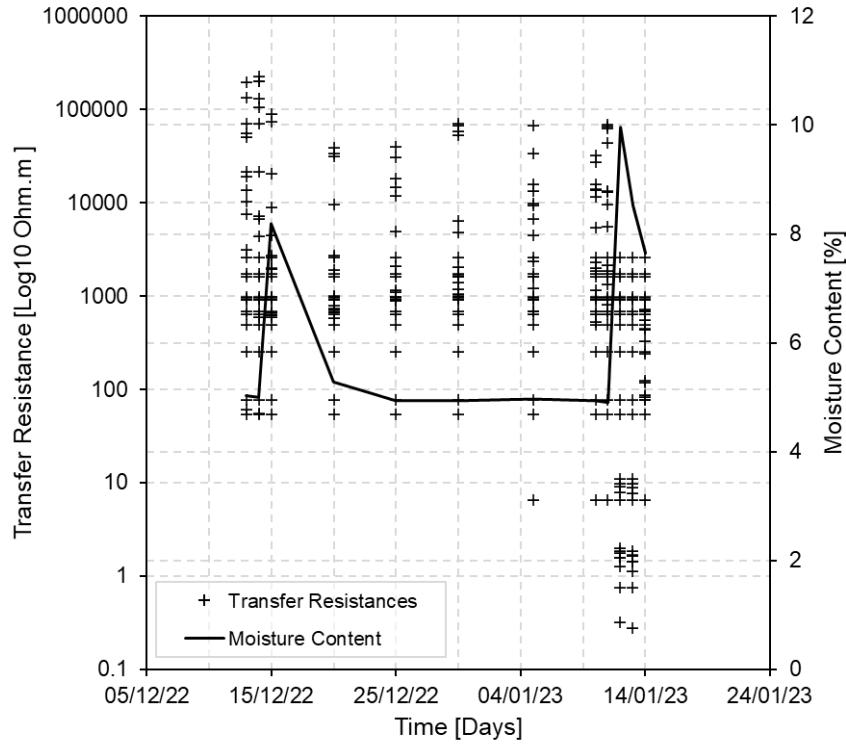


Figure 4. 5 Transfer resistances of the gravel layer in the gravel-filled capillary barrier system soil column experiment during Storm Events 1 and 2.

Producing an acceptable 4D ERT model from the gravel-filled CBS was impossible. Due to the low starting moisture content of both the topsoil and gravel layers, high contact resistances (CRs) were generated before water was introduced to the soil column. High CRs persisted despite water being added to the column during Storm Events 1 and 2. This was due to the large grain size of the gravel layer, resulting in large void spaces and poor electrode-to-soil contact. Transfer resistance data demonstrated that the electrodes accurately measured changes in resistivity throughout the experiment. However, the inversion failed to converge due to significant reciprocal errors measured throughout the experiment. This is attributed to the high hydraulic conductivity of the soil.

4.3 Sand-Filled Capillary Barrier System

In light of difficulties inverting the gravel CBS geoelectrical measurements, the soil column experiment was repeated, and the gravel layer was replaced with sand. It was important to gauge the response of the ERT soil column to various materials with different starting moisture contents and grain sizes. Therefore, a finer-grained material was substituted for the gravel to reduce the contact resistances (CRs) and percentage of errors. As with the gravel CBS experiment, the sand and topsoil were oven-dried before being added to the soil column.

Figure 4.6 shows the changes in moisture content during the experiment. Similar to the gravel-filled experiment, moisture content peaks during the two simulated storms. During the first storm, moisture content in below the capillary barrier remains constant as the barrier effect prevents water from percolating through to the coarser underlying sand layer. A detailed analysis of the changes in moisture content throughout this experiment is given in Appendix C.

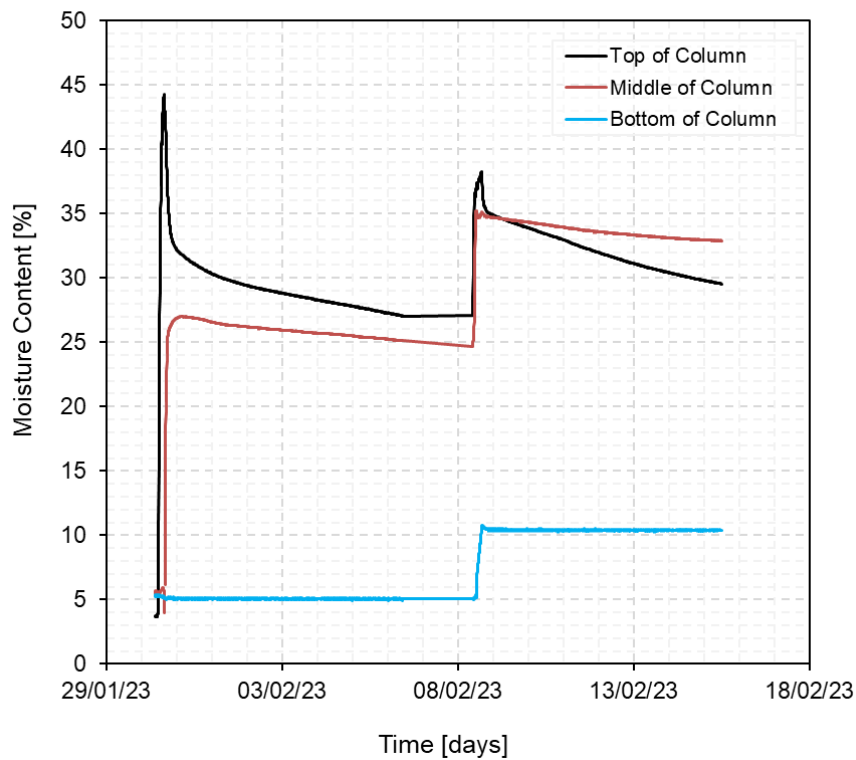


Figure 4. 6 Moisture content data captured by TEROS 12 sensors in the sand-filled capillary barrier system column experiment during two simulated storm events.

Table 8 compares the contact resistances of the gravel and sand-filled CBSs. CRs before water was introduced to the column are similar to values observed in the gravel-filled column. However, unlike the gravel-filled column, there is a noticeable decrease in CRs in the sand. The range of CRs is high after Storm Event 1 because of the contrasting moisture contents and grain

sizes of the topsoil and sand layers. Moisture content measurements in Figure 4.6 show that levels in the sand remain low throughout Storm Event 1. Due to the larger grain size of the sand compared to the overlying topsoil, the absence of water in the air voids would have contributed to the poor contact between the electrodes and sand particles, resulting in the extensive CR range observed after Storm Event 1. As water breaks through the capillary barrier during Storm Event 2, the moisture content in the sand increases. This is reflected in the CR data, which shows reduced CRs in the sand-filled CBS.

Material	CR values (ohm), bin counts = 3,000		
	Before storm event	After storm event 1	After storm event 2
Gravel-filled CBS	20,000	20,000	2000 - 20,000
Sand-filled CBS	20,000	2000 - 20,000	1000 - 5000

Table 8 The contact resistances of the gravel-filled and sand-filled CBS before and after the two simulated storms.

Reducing the grain size of the coarse-grained layer did not improve error probability distributions (EPDs) compared to the gravel soil column. Figure 4.7 shows the EPDs in the sand-filled column experiment before and after Storm Events 1 and 2. Because of the number of errors $\geq 50\%$, applying any reciprocal error filtering caused software crashes or the inversion process to fail.

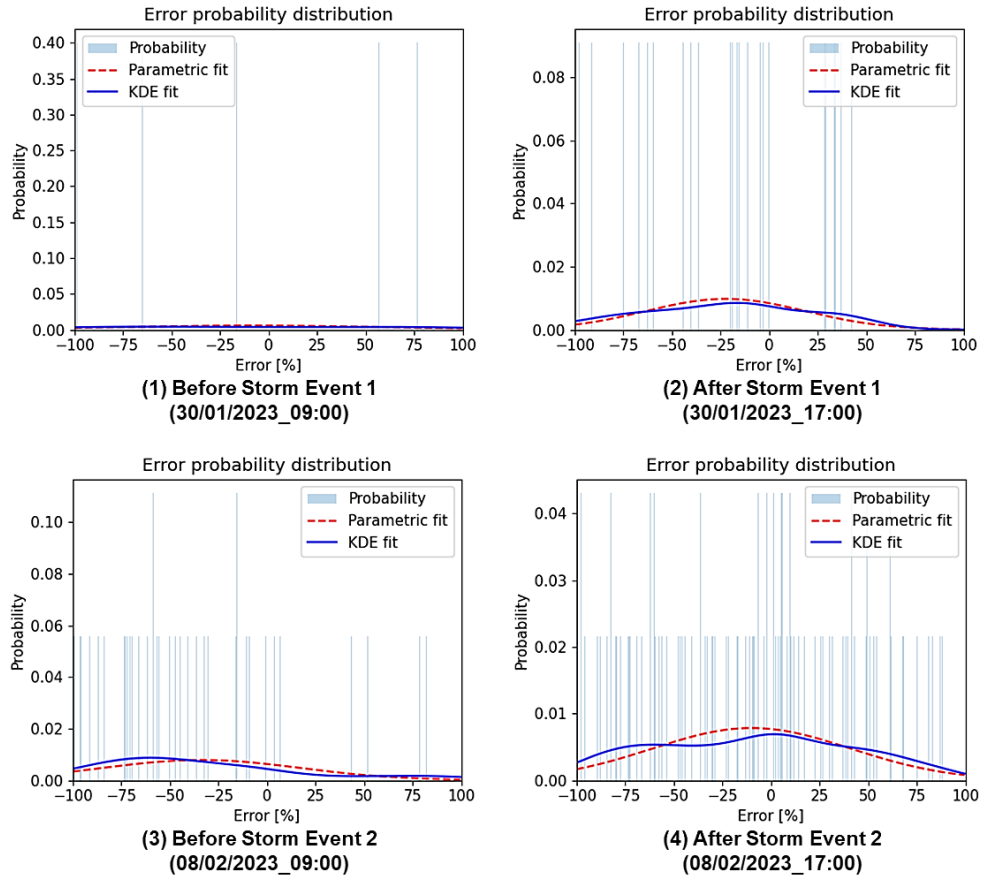


Figure 4. 7 Error probability distributions of sand-filled capillary barrier system during Storm Events 1 and 2.

A sample of the time-lapse survey derived from the sand-filled CBS column experiment is shown in Figure 4.8. Timesteps were selected depending on notable changes during the experiment. Each timestep in the series depicted from left to right shows (1) the resistivity through a cross-section of the soil profile, (2) the resistivity at the column wall, and (3) the percentage difference in resistivity. Storm Event 1 took place on January 30th 2023. At the start of the experiment, electrical resistivity across the column was expectedly high due to the low starting moisture content of the materials. As the water is introduced to the column, an uptick in resistivity occurs (11:30-12:30). Resistivity starts to normalise at 13:30 before decreasing significantly between 13:30 and 14:30. Towards the end of Storm Event 1, between 15:30 and 16:30, a significant percentage difference in resistivity is observed at the topsoil-sand interface. The resistive region in red decreases over time as the wetting front progresses. Storm Event 2 occurs one week after Storm Event 1 on February 8th 2023. However, no further changes in resistivity are observed as both the topsoil and sand layers are 100% less resistive than the

baseline inversion. At the end of Storm Event 2 (08/02/2023 – 16:30), a band of high resistivity forms at -400mm.

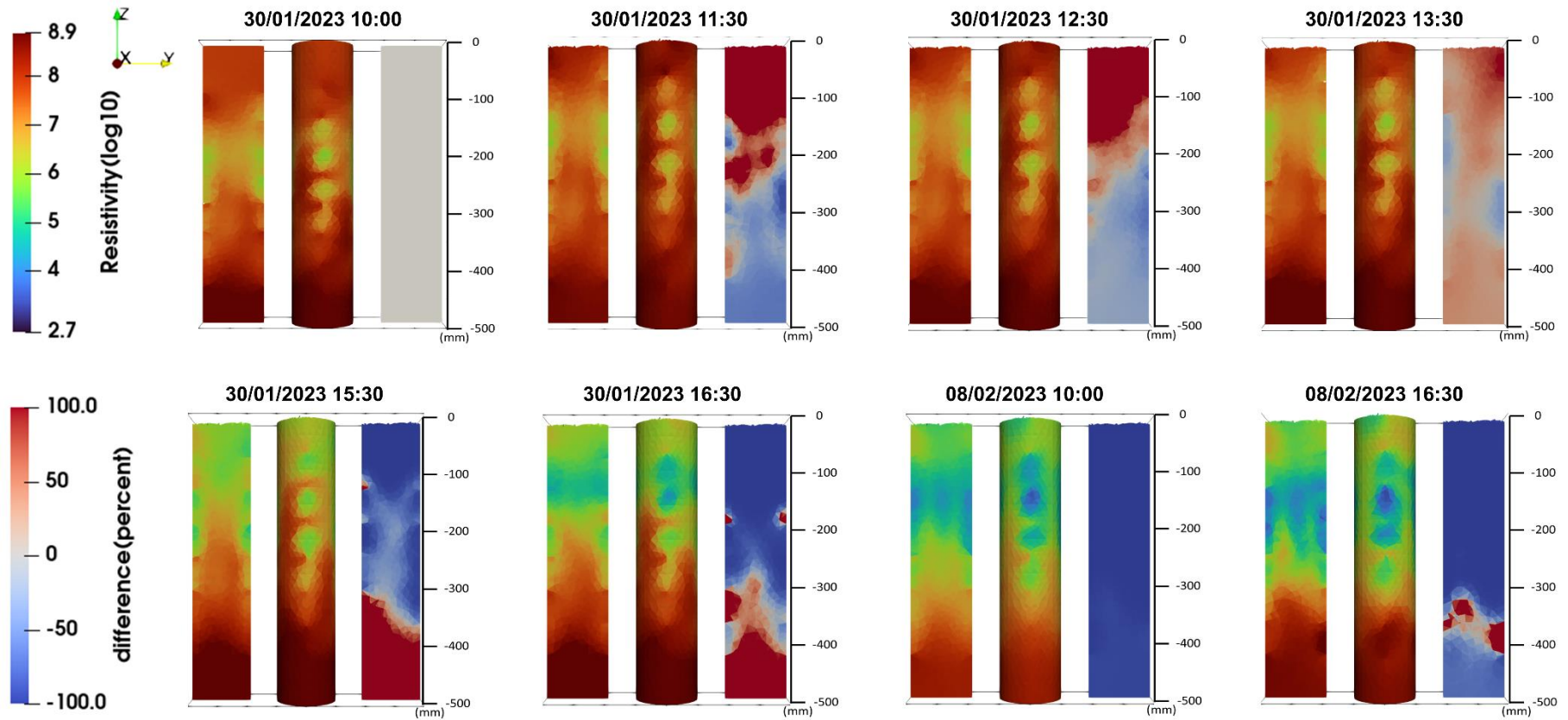


Figure 4. 8 Timelapse survey of sand-filled CBS column during Storm Events 1 and 2 showing a wetting front progressing through the soil. ERT images show the cross-section of the column (left of each timestep), the resistivity at the column wall (middle) and the percentage difference in resistivity (right).

The time-lapse imaging results shown in Figure 4.8 contain the first observable artefacts in the modelled data. ERT images show that as tap water is added to the column during Storm Event 1, the percentage difference in resistivity increases by up to 100%. However, point sensor data in Figure 4.6 indicates that moisture content did not decrease significantly during the experiment enough to exhibit a percentage decrease in electrical resistivity like those observed in the ERT images. Figures 4.9 and 4.10 show the transfer resistances in the topsoil and sand layers during Storm Event 1. The transfer resistances in both materials are consistent with the moisture content data. In the topsoil (Figure 4.9), transfer resistances are high before water is introduced to the soil. Moisture content increases to 44.1%, and resistivity falls accordingly. In the sand layer (Figure 4.10), moisture content changes are minor ($\leq 1\%$). This is also seen in the transfer resistance data, which shows little to no changes throughout the first storm event.

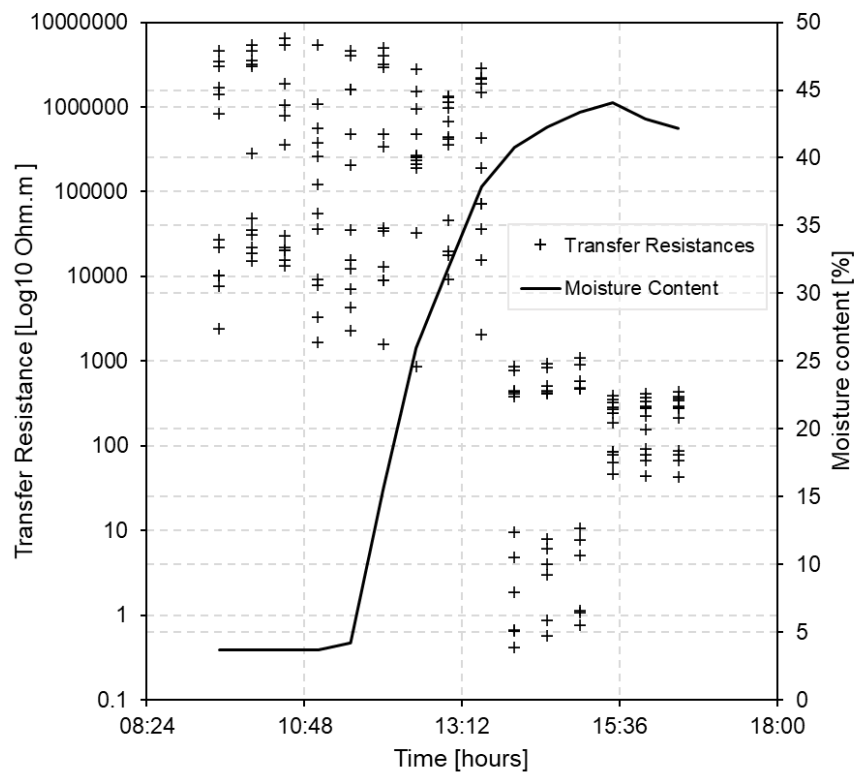


Figure 4. 9 Transfer resistances of the topsoil layer in the sand-filled capillary barrier system soil column experiment during Storm Event 1.

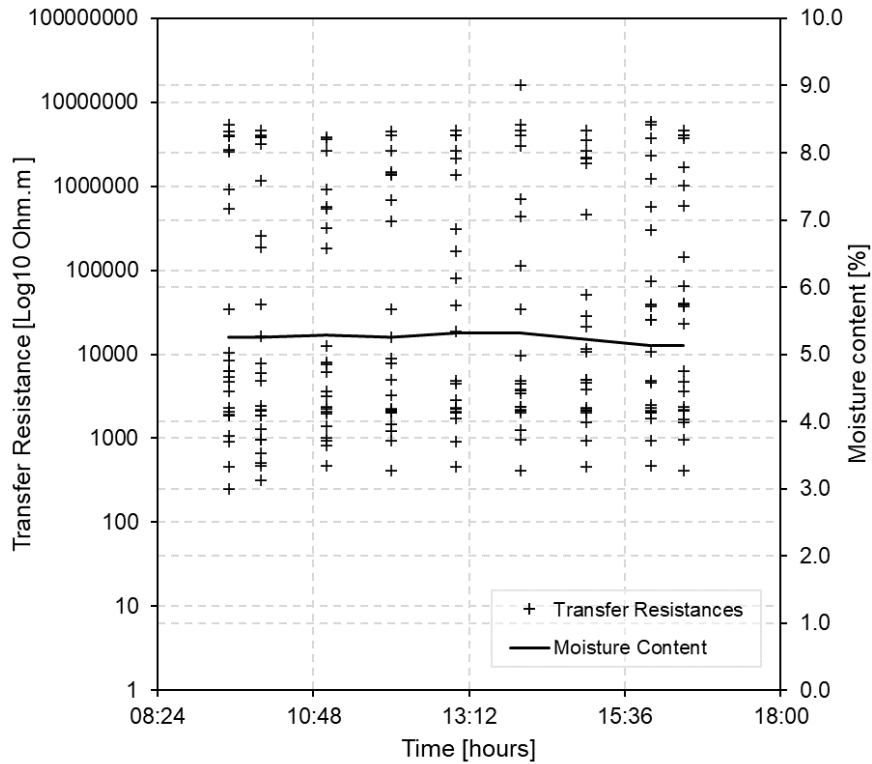


Figure 4. 10 Transfer resistances of the sand layer in the sand-filled capillary barrier system soil column experiment during Storm Event 1.

Reducing the grain size of the coarse layer in the CBS from gravel to sand helped reduce contact resistances when water was added to the column during Storm Events 1 and 2. However, error probability distributions remain high throughout the experiment, preventing reciprocal filtering during preprocessing. With a reduction in the contact resistances (compared to the gravel-based experiment) but high reciprocal errors, the subsequent time-lapse inversion could not be filtered at 5% and probably contributed to the appearance of modelling artefacts, which did not accurately portray spatial distributions in resistivity. By Storm Event 2, ERT imaging depicts that resistivity has decreased in the column. However, artefacts persisted in the time series. Plotting the transfer resistances from the sand and topsoil layers during Storm Event 1 reveals that the electrodes accurately measure changes in resistivity as moisture content increases. However, this is not conveyed in the modelled data, possibly due to the high contact resistances and error values that could not be filtered from the data.

4.4 Compacted Clay Topsoil Column Experiments

Data collected from the capillary barrier experiments (sand and gravel) reveal the sensitivity of the ERT soil column to high contact resistances and reciprocal errors (REs) that interfere with the electrical surveys. The capillary barrier experiments at low starting moisture contents ($\leq 5\%$) utilise higher permeability materials that yield high REs. Soil column experiments were carried out on compacted clay topsoil (CT) to attenuate rapid changes in moisture content and reduce the percentage of errors in the error probability distributions. The soil is compacted and added to the columns at three dry densities: (1) 1.46 Mg/m^3 , (2) 1.69 Mg/m^3 , and (3) 1.57 Mg/m^3 . A single 1 in 100 storm event was simulated during each experiment to assess the ability of the ERT soil column to monitor variable spatial distributions in resistivity in fine-grained soils. Initial tests at each dry density produced significant ponding during the storm events, with water reaching the brim of the soil column in all the experiments (50mm of surface water). Given the clay topsoil's low porosity and highly compacted states, water infiltration was limited.

The accumulation of surface water during storm events resulted in modelled artefacts. These artefacts appear as regions of high resistivity elements that did not accurately portray the soil moisture dynamics throughout each experiment. Point sensor data collected simultaneously in a neighbouring column with the ERT survey show significant contrasts to the modelled data, therefore putting the reliability of the ERT images into question. Where these artefacts appeared, the transfer resistances were examined to determine the accuracy of the ERT images. Ponding on the soil surface can change the boundary conditions of the resistivity models by increasing the known volume of the inversion. Due to the effects of ponding, two tests were performed on each compacted CT:

- Experiment 1 (Exp. 1): Ponding allowed
- Experiment 2 (Exp. 2): Surface water runoff enabled

In Exp. 2, an outflow tube was fitted at the soil surface to the wall of the column. The tube was connected to a tipping bucket to quantify the water loss as surface runoff. A mesh was fixed to the aperture to prevent fine material from entering the tube and blocking the tipping gauges. Figure 4.11 shows the runoff measured by the tipping gauges during the storm for each compacted CT during Exp. 2. The runoff tube had the desired effect of removing water, although removal was intermittent, and as a result, some ponding still occurred. Inconsistent surface water drainage in Exp. 2 occurred in soils compacted at a dry density of 1.46 Mg/m^3 and 1.57 Mg/m^3 , resulting in artefacts appearing in the modelled data. At 1.69 Mg/m^3 (maximum dry density), surface water drainage was consistent because of low infiltration levels and soil

surface erosion during the storm. A detailed examination comparing surface runoff in each experiment is provided in Appendix C.

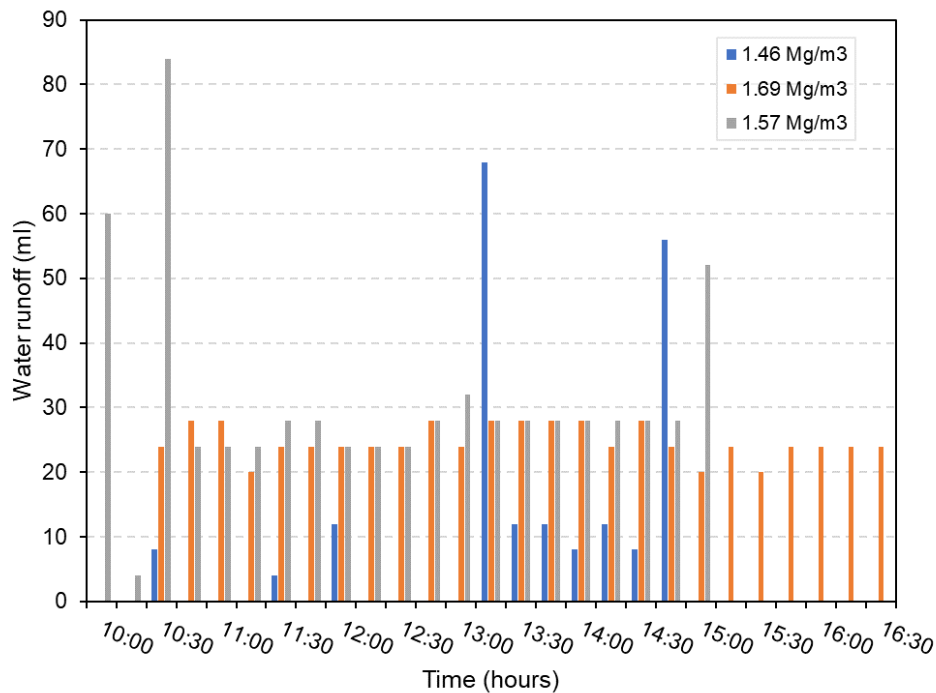


Figure 4. 11 Tipping gauge data comparing surface runoff during simulated storm events in clay-topsoil compacted at different dry densities.

4.4.1 Contact Resistances and Reciprocal Errors

Fine-grained clay topsoil (CT) was tested in the soil column experiments to reduce contact resistances (CRs) and improve the percentage of error in the error probability distributions. CRs are significantly reduced in the CTs, as seen in Table 9, where CRs are compared between the gravel, sand and CT. The data indicates that CRs are influenced by soil grain size. In each CT, CRs are reduced after water is added to the soil. Moisture content and grain size are essential for low CRs, but the data also highlights the effects of soil compaction on resistivity. At 1.46 Mg/m³ (lowest dry density), CRs before the storm event are highest. However, after water is added to the soil, the range of CR decreases the most compared to the other two soils at a higher dry density. This is expected, given that the soil (CT, 1.46 Mg/m³) has a higher permeability at a lower dry density. This is also reflected in the ERT imaging, which shows a visible wetting front extending through the soil at 1.46 Mg/m³ (see Section 4.4.3). Something that is not seen at a dry density of 1.69 Mg/m³ and 1.57 Mg/m³.

Material	CR values (ohm), bin counts = 3,000		
	Before storm event	After storm event 1	After storm event 2
Gravel-filled CBS	20,000	20,000	2000 - 20,000
Sand-filled CBS	20,000	2000 - 20,000	1000 - 5000
Clay Topsoil (1.46mg/m3)	5000	>0 - 1000	na
Clay Topsoil (1.69mg/m3)	1000 - 5000	500 - 2000	na
Clay Topsoil (1.57mg/m3)	1000 - 5000	>0 - 3000	na

Table 9 Contact resistances of compacted clay topsoils, sand, and gravel-filled soil columns at critical stages of the soil column experiments.

Reciprocal errors also improved significantly compared to the gravel and sand-filled CBSs. Figure 4.12 shows the error probability distributions (EPDs) of the different soils before water was added to the columns. Improvements to the error distributions in each clay-based experiment enabled a reciprocal filter of 5.0% to be applied to each dataset in the time-lapse surveys, ultimately improving survey accuracy.

Despite lowering the contact resistances and percentage reciprocal error, artefacts appear in the CT time-lapse surveys. Artefacts in the CT are a product of soil moisture contrasts when water was added to the columns and ponded on the surface. This problem is further exacerbated by the dipole-dipole array configuration, which studies have proven is more susceptible to modelling errors (Carey et al., 2017). However, the impact of the electrode configuration and soil moisture contrasts generated during storm simulations on producing modelling artefacts was unknown when conducting soil column experiments and assessing the ERT images.

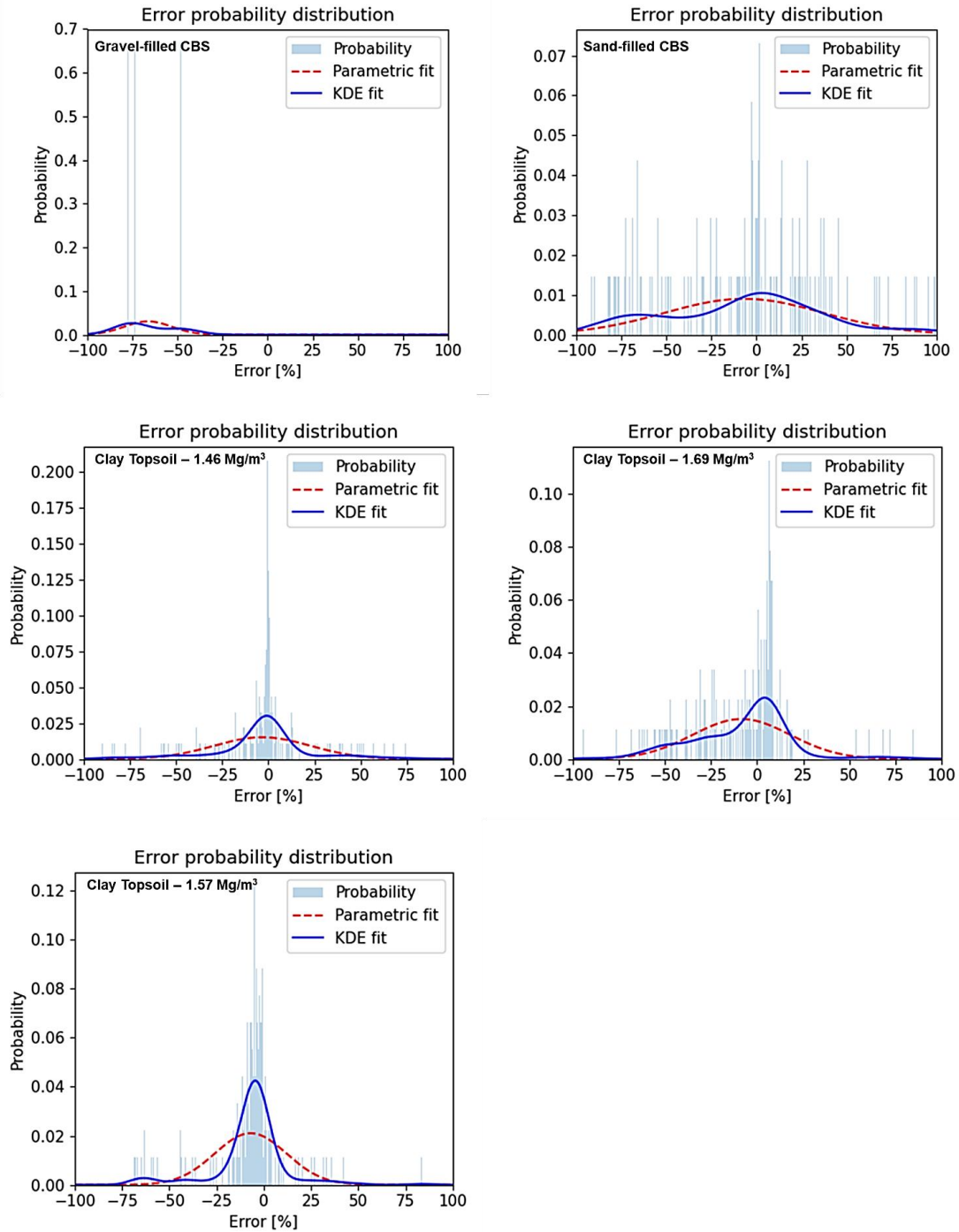


Figure 4. 12 Error probability distributions of gravel-filled CBS, sand-filled CBS and clay topsoil compacted at different dry densities before a simulated storm event.

4.4.2 Experiment 1

Exp. 1 consists of three soil column experiments performed at different dry densities (1.46 Mg/m^3 , 1.69 Mg/m^3 and 1.57 Mg/m^3). Immediately after the first experiment (1.46 Mg/m^3), it was clear that a method for reducing ponding was necessary due to the influence surface water can have on ERT imaging. However, the decision was made to complete the two remaining

compacted CT experiments (at 1.57 Mg/m^3 and 1.69 Mg/m^3) to quantify the impact ponding could have on 4D ERT-integrated soil column tests. Subsection 4.4.3 – 4.4.5 examines the effects of ponding on ERT soil column experiments. Point sensor data is compared to the ERT imaging and soil transfer resistances.

4.4.3 Clay Topsoil Compacted to 1.46 Mg/m^3 Dry Density

In Experiment 1, where ponding occurred, the first column experiment conducted on the compacted CT was at 1.46 Mg/m^3 . Figure 4.13 depicts the changes in moisture content during a storm. The data shows that moisture content increases in the near surface and middle of the material after the storm. Moisture level increases towards the base of the material is minimal. See Appendix C for a detailed account of the changes in MC

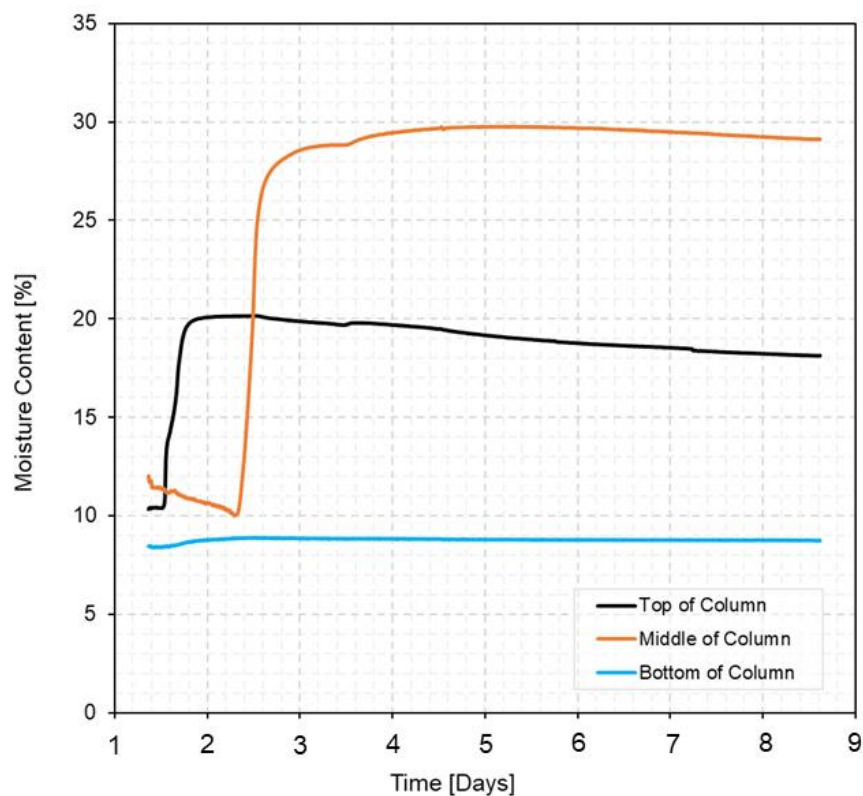


Figure 4. 13 Point sensor data collected from soil column experiment on clay topsoil compacted to 1.46 Mg/m^3 .

Figure 4.14 shows time-lapse results for soil added to the column at a dry density of 1.46 Mg/m^3 in Exp. 1, where no runoff tube was used. The storm was initiated at 10:00 on day 1. Water ponding began approximately three hours into the storm. At the end of the storm, 15 mm of

surface water was recorded. Little to no change in resistivity was measured until 16:00, where artefacts (presenting as regions of increasing resistivity) appear in the modelled data at surface level, -100mm and -400mm. At 16:30, artefacts disappear from the image, and a clear wetting front is discernible, extending from the soil surface to -180 mm depth. From 16:00 to 16:30, the percentage difference in resistivity suggests that resistivity decreases by 50% in the near-surface. However, given the low porosity of the soil, it is unlikely that the stormwater percolated so far through the material in 30 minutes. It is more likely that, at 16:00, artefacts presenting as regions of increasing electrical resistivity are masking the wetting front observed at 16:30. Scheduled geoelectrical measurements stopped at 16:30 and resumed at 09:30 on day 2. ERT imaging shows that the wetting front has continued to extend through the soil to a depth of -300mm. In subsequent timesteps, no further progression of the wetting front is captured in the time-lapse data. At the base of the column, resistivity increases by up to 50%. This is also attributed to modelling artefacts.

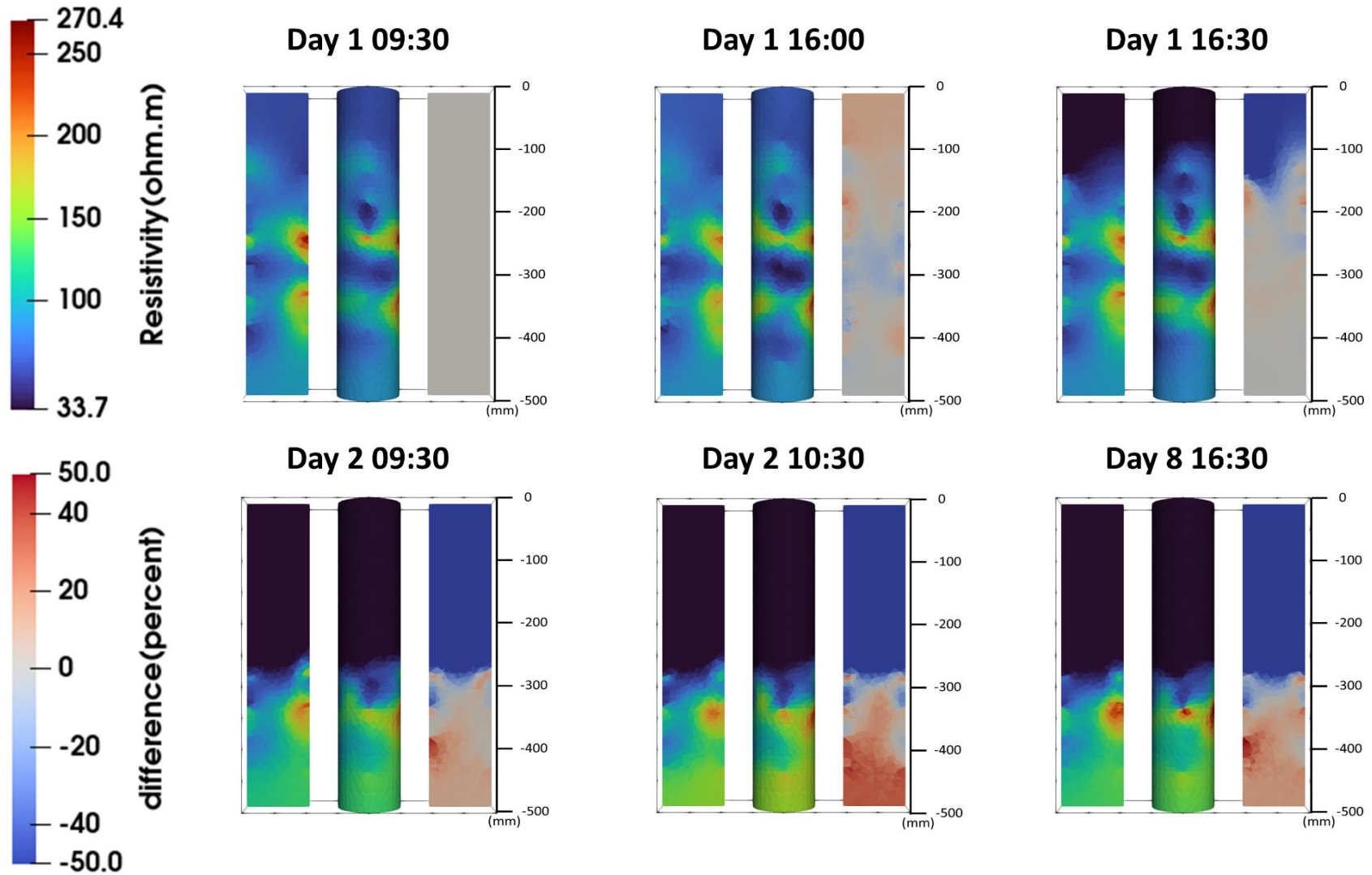


Figure 4. 14 A timelapse survey of clay topsoil compacted to a dry density of 1.46 Mg/m^3 . Data was collected during Experiment 1, where surface water ponding occurred. ERT images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

On day 2, areas of high resistivity are observed at the base of the soil column. To determine whether these regions of high resistivity are modelling artefacts or accurate measurements, the transfer resistances from 09:30 to 10:30 on day 2 are analysed. Specifically, the bottom four electrodes of each array are examined. The data in Figure 4.15 indicates that moisture content remains relatively stable (within 0.1%). Similarly, the corresponding transfer resistances also remain unchanged, suggesting that the artefacts result from inaccurate modelling and not actual measurements.

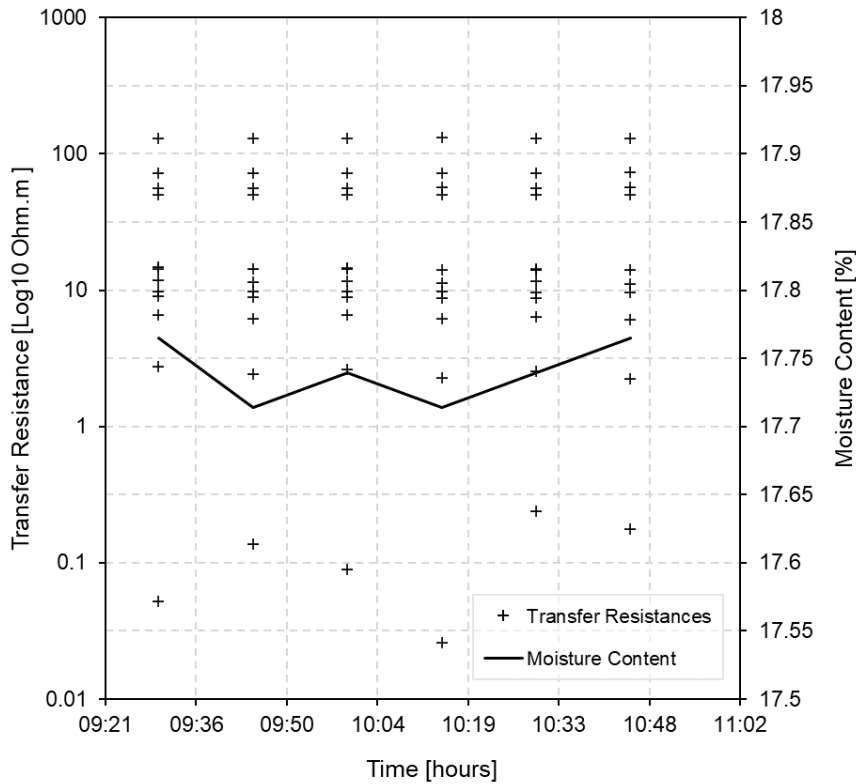


Figure 4. 15 Transfer resistances of the clay topsoil compacted to a dry density of 1.46 Mg/m^3 on February 18 2023, one day after the simulated storm.

4.4.4 Clay Topsoil Compacted to 1.69 Mg/m^3 Dry Density

After the soil column experiment on clay topsoil at 1.46 Mg/m^3 , the column was refilled and compacted at a dry density of 1.69 Mg/m^3 (maximum dry density). Figure 4.16 shows the changes in moisture content during a single storm event in Experiment 1, where ponding occurred. Moisture content is only recorded to increase at the top of the column by approximately 1%, which is logical, given that the soil was compacted to maximum dry density. Despite significant surface water build-up throughout the storm simulation ($\leq 50\text{mm}$), little water infiltration occurred because the soil was compacted at maximum dry density.

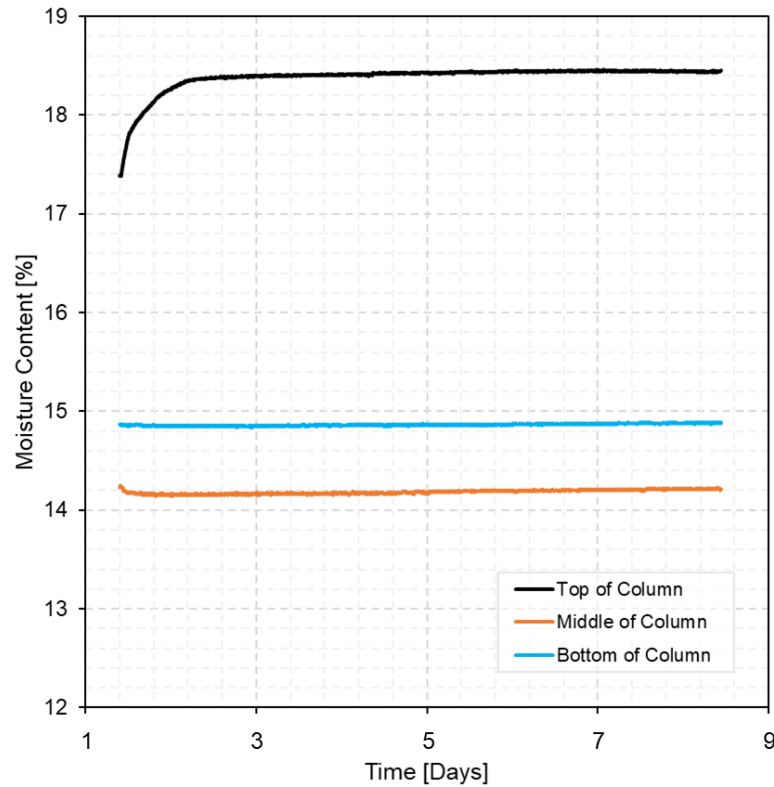


Figure 4. 16 Point sensor data was collected from a soil column experiment on clay topsoil and compacted to 1.69 Mg/m^3 (maximum dry density). Changes in moisture content over time (days) were collected during Experiment 1, where significant ponding occurred.

Figure 4.17 shows a timelapse survey on CT compacted at 1.69 Mg/m^3 during Experiment 1. Water was added to the column on day 1. Before the first addition of water, concentrated areas of high resistivity are observed at depths of -220mm and -340 mm . Artefacts are seen throughout the timelapse survey and appear close to the electrodes at the soil boundaries. From 10:30 to 12:30, resistivity decreases up to -200mm and increases towards the base of the material. At 13:00, artefacts are observed throughout the soil. From 13:00 to 16:00, artefacts are seen to varying degrees and appear to change slightly at each timestep. Figure 4.18 shows a time-lapse survey of the clay topsoil one day after the storm simulation (day 2). Pondered water levels had remained high (50mm), and little infiltration had occurred. However, artefacts in the data persist but are concentrated in the lower regions of the soil profile ($-250\text{mm} - -500\text{mm}$).

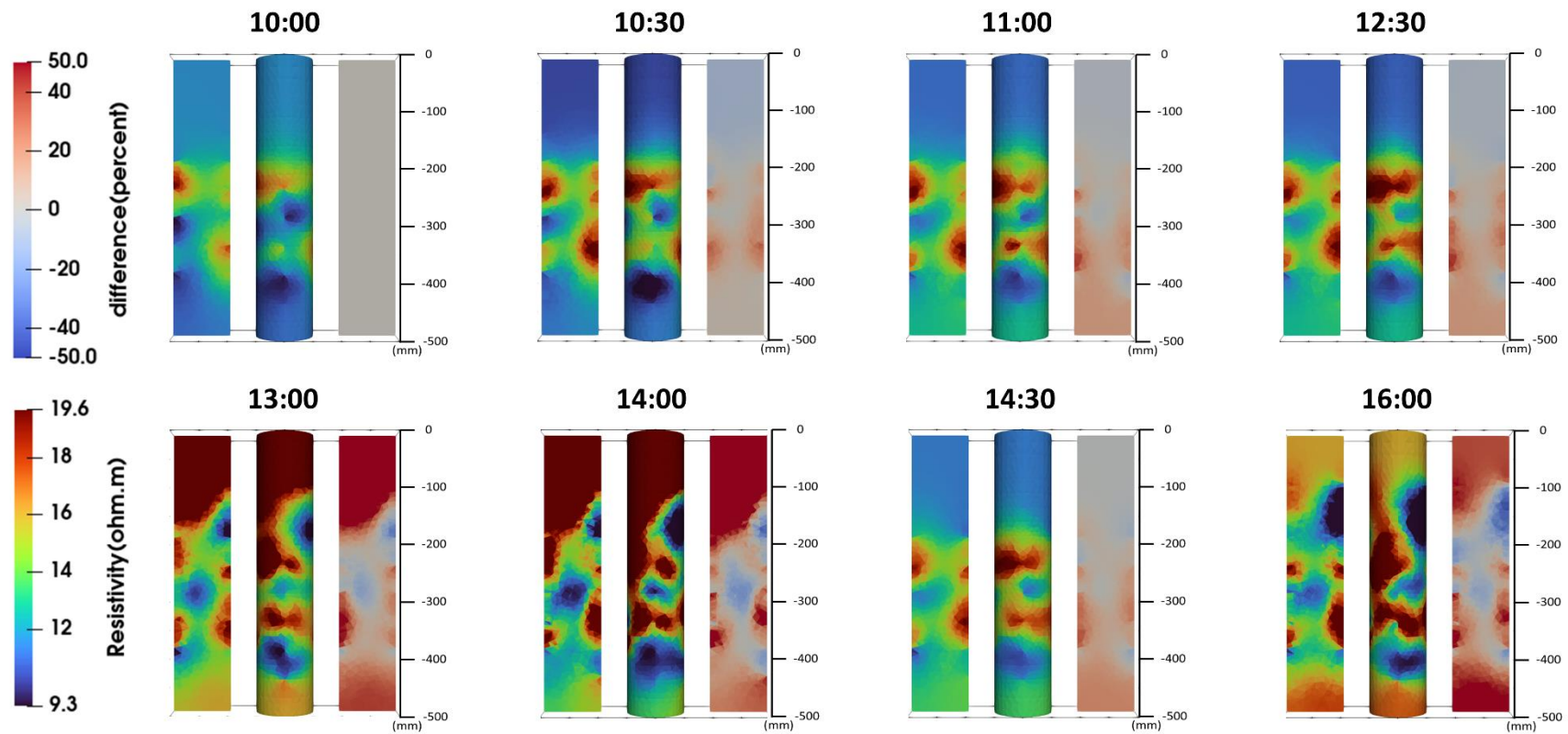


Figure 4. 17 A timelapse survey of clay topsoil compacted to a 1.69 Mg/m³ dry density. Data was collected during Experiment 1, where surface water ponding occurred during the storm simulation.

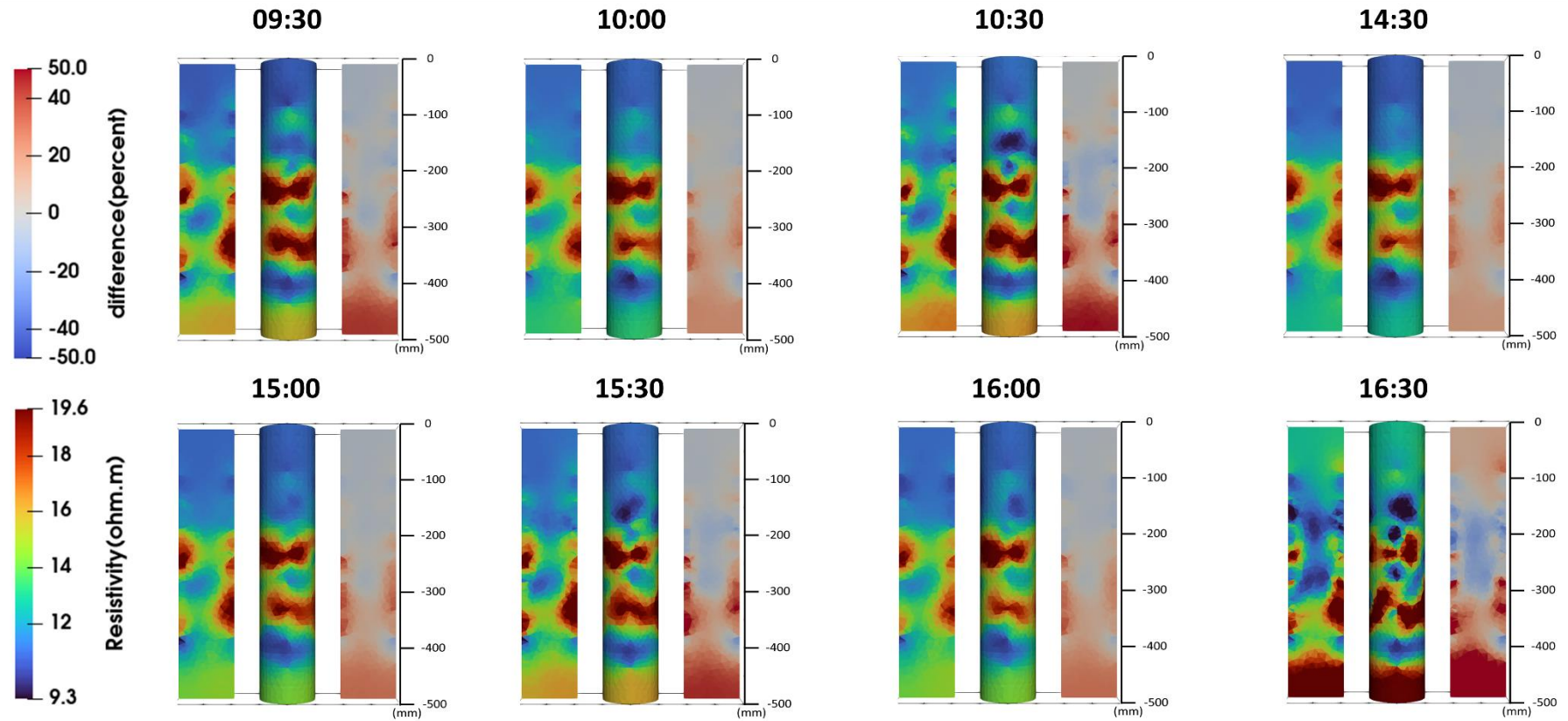


Figure 4. 18 A timelapse survey of clay topsoil compacted to a dry density of 1.69 Mg/m^3 one day after the six-hour storm. Data was collected during Experiment 1, where surface water ponding occurred.

The prevalence of artefacts in the ERT imaging at 1.69 Mg/m^3 is higher than at 1.46 Mg/m^3 . Figures 4.19 and 4.20 show the transfer resistances measured by the electrodes during the soil column experiment (at 1.69 Mg/m^3). Like the ERT images depicted in Figure 4.14 (CT at 1.46 Mg/m^3), the modelled artefacts at 1.69 Mg/m^3 are likely a product of the ponded water and not actual measurements. The appearance and prevalence of artefacts at maximum dry density are greater than those observed at 1.46 Mg/m^3 because little water infiltration occurred at the higher compacted state. See Appendix C for a description of the CT transfer resistances.

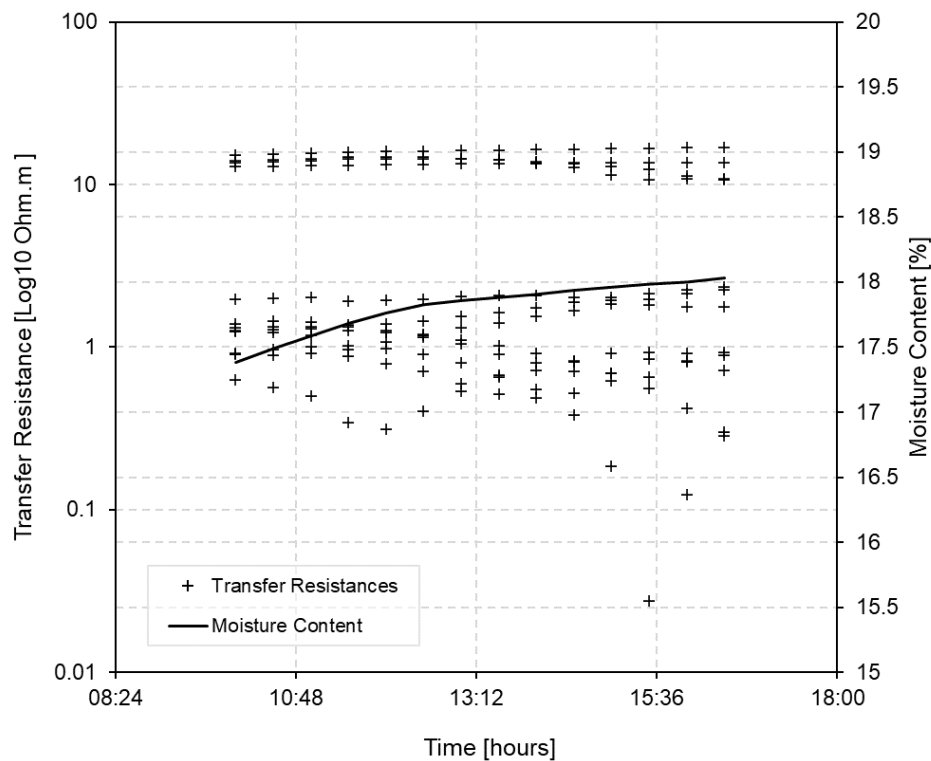


Figure 4. 19 Transfer resistances of the clay topsoil compacted to a dry density of 1.69 Mg/m^3 . Data shows the changes in moisture content and transfer resistances during the storm event from the soil surface to -250mm depth.

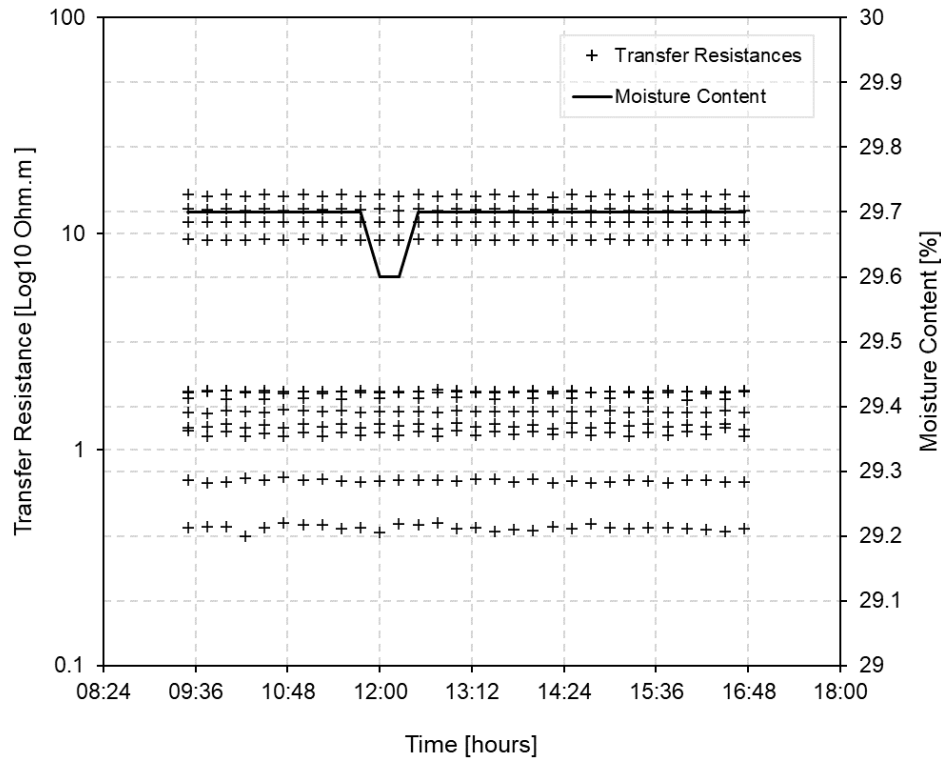


Figure 4. 20 Transfer resistances of the clay topsoil compacted to a dry density of 1.69 Mg/m^3 . Data shows the changes in moisture content and transfer resistances one day after the storm event from -250mm to the base of the soil (-500mm).

4.4.5 Clay Topsoil Compacted to 1.57 Mg/m^3 Dry Density

Before the outflow tube was fitted to the soil columns to prevent ponding, the final clay-based experiment was done at a dry density of 1.57 Mg/m^3 . The soil was mixed with water at a moisture content of approximately 20.2%, making it the wettest of the tested clay-based soils. Figure 4.21 shows the change in moisture content at the top, middle and bottom sections of the soil during the wetting and drying stages of the experiment. Point sensor data captures an initial increase in moisture content in the top of soil during the storm event before moisture content throughout the column decreases. During the storm, moisture content in the middle and bottom of the soil did not increase, indicating that water did not percolate further than 100mm – 150 mm into the soil. Ponding occurred throughout the experiment, and approximately 50mm of surface water is recorded at the end of the six-hour storm event. The accumulation of surface water and steady decrease of soil moisture content indicates low infiltration in the soil. Surface water evaporated over 48 hours, and moisture levels in the soil continues to decrease as the material dried. The tipping gauge measuring drainage from the base of the column measures that a total of 8 mm of water was removed from the soil.

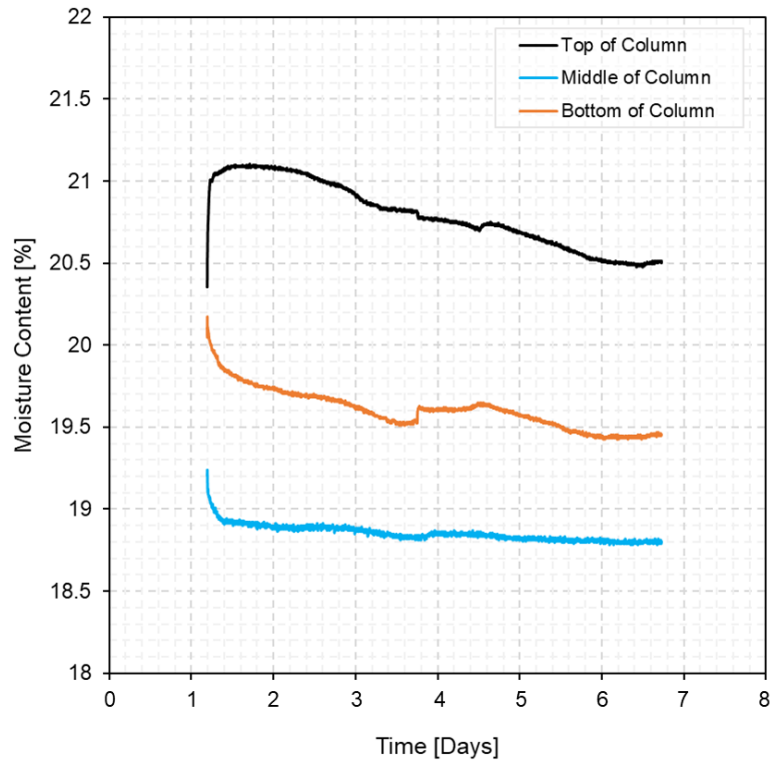


Figure 4. 21 Point sensor data was collected from a soil column experiment on clay topsoil compacted at 1.57 Mg/m^3 during Experiment 1, where ponding occurred.

Figure 4.22 shows a time-lapse survey of the spatial distribution and percentage difference in resistivity for clay topsoil compacted at 1.57 Mg/m^3 . Looking at the scale for electrical resistivity and the percentage difference, changes in resistivity are low ($\leq 10.0\%$). Water was added to the soil column on day 1 at 10:00. No change in resistivity occurs until 12:00, when a 2.5% percentage decrease is captured, extending from ground level to -150mm. The following noticeable change occurs at 14:30, where suspected artefacts appear again in the ERT imaging. These artefacts extend throughout the soil profile but are more prominent between 0mm and -180mm depth. Similar to the previous ERT surveys (CT at 1.46 Mg/m^3 and 1.69 Mg/m^3 dry densities), the prevalence of artefacts varies from timestep to timestep. At 14:30, extensive modelling artefacts are observed throughout the column. However, at 15:00, in the next timestep, these artefacts disappear from the inversion, providing a more realistic insight into the changes in resistivity that correspond more with measurements made by the point sensors (Figure 4.21).

A summary of the key differences in resistivity between each of the compact CTs is provided in Appendix C.

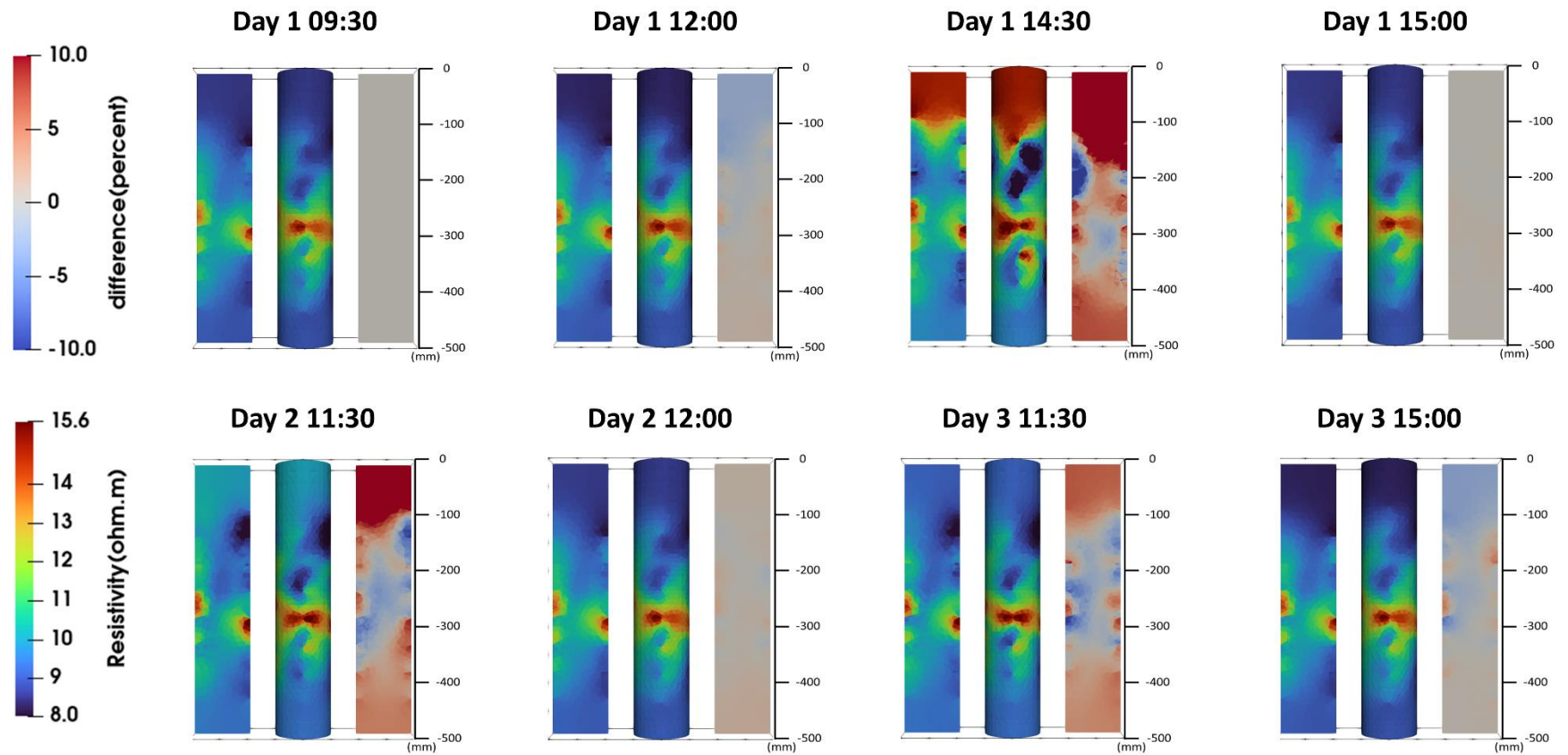


Figure 4. 22 A timelapse survey of clay topsoil compacted to a dry density of 1.57 Mg/m^3 during and after a simulated storm. Data was collected during Experiment 1, where ponding occurred.

4.4.6 Experiment 2

In the first suite of soil column experiments on clay topsoil (CT), artefacts in the ERT images were attributed to significant ponding during storm simulations. A surface water runoff tube was fitted at the soil surface to mitigate ponding and reduce artefacts. The experiments were repeated at each dry density (1.46 Mg/m^3 , 1.69 Mg/m^3 and 1.57 Mg/m^3). This had the desired effect of reducing ponding. However, soil surface drainage was intermittent due to soil settlement and fines blocking the drainage aperture during the storm. Sections 4.4.6 – 4.4.9 analyse CT column experiments after fitting the surface water drainage tube (Experiment 2). Soil moisture content is compared between Experiments 1 and 2 to demonstrate the effect the drainage tube had on water infiltration during wetting events, and ERT time-lapse surveys are analysed at each dry density. The transfer resistances of the soil are not examined as they have been used in previous sections to prove that the ERT column accurately measures electrical resistivity but does not model the data correctly in the inversion.

In each of the compacted CT experiments done where surface water was drained, modelling artefacts in the inversion did not diminish, and in some instances, increased (e.g., Figure 4.23) Where resistivity contrasts were higher than those recorded in Section 4.4.3 despite the same soil/state of compaction being used. A detailed account of the changes in resistivity for each compacted topsoil in Experiment 2 is given in Appendix C which compares the soil moisture content from Experiments 1 and 2 and describes the spatial distribution of artefact in the tomograms.

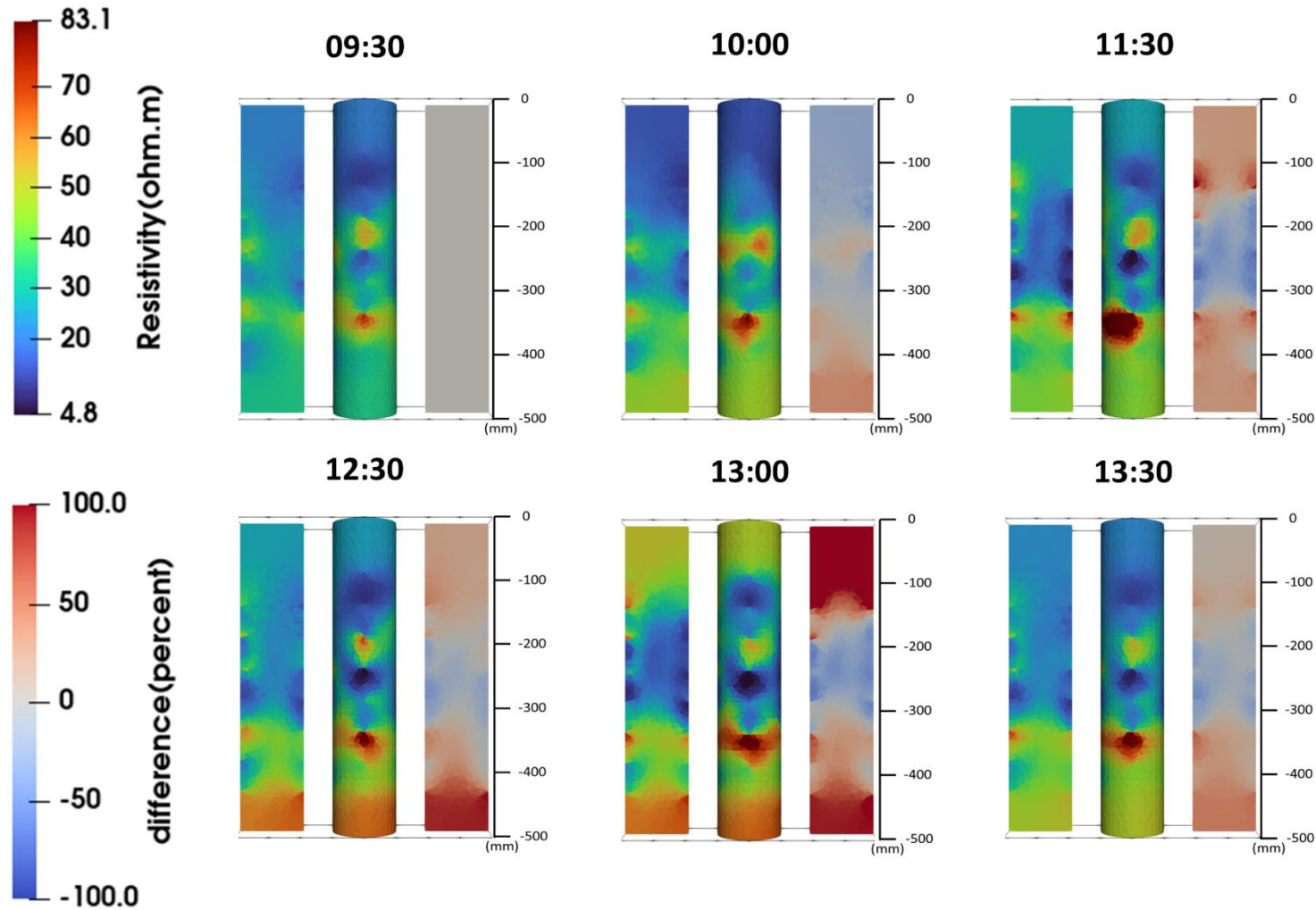


Figure 4. 23 A timelapse survey of clay topsoil compacted to a dry density of 1.46 Mg/m^3 . Data was collected during a simulated storm in Experiment 2 after deploying a surface water outflow tube. Images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

4.5 Bourne Amenity Topsoil Column Experiment

The final soil column experiment in Series 1 was conducted on Bourne Amenity topsoil (BAT). Column experiments carried out on the gravel and sand-filled CBSs indicated that starting conditions could not be too dry (close to 0% moisture content) as this would generate large contact resistance (CR) and reciprocal error (RE) values during the experiment. Clay topsoil column experiments have reduced CRs and REs, making geoelectrical modelling more reliable (e.g., assigning an error threshold without software crashes). However, due to the low porosity of the soil, ponding occurred, which led to modelling artefacts.

In Exp.2 (addition of a runoff tube), ponding was reduced, but minimal water infiltration occurred. Therefore, no wetting front could be observed in the ERT imaging (e.g. clay topsoil at 1.69 Mg/m^3 , Exp.2). To reduce artefacts and ultimately improve the quality of the ERT imaging, previous soil column experiments indicated that reducing ponding during a storm and decreasing CRs and REs was necessary. Therefore, a soil column experiment consisting of topsoil was devised to mitigate the problems experienced in the previous experiments (CBSs and CT tests).

The topsoil was added to the column at a starting moisture content of 10% (as seen in Figure 4.24). Soil moisture content increased during the storm event before steadily declining days after. An in-depth description of soil moisture changes in the topsoil is given in Appendix C.

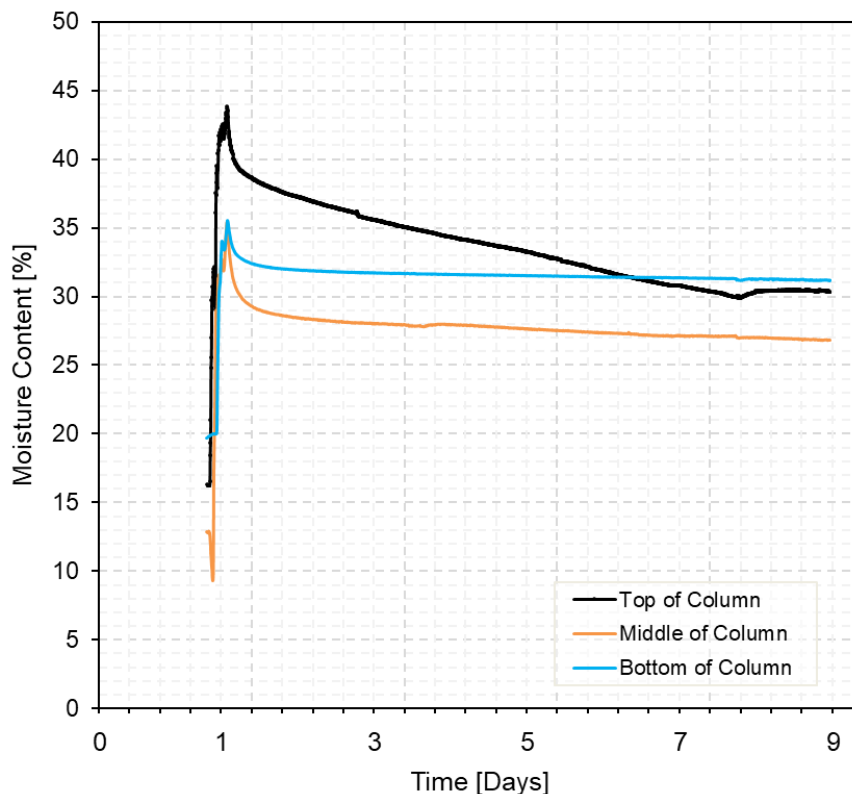


Figure 4. 24 Point sensor data collected from soil column experiments on topsoil during and after a simulated storm.

Starting at a higher moisture content (10%) compared to the CBS column experiments had the desired effect of reducing CRs, which measured between 500 and 1500 ohms. However, on day 1, before the storm was initiated, many RE values were greater than 25%. Figure 4.25 shows the evolution of reciprocal errors during the storm. The data from the graphs demonstrate that the distribution of errors decreases throughout the storm, and by 16:30 (the end of the storm), approximately 95% of errors have less than 25% error probability. High REs indicate misalignment between the forward and reciprocal measurements during the electrical survey. Therefore, it is not uncommon for the percentage of error distribution during a simulated storm to increase as the wetting front outpaces the time it takes for the PRIME system to complete one set of forward and reciprocal measurements. However, error percentages are high (40% $\geq$ 25%) before the storm was initiated (09:30). It is difficult to determine why this is. Point sensors indicate that significant moisture movement did not occur before the storm. Additionally, it is unlikely that a significant amount of settlement occurred in the 30 minute window in which geoelectrical measurements were made (at 09:30) by the PRIME system. Starting soil moisture content was high and CRs were low before the storm. Given these factors, it is suspected that the injected current (2 mA) was too low resulting in high REs at the start of the experiment. If the current is not high enough to register a consistent potential signal on the potential electrodes this could result in a low sensitivity. In Series 2 of the soil column experiments, the injected current was increased to 10 mA in an effort to improve EPDs by reducing REs.

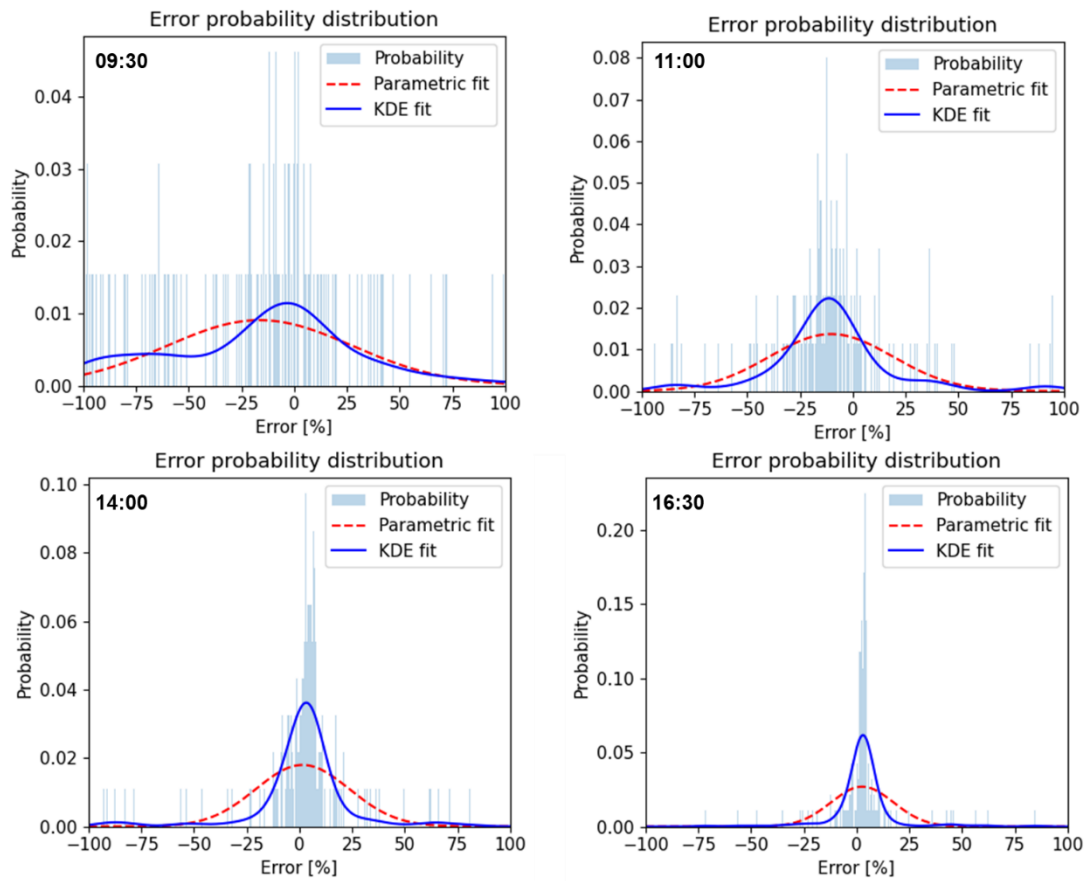


Figure 4. 25 Error probability distributions of Bourne Amenity Topsoil before (09:30) and during (11:30-16:30) the storm simulation.

ERT imaging from the topsoil experiment is given in Figure 4.26. The time-lapse survey shows timesteps from day 1 during the simulated storm. Despite the appearance of artefacts in the data, a wetting front progressing through the material during the storm simulation is visible. At 09:30, before water was added to the column, spatial distributions in resistivity suggest that electrical resistivity increases towards the base of the soil profile. Water was first added to the column at 10:00. From 10:00 – 10:30, artefacts appear in the data despite no ponding occurring during the experiment. The prevalence of artefacts in the modelled data decreases in subsequent timesteps, and by 12:00, moisture content up to a depth of -300 has increased to approximately 25%. By 13:00, the wetting front has extended to the topsoil base. After 13:00, no further changes in spatial distributions in resistivity or percentage changes in resistance were captured. The cause of the artefacts in the topsoil is attributed to the soil moisture contrast generated during the simulated storm. This is explored in greater detail in Section 4.6.

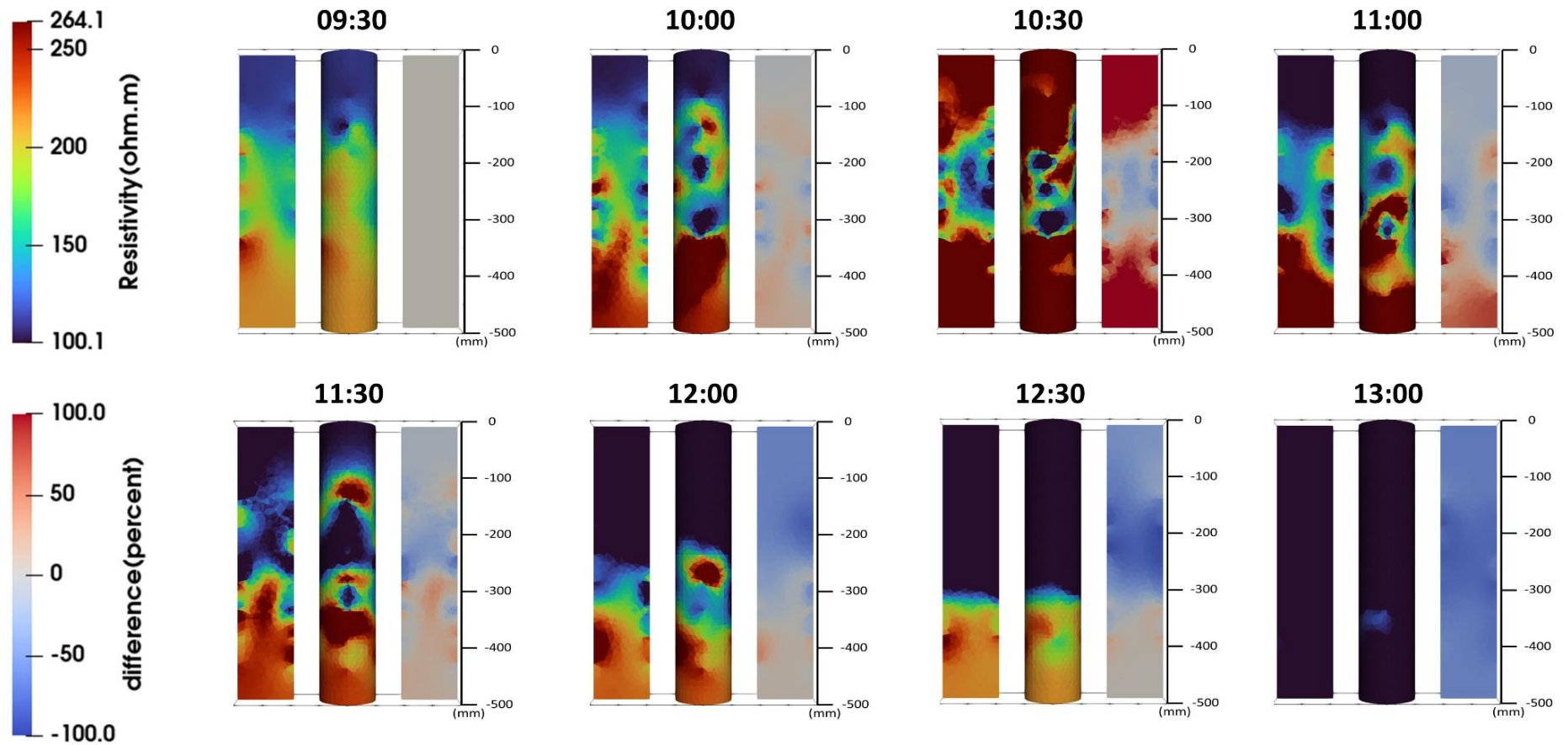


Figure 4. 26 A timelapse ERT survey from the topsoil column experiment during a simulated storm. Images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

4.6 Forward Modelling to Investigate Artefacts in Time-lapse ERT

After processing the geoelectrical measurements from the capillary barrier systems (CBS), clay topsoil (CT) and Bourne Amenity topsoil (BAT) column experiments, it was clear that attempts to reduce artefacts in the electrical surveys were unsuccessful. Experiments performed at a low starting moisture content on granular materials (sand and gravel-filled CBSs) made inverting the geoelectrical data challenging due to high reciprocal errors (REs) and scattered error probability distributions (EPDs). Where the inversion had successfully converged, the time-lapse surveys contained many artefacts presenting as regions of high and low resistivity that did not accurately portray the true electrical resistivity of the soil. Plotting the soil transfer resistances from the storms has verified that when water is added to the soils, transfer resistances decrease, contrary to the timelapse surveys of many soils indicating that resistivity increases at various stages of the wetting event (e.g. figures 4.24 and 4.28). As experiments from Series 1 were concluded, inverting the geoelectrical data showed artefacts across the surveys despite reduced CRs and REs.

In the CT column experiments (Exp. 1), where ponding occurred, artefacts in the inversions were anticipated due to the presence of surface water. However, as seen throughout Section 4.4, in Experiment 2, Exp. 2 (where ponding was reduced), the prevalence of these artefacts in each CT experiment (dry densities: 1.46 Mg/m^3 , 1.59 Mg/m^3 , and 1.69 Mg/m^3) was high. It was recognised that surface water drainage had been intermittent during Exp. 2. However, the exact cause of the artefacts was unknown, as they were also present in the proceeding topsoil-filled column experiment (see Section 4.5).

In a study by Carey et al. (2017), forward modelling is used to investigate inversion artefacts that occurred when using ERT during rainfall simulations. Using synthetic data, a two-layer system consisting of saprolite overlain by soil was created (Figure 4.27), and changes in volumetric moisture content and electrode configuration were tested to understand artefact development better.

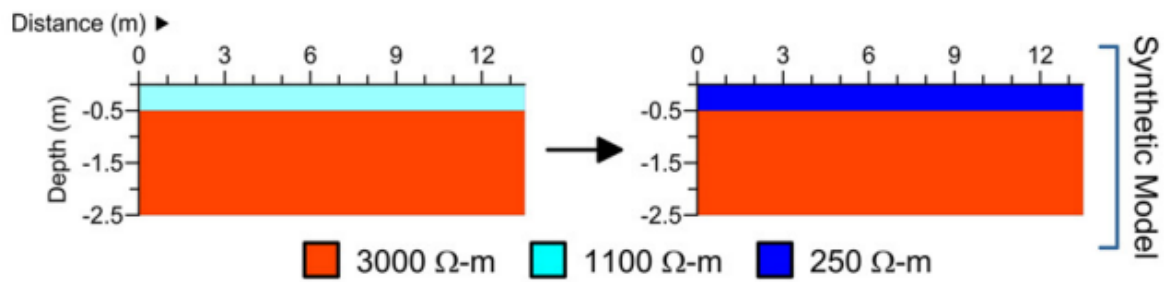


Figure 4. 27 A synthetic model showing the two profiles tested with the same resistivity value for the bottom layer and different top layer values (Carey et al., 2017).

The field study and forward modelling tests identified significant resistivity contrasts due to subsurface moisture changes, leading to inversion artefacts that did not accurately reflect actual moisture dynamics. Eight electrode array configurations were tested (e.g., Schlumberger, Wenner-alpha, gradient, etc.). Findings indicated that a dipole-dipole array incur the highest number of artefacts in forward modelling tests, and a modified pole-dipole array minimises artefacts most effectively and accurately imaged the infiltration zone. In a dipole-dipole array, placing the potential electrodes outside the in-line current electrodes resulted in lower potential measurements at depth, which are challenging for the inversion software to resolve accurately (Carey et al., 2017). The study highlights that a significant moisture contrast between the infiltrated top layer and the drier bottom layer exacerbates artefact development. A dipole-dipole array is particularly sensitive to such contrasts, leading to more pronounced artefacts.

A dipole-dipole array is used in the soil column experiments due to the limitations of conducting electrical surveys in a closed system. Other array types (pole-dipole) rely on an infinite distance established in most field experiments, whereby one of the current electrodes is placed far from the measurement area (Neyamadpour et al., 2010). In a soil column experiment, space constraints make using a pole-dipole array impossible, and the proximity of electrodes can lead to inaccurate resistivity data due to field overlap and boundary effects (Loke, 1999).

Storm events were simulated throughout the soil column experiments on different materials (CT, sand, and BAT) in a controlled environment. In each experiment, artefacts appeared in the inversions under various conditions (e.g., when the column was drained of surface water or when water was initially added to the soil). A sample of time steps from different soil column electrical surveys was assessed to understand better when artefacts appear in the soil column inversions. Figure 4.28 shows a time-lapse series showing the spatial distribution of resistivity (left image of each timestep) alongside the percentage change in resistivity (right of each

timestep) in CT (1.46 Mg/m^3) during a simulated storm. Data was collected from Exp. 1, where ponding occurred during the storm. ERT imaging demonstrates a reduced electrical resistivity by approximately 2% between 0mm and -100mm depth during hour 1 of the storm. Artefacts (small high resistivity areas near the column wall) near the electrodes are observed with a resistivity of 250 ohm.m. Beneath the wetter overlying soil (0mm—100mm depth), resistivity throughout the column profile increases between 1% and 3%. As the resistivity of the overlying soil decreases (hour 1.5), artefacts in the underlying soil become more pronounced and increase in resistivity. Regions of high and low resistivity alternate from timestep to timestep, which does not accurately portray the true electrical resistivity of the soil. An example is given in hours 5.5 and 6 at the end of the storm. At 5.5 hours, high resistivity artefacts are observed at the soil surface (percentage difference in resistivity of approximately 28%), extending to -230mm depth with smaller regions of artefacts present throughout the rest of the soil profile. By hour 6, widespread artefacts in hour 5.5 (0mm - -230mm depth) are now observed as a low resistivity wetting front, dotted with small localised regions of high resistivity.

Like Carey et al. (2017), significant resistivity contrasts in the inversion are thought to be due to subsurface moisture changes that occurred as water is added to the column. As the upper layer of soil becomes increasingly wet (see 1.5 hours), high resistivity artefacts appear in the drier underlying soil. However, at 5.5 hours, resistivity changes in the inversion are primarily attributed to the accumulation of surface water throughout the storm and the moisture contrasts at different soil depths. Ponding on the surface can change the boundary conditions of the electrical survey. This alteration can distort the electric field distribution (generated by injecting current into the survey location) (Loke & Lane, 2004), leading to incorrect inversion results that do not accurately reflect the actual resistivity of the subsurface. Additionally, changes to the survey volume (due to surface water accumulation or loss) are not factored into the synthetic model, resulting in misinterpreting the electrical data and incorrect inversion results presenting as artefacts.

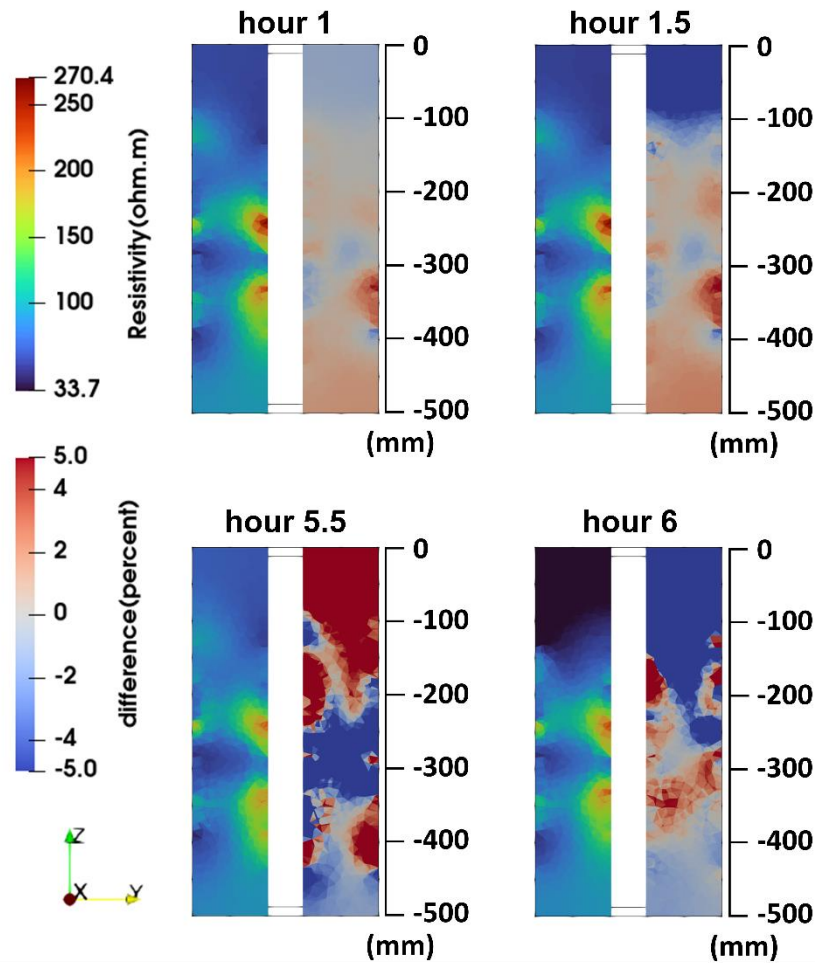


Figure 4. 28 A sample of the timelapse images of clay topsoil compacted to a dry density of 1.46 Mg/m^3 in Experiment 1, where ponding occurred. Images show the spatial distribution of resistivity (left of each timestep) alongside the percentage difference in resistivity (right of each timestep) in moments when artefacts appeared in the inversion.

In Exp. 2 of the CT column experiments, a surface water outflow tube was fitted at a surface level (500mm) to prevent ponding. Drainage of surface water was intermittent due to soil settlement and washing of fines into the tube during the storm simulation. As a result, artefacts persist in the second set of column experiments performed on the CTs at different densities. Figure 4.29 shows a time-lapse of the spatial distribution of resistivity and percentage changes in resistivity in CT (1.46 Mg/m^3) during a storm when surface water drainage was intermittent. ERT imaging at hour 1.5 shows that the percentage difference in resistivity increases by approximately 13% throughout most of the column, except for small percentage decreases observed between -160mm and -400mm depth along the right-hand side of the column. During hour 2, many of the high resistivity artefacts observed in the previous timestep have diminished,

and the percentage difference in resistivity is reduced by approximately 15%. At the base of the column, the percentage difference in resistivity is still elevated. At hour 2.5, 4ml of surface water was drained from the column. Artefacts in the inversion appear much more substantial than in previous timesteps. Between hours 2.5 and 3.5, surface water accumulated, and the distribution of artefacts in the inversion remained unchanged. However, at hour 4 (the end of the storm simulation), 68ml of water was drained from the surface. This sudden removal of the ponded water resulted in the artefacts from the soil surface and base becoming more apparent, with the percentage difference in resistivity increasing at the soil surface and base by $\geq 100\%$.

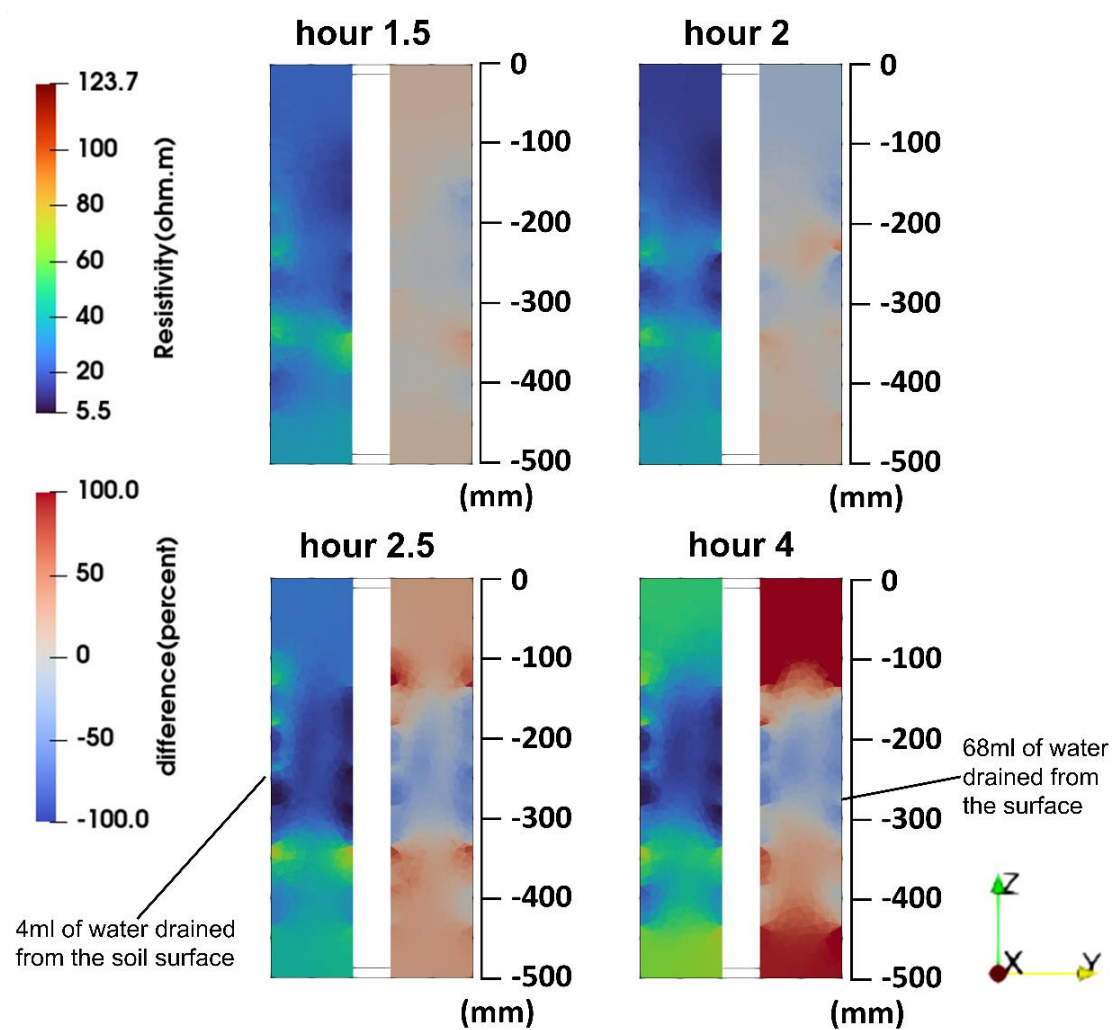


Figure 4. 29 A sample of the timelapse images of clay topsoil compacted to a dry density of 1.46 Mg/m^3 in Experiment 2, where surface water was drained from the column intermittently. Images show the spatial distribution of resistivity (left of each timestep) alongside the percentage difference in resistivity (right of each timestep) in moments when artefacts appeared in the inversion.

The time-lapse results given in Figure 4.29 demonstrate that modelling artefacts become more pronounced after the ponded water is drained from the surface of the soil. When processing data from Exp. 2 (after the surface water runoff tube was fitted), the relationship between surface water drainage and inversion artefacts becoming stronger was not realised. To understand this phenomenon better, a forward modelling test inspired by Carey et al. (2017) was done. A synthetic model was created in ResIPy using a cylindrical mesh consisting of two layers with different resistivity values (Figure 4.30). The two layers imitate a soil column experiment with 100mm of ponded water. The second synthetic model removed the less resistive top layer (surface water) from the inversion. A time-lapse sequence utilising this forward model would recreate a scenario in which a significant volume of surface water is removed from the soil column, similar to observations made during the laboratory tests.

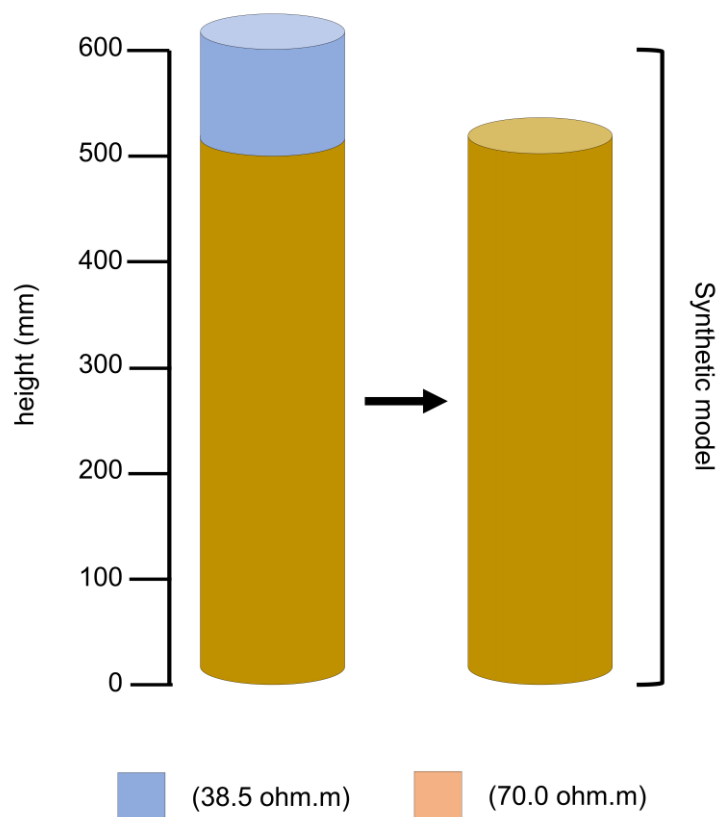


Figure 4. 30 A synthetic model showing the two soil profiles tested in the forward modelling experiment. The image shows the less resistive layer (surface water) overlying the more resistive homogenous soil. The overlying layer is removed in the second model.

Figure 4.31 shows a time-lapse image of the forward model. The percentage difference in resistivity is displayed on the left of each timestep, and the spatial distribution of resistivity is displayed on the right. Image (a) shows the column regime with 100mm water ponding on the soil surface. Suspected artefacts are shown in captions. (1) highlights five small, localised regions of high resistivity close to the electrodes at the walls of the soil column. These artefacts are considered complexities in the electrode placements that were unaccounted for in the synthetic model. The holes for the electrodes were machine-drilled to guarantee precise spacing of the array. The dimensions for each electrode were identical and placed flush to the interior of the column. Furthermore, electrode-wire resistance was tested between the column electrodes and the PRIME system, which confirmed that the difference in resistivity between each was negligible. However, it is possible that even the slightest discrepancy in electrode placements or geometry in such a small survey area (500mm height, 110mm width) could cause artefacts observed in the forward model (figure 4.31) or laboratory column tests (e.g., figures. 4.38 and 4.39). Caption (2) highlights two regions of low resistivity at the soil surface and base that extend towards the middle of the column. Similar observations were made in laboratory experiments (e.g., figures. 4.14, 4.17 and 4.22). However, these were observed as regions of high resistivity at the soil surface and base, as opposed to the low resistivity contrast observed in the forward model. The synthetic model (figure 4.30) added a 100mm, low resistivity layer to the 500mm column mesh, simulating a scenario whereby the soil was overlain by surface water. In the time-lapse image, the less resistive overlying layer (surface water) is unaccounted for in the inversion and likely caused the artefacts highlighted in caption (2). In image (b), the surface water is removed from the time-lapse. The percentage difference in resistivity image demonstrates that the percentage difference in resistivity has increased at the top and bottom of the soil column in response to removing the water (caption 3). The distribution of artefacts in the inversion looks remarkably similar to those observed throughout Section 4.4 and the time-lapse in Figure 4.29 when water was drained from the soil surface.

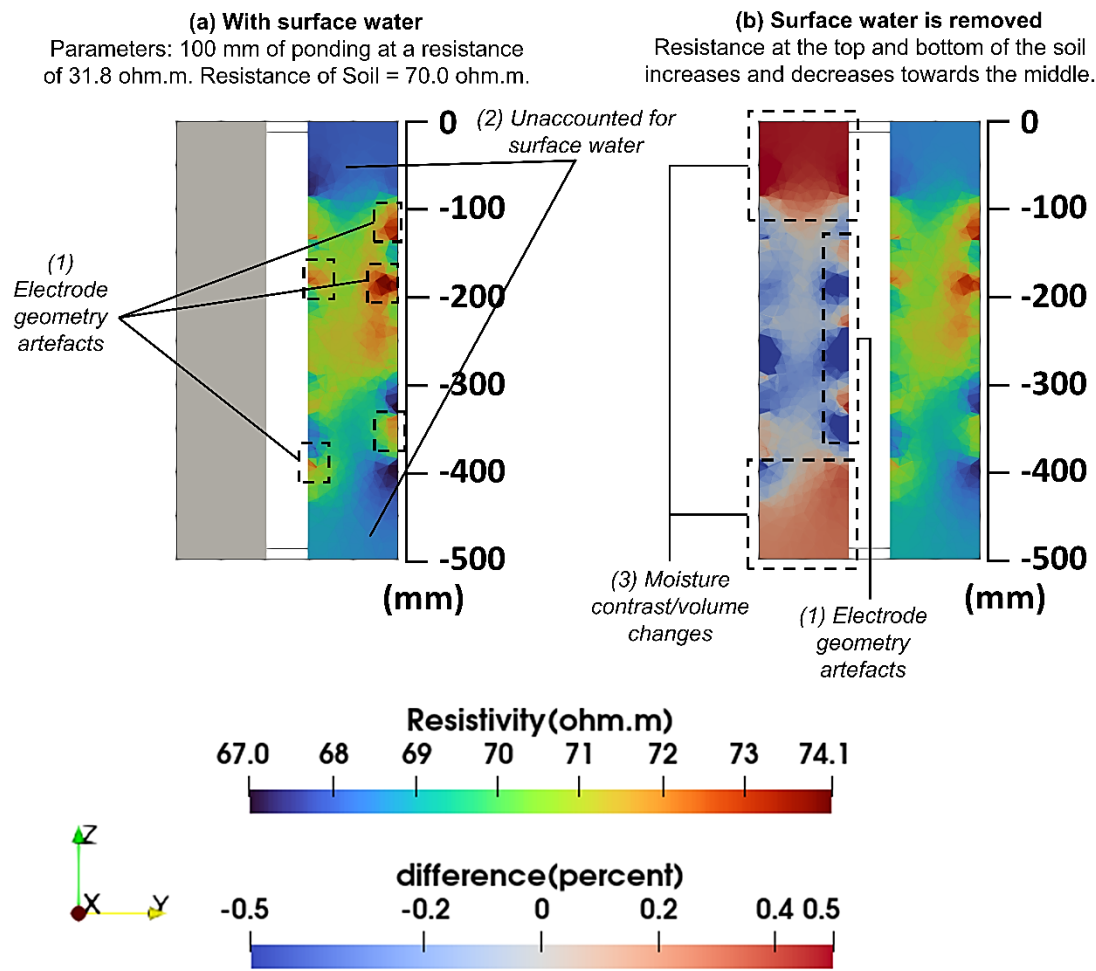


Figure 4. 31 A time-lapse survey derived from the forward modelling test demonstrates the percentage distribution in resistivity (right view) and percentage difference in resistivity (left view). Imaging shows the effects of removing surface water from the experiment on the prevalence and distribution of artefacts in the inversion.

4.7 Water-Based ERT-Soil Column Diagnostic Tests

4.7.1 Introduction

The results of Series 1 indicated that a second set (Series 2) of experiments was necessary to improve the quality of the ERT imaging by ultimately reducing the presence of artefacts from the models. However, in order to deploy more sophisticated analysis techniques to address the specific questions raised by the Series 1 results, it was necessary to conduct ERT column experiments on a water-filled column to target the sources of artefacts unimpeded by soil material properties such as soil heterogeneity.

4.7.2 Time-lapse ERT Observations

The ERT column was filled with CAT-5 tap water on day 1, providing a homogenous medium with which to analyse and collect geoelectrical data. The conductivity of the water in the column was 345.6 Micro Siemens per cm ($\mu\text{S}/\text{cm}$) and was filled to 500mm, the same height as the soils added to the column in previous experiments. A plastic lid was fitted to the top of the column to prevent evaporation, as changes to the volume of the water would influence the ERT images. Figure 4.32 shows a time-lapse of the water-filled column. A baseline-constrained inversion was applied to the data, and timesteps were analysed over two days. The data shows artefacts present throughout the column of water. Artefacts are observed extending from the top and base of the column towards the centre. Regions of localised high resistance are also observed close to the electrodes (situated at 50mm intervals along the column wall). The advantage of conducting an electrical survey on a column filled with water is that it rules out parameters such as grain size or error probability distributions from the list of contributing factors (regarding why artefacts occur in the ERT images). There is some variation in the spatial distributions in resistivity. However, the distribution of artefacts remains consistent throughout the time-lapse survey, suggesting that the electrode array or soil column design is, to some degree, responsible for the appearance of artificial results.

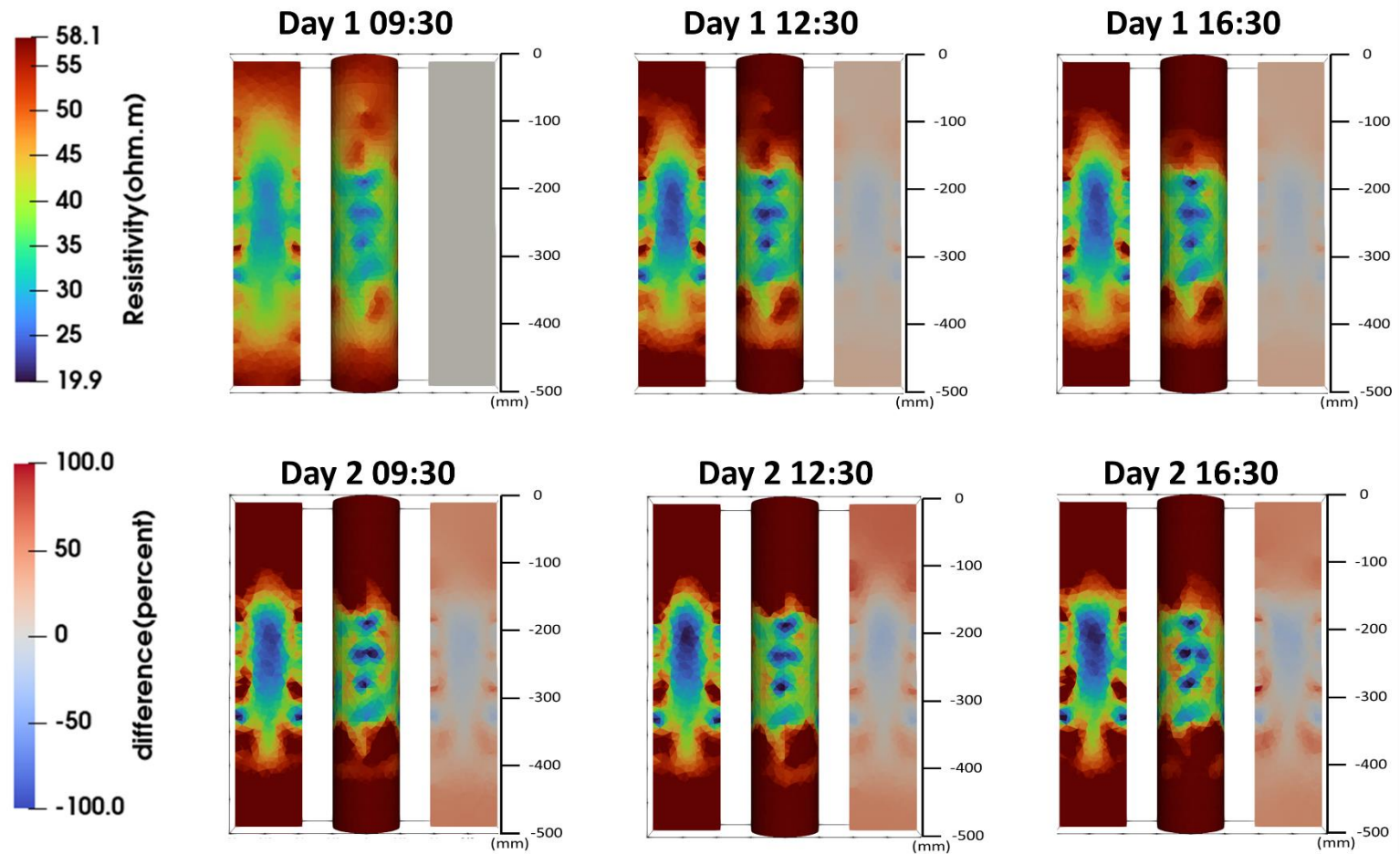


Figure 4. 32 Time-lapse imaging results for a water-filled column experiment showing spatial distributions in resistivity (left and centre of each timestep) and the percentage difference in resistivity (right of each timestep).

4.7.3 The Effects of Material Temperature on ERT Imaging

The transfer resistances of the water-filled column are shown in Figure 4.33. Data was collected from the top four lines of electrodes where electrical resistivity appears to be the highest (Figure 4.32). Transfer resistances remain low, which is expected of a water-filled column. Interestingly, on day 1, when the column was filled with water, resistivity increased between 15 and 20% over three hours. The graph shows transfer resistances stabilise to values observed on day 2, one day after the column was filled with water. As transfer resistances increased, contact resistances increased by approximately 13%. 78% of values are below 5% reciprocal error in the morning (pre-stabilisation), and 85% are below 5% in the afternoon (post-stabilisation). This improvement in reciprocal errors occurred despite contact resistances continuing to increase. This event whereby the transfer resistances increased before stabilising is thought to be due to the temperature of the water regularising to the conditions of the environment chamber shortly after the PRIME system was switched on. Given the absence of soil or geological structure, changes in electrical resistivity are likely due to temperature or pore fluid changes in the subsurface (Waxman & Smits, 1968; Boyd et al., 2021). On day 2, there were little to no changes in transfer resistances.

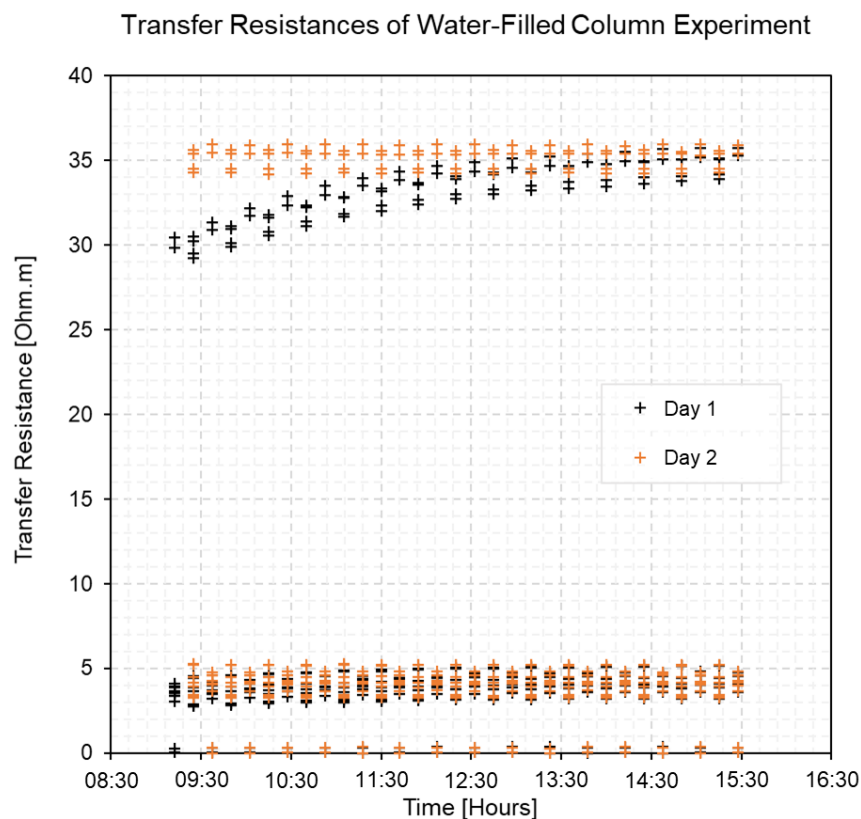


Figure 4. 33 A graph showing the transfer resistances of a water-filled column for two days.

4.7.4 Increasing the Injected Current to the Column Electrodes

Despite the necessity of using a dipole-dipole array configuration, changes were also made to the soil column experiment in other areas to reduce the appearance of artefacts in the data (as described in Section 3.6). Decreasing the injected current reduces voltage clipping and drastically improves ERT imaging (Section 3.3.2). Subsequently, the injected current was reduced from 20 milliamps (mA) to 2 mA. Geoelectrical measurements provided in Sections 4.2 and 4.3 indicate that high error percentages observed during inversion pre-processing made producing time-lapse surveys during storm simulations challenging. It is hypothesized that if the injected current was increased (from 2 mA), EPDs may improve ultimately leading to a smoother geoelectrical modelling process (fewer software crashes and improved ERT imaging).

Figure 4.34 compares the EPDs in different materials tested in Series 1. EPDs provided are measured 3 hours into the simulated storms. Error distributions indicate that more granular materials exhibit higher error probabilities. High EPDs in the gravel and sand-filled CBS are unavoidable due to the large soil grain size. In the topsoil experiment, the material was added to the column uncompacted so as not to obstruct a wetting front extending to the base of the soil. As a result, EPDs during the storm were high. Data in Figure 4.34 also examines the error percentage in clay topsoil (CT) at different dry densities during the storm. Of the six distributions provided, all graphs demonstrate a normal distribution, except CT at 1.69 Mg/m^3 (Exp. 1). However, the percentage of errors greater than 25% is remarkably high in most distributions despite the low hydraulic conductivity of the soil and slow progression of the wetting front observed in the timelapse inversions. The survey will have a low sensitivity if the current (2 mA) is not high enough to register a consistent potential signal on the potential electrodes. Increasing the injected current increases sensitivity, and the SNR is potentially improved. However, it is important not to increase the current significantly, as this can lead to voltage clipping in the results.

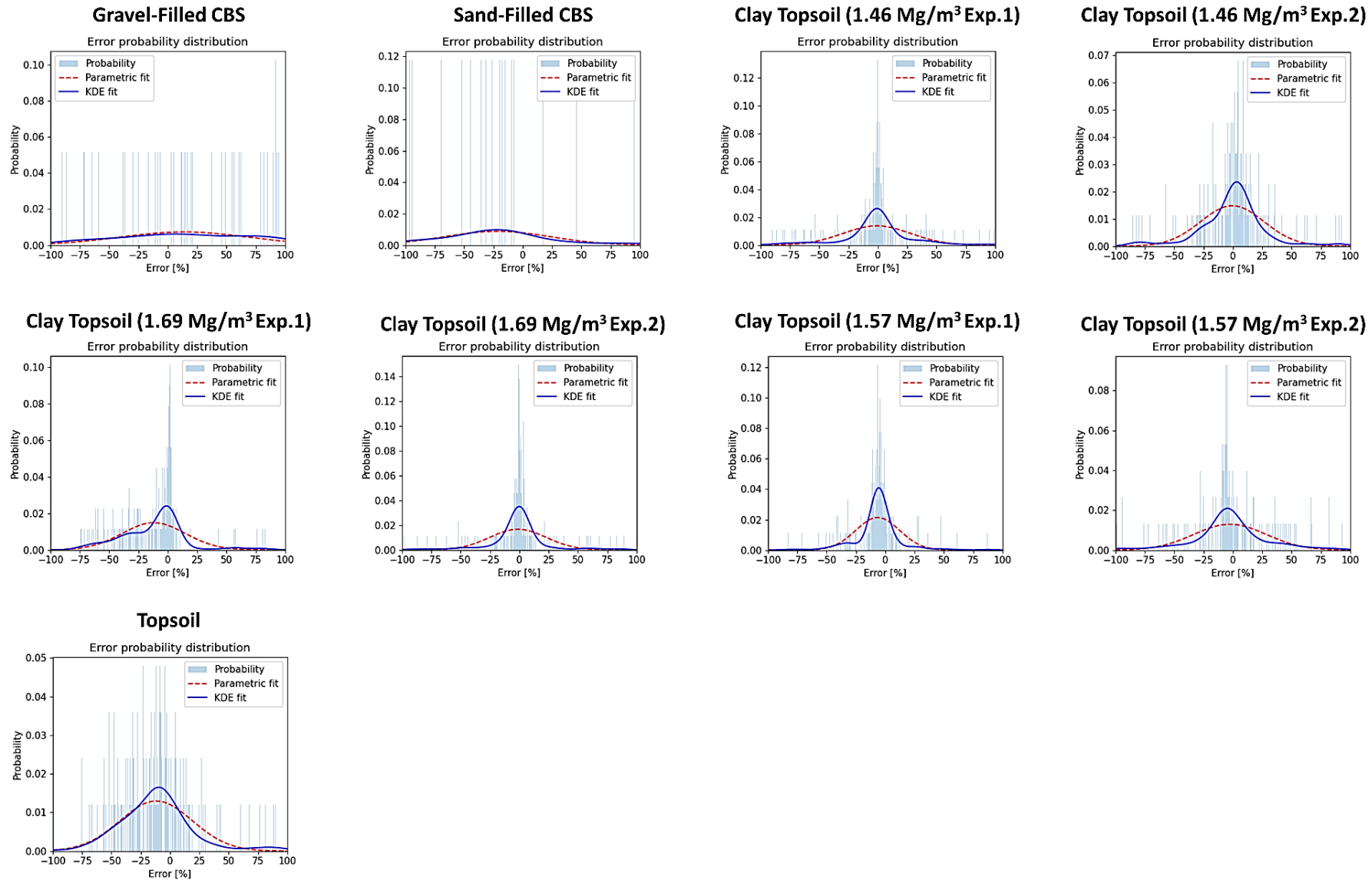


Figure 4. 34 Error probability distributions of soils examined during the Series 1 soil column experiments. The data provided was measured 3 hours into a simulated storm.

On day 7, the current input was increased from 2 mA to 10 mA to reduce high-percentage errors and improve the SNR. Figure 4.35 compares the transfer resistances of the water-filled column at 2 mA and 10 mA and demonstrates that transfer resistances remain stable at 10 mA.

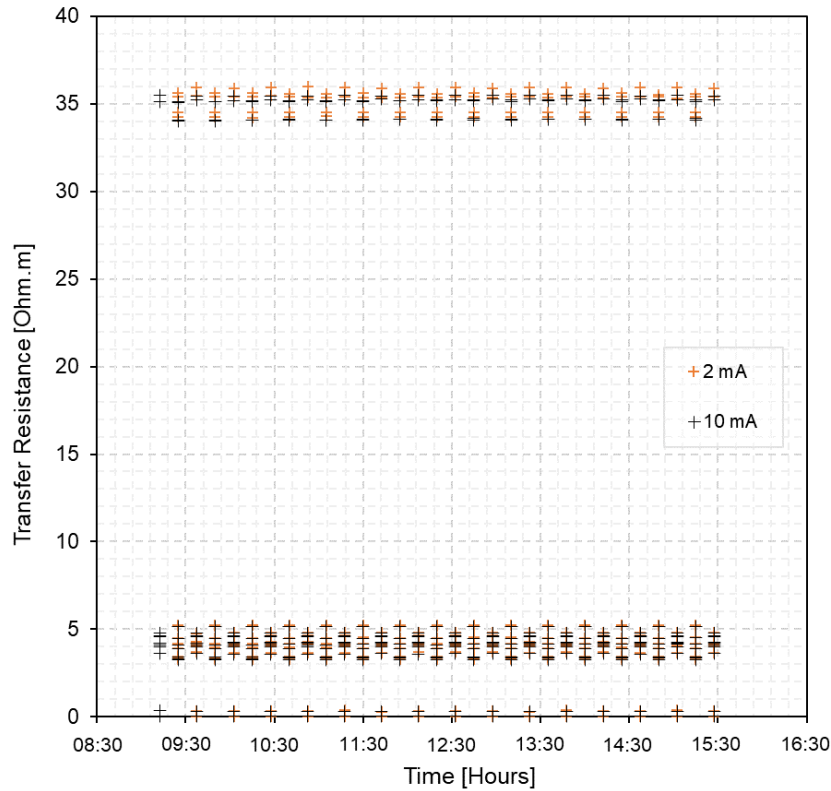


Figure 4. 35 Transfer resistances of the water-filled column with different current inputs.

Figure 4.36 shows a time-lapse inversion of the water-filled column after the current input was increased to 10 mA. The spatial distribution and percentage difference in electrical resistivity are scaled to levels observed in Figure 4.32 (time-lapse inversion of water at 2 mA). Variable spatial distributions in resistivity remain consistent with those observed at 2 mA. However, the percentage difference in resistivity has decreased from $\leq 50\%$ to $\leq 30\%$.

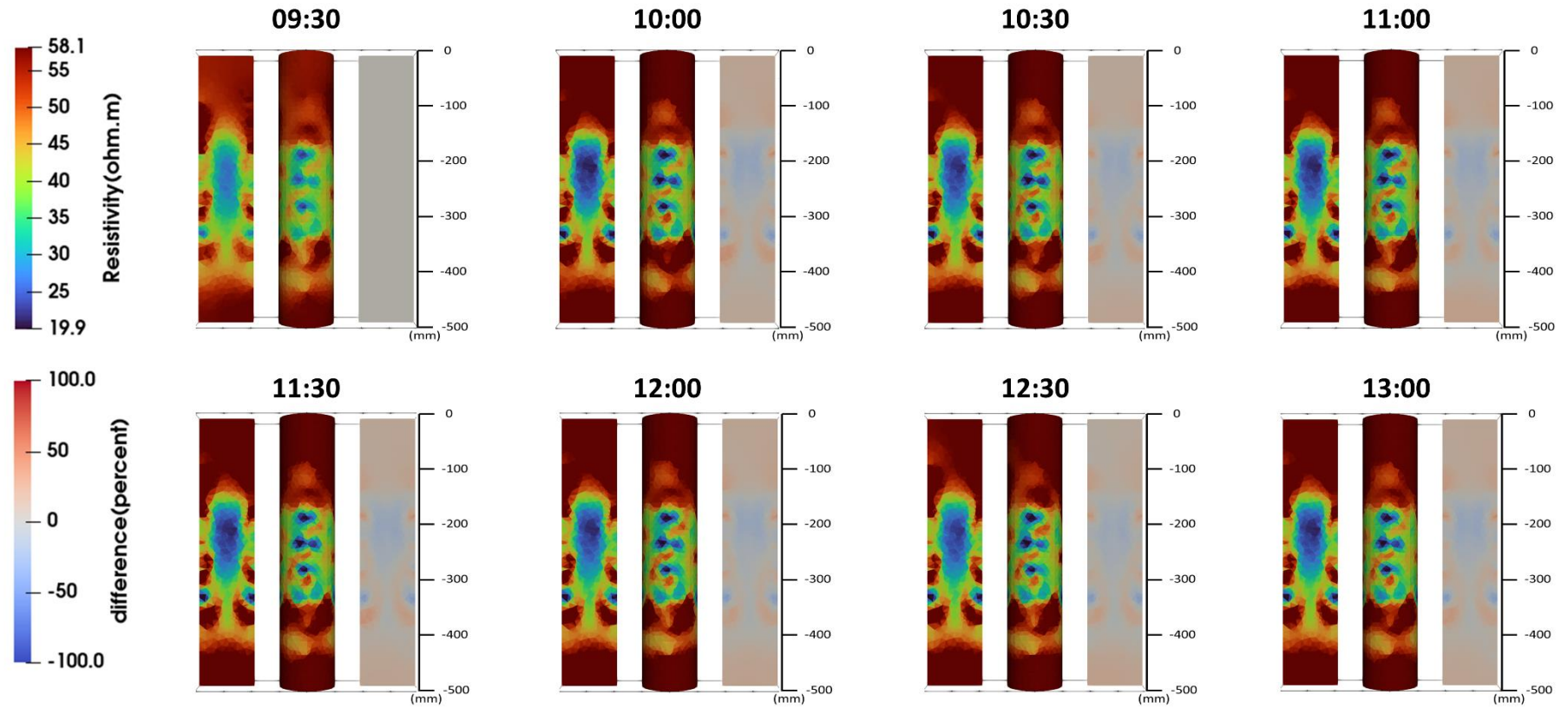


Figure 4. 36 Time-lapse inversion of the water-filled column after the current input was increased to 10 Milliamps. Images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

4.8 Series 2 Soil Column Experiments

Section 3.6 of the Methodology provides a detailed description of the changes that were made to the soil column experiments in Series 2. To summarise, changes to the method include:

1. Reducing the complexity of the soil column experiments by not including dual-layer systems (such as the capillary barrier systems).
2. Using a salt tracer during storm simulations.
3. Adding water to the columns outside of forward and reciprocal measurement windows.
4. Adding soil to the columns at approximately 10% moisture content to reduce CRs.
5. Leaving sufficient time before the storm for soil temperatures to stabilise in the environment chamber.

Series 2 examines changes in electrical resistivity using 4D ERT in three soils: sand, clay topsoil (CT) and Bourne Amenity topsoil (BAT). With changes to the soil column design and methodology, the geoelectrical data was less challenging to process in Series 2, and wetting fronts in each material were more discernible in the electrical data. However, modelling artefacts still emerged, and like Series 1 time-lapse surveys, these are typically observed during storm simulations.

Section 4.8 indicates that soil/water temperatures can significantly influence electrical resistivity (Liu et al., 2022). The relationship between soil temperature and resistivity suggests that as temperature decreases, electrical resistivity increases (e.g., Figure 4.33). In research by Lie et al. (2022), changes in soil temperature were analysed over a difference of 25°C, a significantly higher temperature change than those observed in this study. Column experiments in Series 2 allow one to study the impacts of soil temperature changes on 4-D ERT imaging in a controlled environment (soil column experiments). A topic that is seldom explored. Therefore, two time-lapse surveys are presented for each soil column experiment (sand, BAT and CT).

1. geoelectrical data is inverted using files with changing soil temperatures.
2. data is inverted using files where soil temperatures are stable.

Like sections pertaining to Series 1 column experiments, and Appendix C point sensor data measuring soil moisture content throughout the experiments indicate the general anticipated changes in electrical resistivity in the time-lapse ERT images. Furthermore, changes in soil temperature versus transfer resistances are explored and discussed alongside 4D ERT imaging.

4.9 Sand-Filled Soil Column Experiment

4.9.1 Point Sensor Measurements

Point sensor results showing changes in soil moisture content in the sand-filled column experiment are shown in Figure 4.37. Water was mixed into the sand to achieve a starting moisture content of 10%. The starting moisture content at the top of the column is lower than the middle or bottom sections of sand. This is due to the large grain size of the material, resulting in water migrating through the sand shortly after being added to the column. The columns of sand were added to the environment chamber on day 1 and left for 24 hours before a storm was simulated. Water was added to the column on day 2. Previous soil column experiments on a sand-filled CBS indicate high reciprocal errors (REs) due to high soil hydraulic conductivity. Therefore, to ensure error percentages are kept low ($\leq 25\%$), the tap at the base of the column was closed to prevent water from draining into the collection tray. This is reflected in the point sensor data, which shows that moisture content in the bottom section of the soil is higher than in the top and middle of the sand. At the end of the storm, the tap was opened, and water was drained from the soil column.

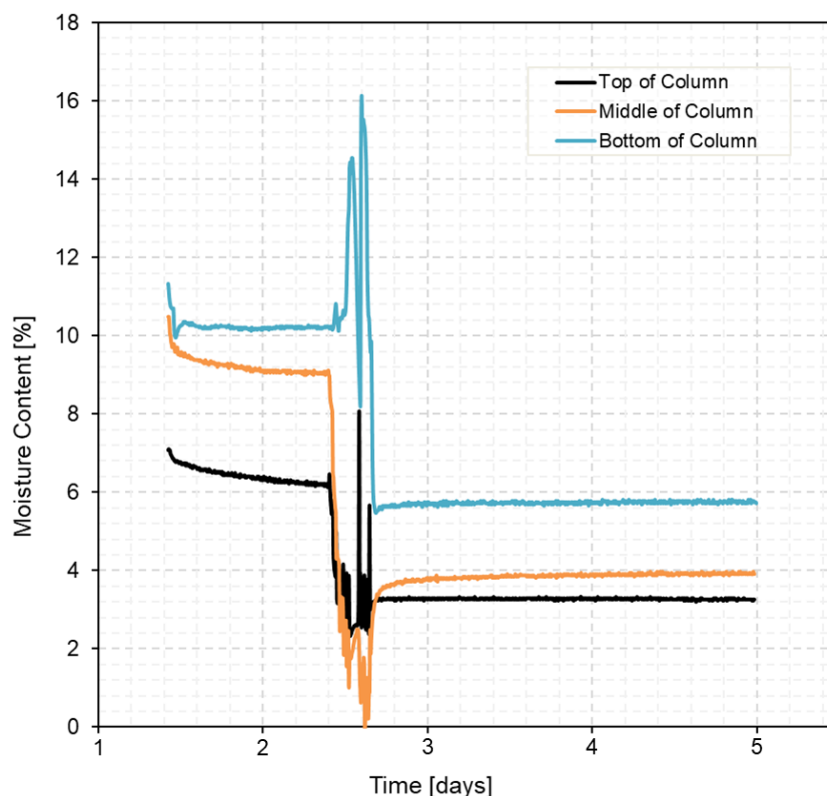


Figure 4. 37 The moisture content of sand-filled soil column experiment during the wetting and drying phases.

Changes in soil temperature are shown in Figure 4.38. The sand was added to the column at 25.6°C and cooled to 16.3°C by 17:00 on the 21st of August. After 17:00, no changes in temperature occurred before the storm on day 2. A slight increase in soil temperature was recorded shortly after the column was filled and placed in the chamber. This is attributed to the PVC pipe insulating the sand, causing temperatures to rise before cooling throughout the day. After the sand was placed in the chamber, the PRIME system was turned on, and geoelectrical measurements were made that captured changes in electrical resistivity as soil temperatures stabilised. As a result, two time-lapse inversions of the sand-filled column were processed. (1) A timelapse survey using geoelectrical data derived from the first measurements from day 1 (when soil temperature was changing); (2) A timelapse survey using data from the first measurements taken on day 2, when the temperature of the sand remained constant. The potential influences of soil temperature changes can be analysed by comparing these two time-lapse surveys.

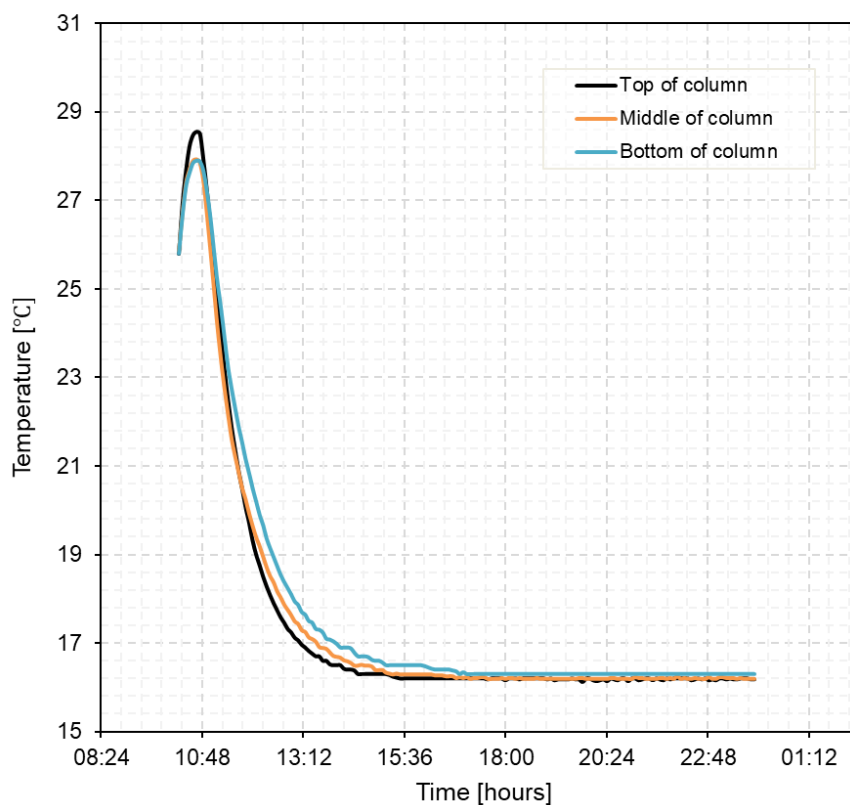


Figure 4. 38 Temperature changes in the sand-filled column placed in the environment chamber. Data was collected one day before a storm event was simulated.

4.9.2 Time-lapse ERT Surveys

The first time-lapse survey was processed using a baseline-constrained inversion (Figure 4.39). The reference survey was taken at 11:00 on day 1, shortly after the sand was placed in the environment chamber and began to cool down. There are considerable artefacts throughout the ERT images, and the distribution of these artefacts is similar to previous examples of spatial distributions in resistivity where zones of high resistivity extend from the soil surface and base of the material (e.g., Figure 4.24). Artefacts appear throughout the ERT images on day 1 and continue into day 2 (the day of the storm). Artefacts that extend from the soil surface are removed from the inversion as the wetting front from the simulated storm percolates through the soil column (day 2, 11:00). By 12:00, the artefacts are removed from the inversion completely due to the high moisture content of the sand. After day 2, the PRIME system did not capture any further changes in spatial distributions of resistivity or percentage differences in resistivity.

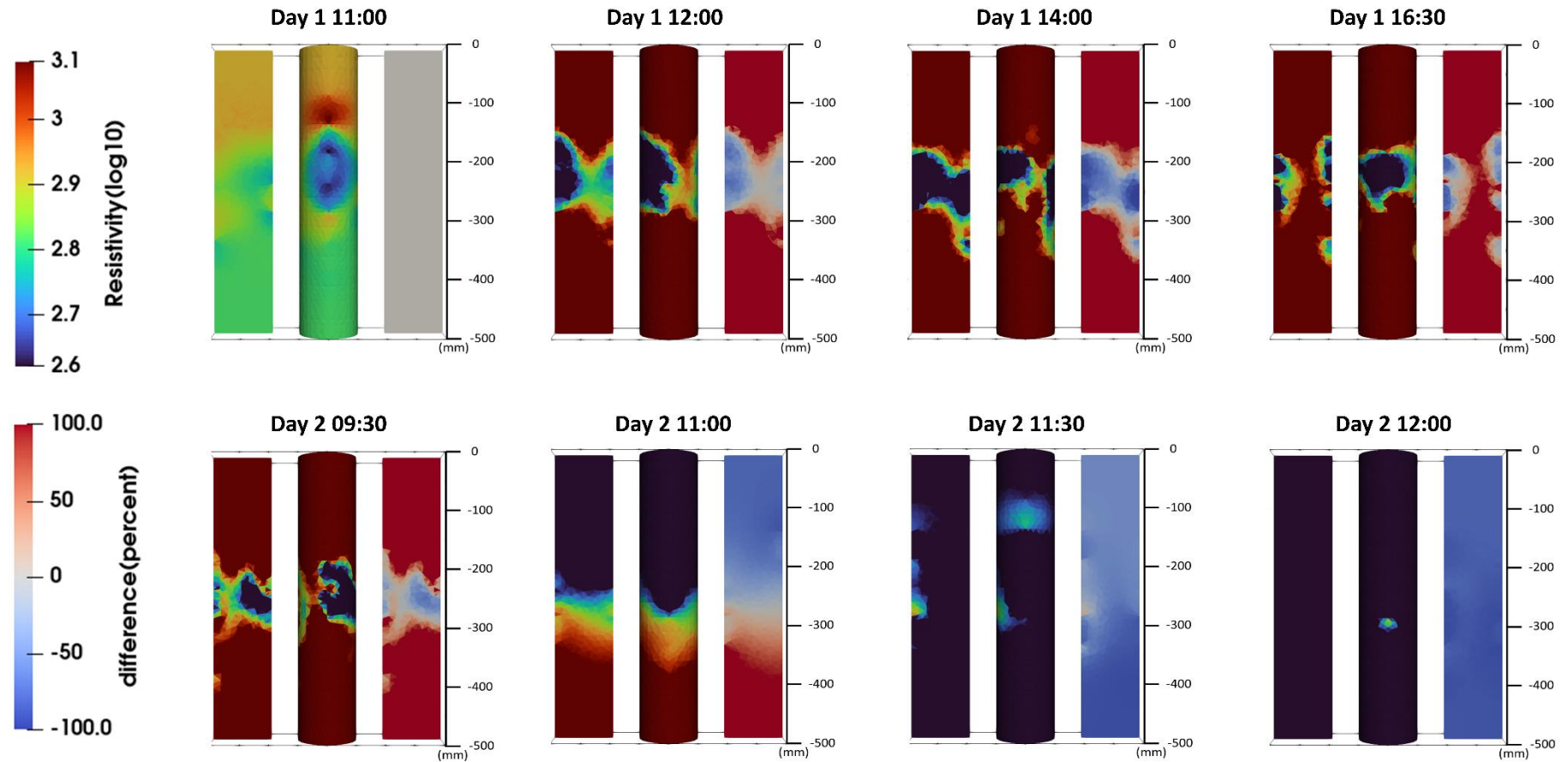


Figure 4. 39 ERT timelapse survey of a sand-filled soil column before and during a simulated storm (day 2). The reference survey for the baseline inversion was set at 11:00 on day 1, immediately after the material was placed in the environment chamber. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

A second time-lapse survey of the sand-filled column is given that excludes measurements from day 1, when soil temperatures decreased over time. Timesteps capture changes in resistivity during the storm. No artefacts appear in the data, except for a small area of high resistivity below the progressing wetting front at a depth of -300mm. ERT images indicate that resistivity decreases with depth due to water in the sand percolating through the material overnight. The percentage difference in resistivity decreases up to 100%, compared to the reference survey by 12:00. Looking at variable spatial distributions in resistivity, the column continues to saturate throughout the storm simulation, with no further changes detected after 14:00. ERT imaging in Figure 4.40 provides a better perspective of changes in electrical resistivity during the storm compared to Figure 4.39. It was noted that the tap at the base of the column was closed to prevent drainage and promote moisture content in the sand to increase during the storm. This is seen in Figure 4.40, which shows that resistivity decreases upwards from the base of the column. This cannot be seen in Figure 4.39 due to modelling artefacts obscuring changes in electrical resistivity.

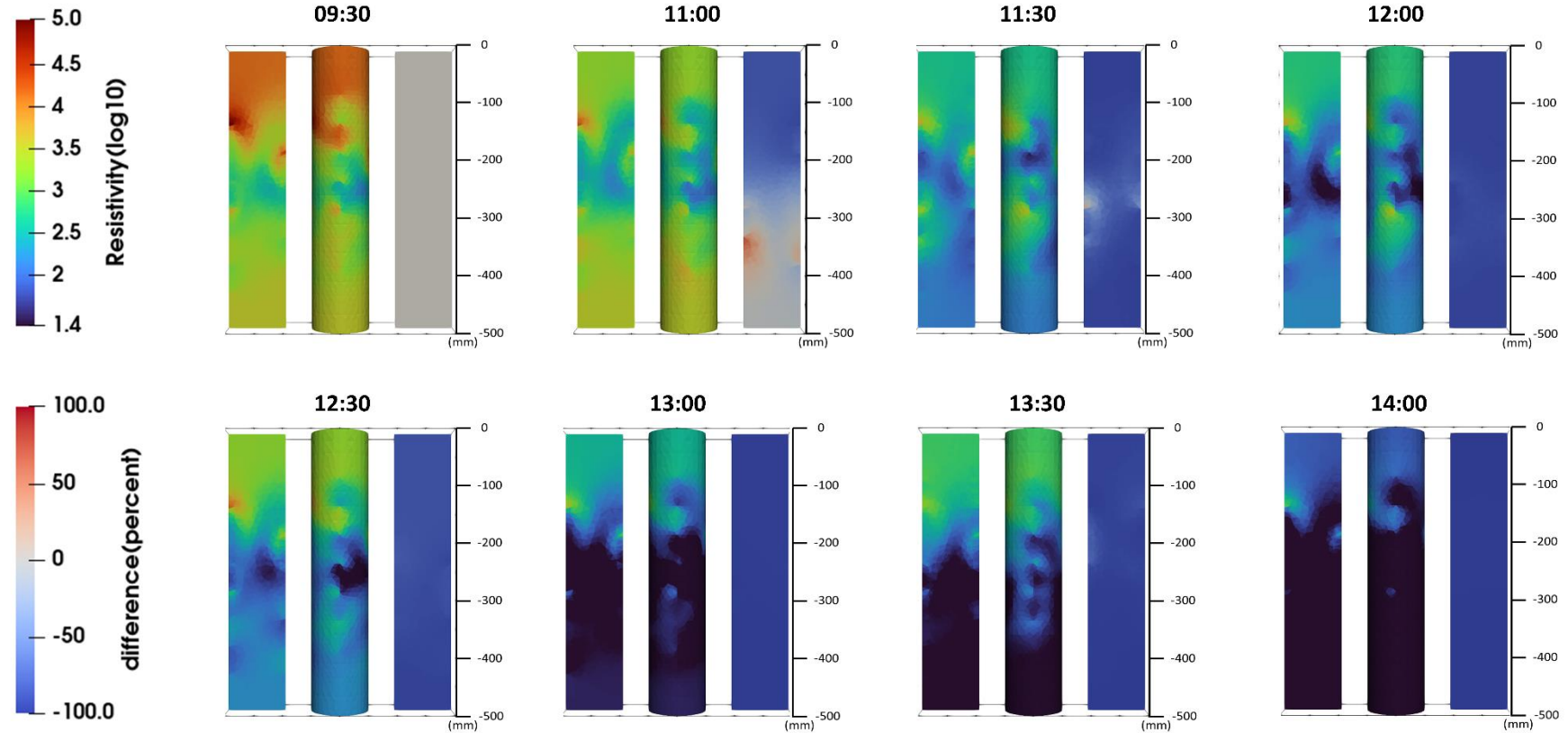


Figure 4. 40 ERT timelapse survey of a sand-filled soil column during a simulated storm. The reference survey for the baseline inversion was set at 09:30 on day 2, one day after soil temperatures stabilised. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right of each timestep).

Due to the large grain size of the sand, contact resistances (CRs) and transfer resistances are high compared to the topsoil and clay topsoil experiments. As a result, a logarithmic scale is used to ensure spatial changes in resistivity are observable in the ERT images. Table 10 compares the CRs of the sand-filled CBS and the sand-filled column. In both experiments, CRs before water was added to the columns were approximately 20,000 ohms. In Series 1, a CBS was created with 300mm of topsoil overlying 200mm of sand. If no topsoil were used, CRs would likely have been significantly higher. After the storm, the range of CRs in Series 1 was higher than in Series 2. This is attributed to the salt solution used during the storm in Series 2 to ensure a wetting front would be discernible in the modelled data and the injected current increased from 2 mA to 10 mA. CRs in the sand-filled CBS are lower (2000 ohms) after the storm than the Series 2 sand because of the topsoil layer.

	Material	CR values (ohm), bin counts = 3,000	
		Before storm event	After storm event
Series 1	Sand-filled CBS	20,000	2000 - 20,000
Series 2	Sand	20,000	5000 - 10,000

Table 10 Contact resistances of sand-filled columns before and after a storm.

Figure 4.41 shows the change in transfer resistances as soil temperature decreases. Like the transfer resistances showcased in the water-filled column (see section 4.4), the data demonstrates how resistances increase as soil temperature decreases. This highlights the importance of ensuring sufficient time is provided before a storm so that the material can regularise to the conditions of the environment chamber.

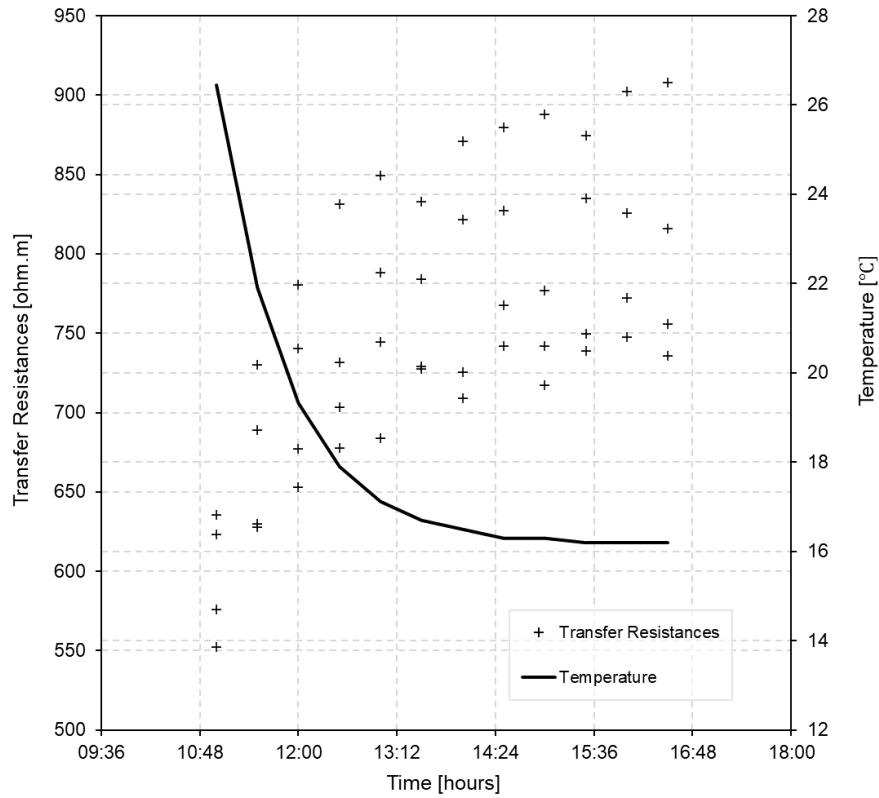


Figure 4. 41 Transfer resistances versus soil temperature in the sand-filled column on day 1.

During Series 1 of the column experiments examining CBSs, data from the gravel and sand-filled CBSs were exceptionally challenging to invert owing to high CRs and REs. Figure 4.42 examines the error probability distributions (EPDs) of the sand-filled columns in Series 1 and 2. High error percentages are attributed to a high soil hydraulic conductivity. In Series 1, REs were high throughout the experiments and did not decrease despite the soil becoming increasingly wetter. Due to the unfavourable distribution of errors, applying a reciprocal error threshold to the graphs was impossible.

In Series 2, REs were still high before adding water to the column. However, they (REs) significantly improved during the storm compared to the sand CBS experiment. As water percolated through the soil between a forward and reciprocal measurement, spatial distributions in resistivity changed as the water migrated through the soil. This disparity in the forward and reciprocal values led to high REs, which impacted the inversion process. In extreme cases, such as the gravel-filled CBS (Section 4.2), time-lapse processing of the data was impossible due to the exceptionally high REs encountered throughout the experiment. Normal distributions are observed throughout the Series 2 data, and at 16:30 on day 3, 24 hours after the storm concluded, 80% of REs are below 10%.

Geoelectrical measurements collected during Series 1 experiments indicate that producing a timelapse inversion on coarse-grained materials would be ineffective due to high CRs and REs. However, despite the high permeability and large grain size of the sand, the subsequent time series produced in Series 2 has very few artefacts and accurately portrays the wetting front progressing through the soil. The distribution of errors throughout the Series 2 experiment is low compared to EPDs in Series 1. Transfer resistances in the Series 2 sand-based experiment were significantly lower compared to Series 1 ($\geq 10,000$ ohms and ≤ 1000 ohms, respectively).

Allowing the material to regularise to the conditions of the environment chamber reduced the appearance of artefacts in the inversions, as seen in section 4.8.3, where different reference surveys were used for the baseline-constrained inversion. Increasing the injected current appears to have reduced REs and improved the signal-to-noise ratio (SNR). However, this is difficult to qualify without testing the material at different injected currents to establish its effect on ERT image quality. Mixing water into the sand to achieve a moisture content of approximately 10% helped to reduce initial CRs and REs, allowing a more stable reference survey to be used during the inversion process. Overall, the changes to the column experiments transitioning from Series 1 to Series 2 were successful when conducting 4D ERT-integrated column experiments on the sand.

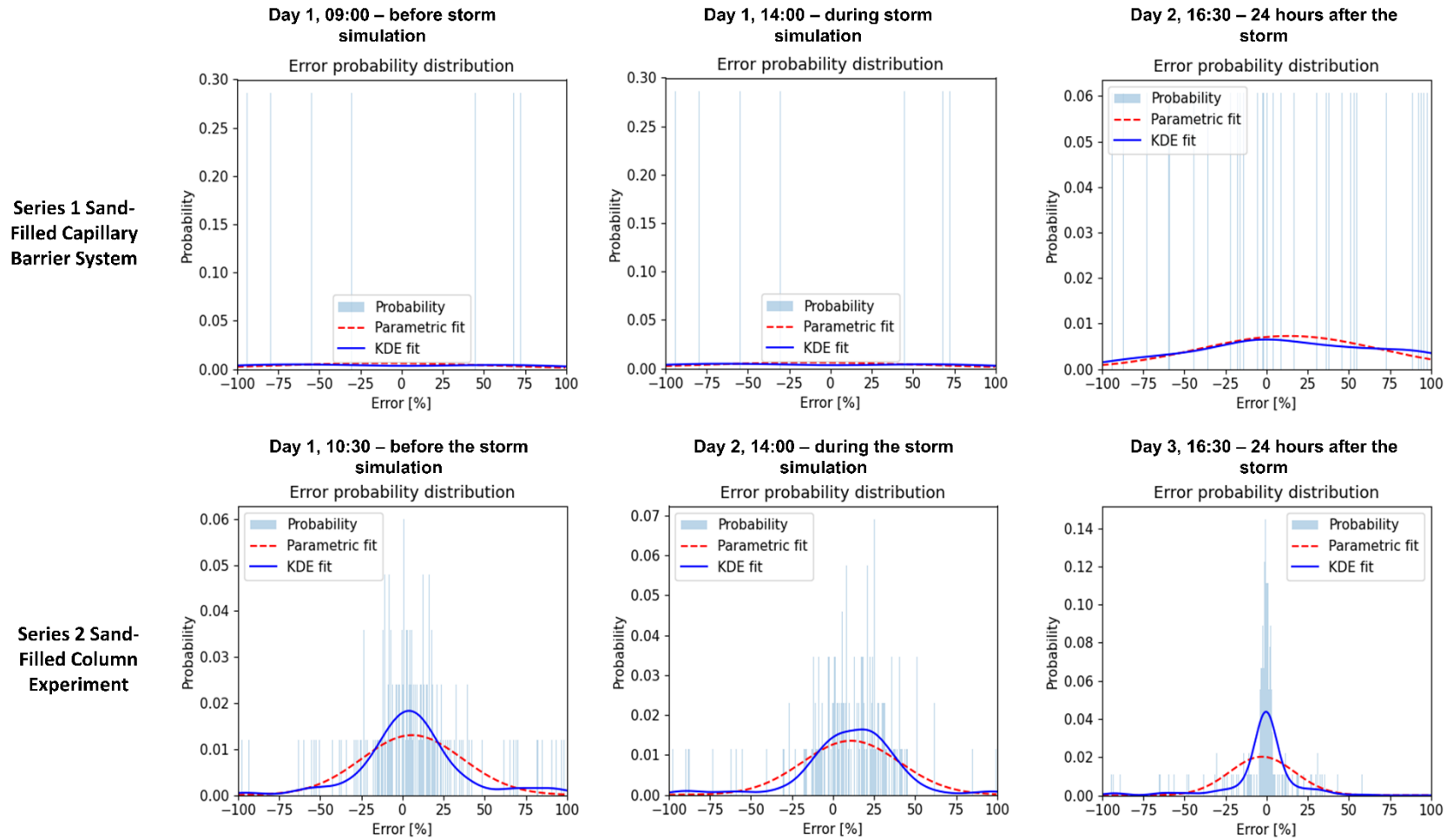


Figure 4. 42 Error probability distributions (EPDs) of sand-based column experiments from Series 1 and 2 of the soil column experiments. Data was captured before, during and after a simulated storm.

4.10 Bourne Amenity Topsoil Soil Column Experiment

4.10.1 Point Sensor Measurements

The topsoil was oven-dried and mixed with water to achieve a moisture content of 10%. However, point sensor data (Figure 4.43) places the moisture content at 7.7%, 6.6% and 7.5% in the top, middle and bottom sections of soil, respectively. To ensure that soil temperatures stabilised, the topsoil was left to regularise in the environment chamber on day 1, and a storm was simulated on day 2. The graph indicates that moisture content in the top section of soil increased throughout the storm and peaked at 25.8%. Days after the storm (day 7), the moisture content in the top fell to 3.1%. In the middle of the soil, there is an initial decrease in moisture content from 6.5% to 4.7%. This is likely caused by the positive head increase from the stormwater, leading to increased pore air pressure below, which drives drainage through the column. This is supported by the increase in moisture content at the top as it decreases in the underlying soil (middle and bottom). After this initial decrease, soil moisture content increased in the middle to 18.5%. On day 7, moisture content fell to 6.0%. Like measurements made in the middle of the soil, there was an initial decrease in soil moisture content at the bottom of the column. Moisture content decreased from 7.8% to 7.4% before peaking at 18.4. After the storm, on day 7, moisture content fell to 14.5%. The final moisture content measurements made on day 7 indicate that moisture content in the bottom section of the soil was higher than in the top and middle of the soil. The soil moisture content at the top is lowest, most likely due to a combination of water percolating through the material and evaporation from the near-surface.

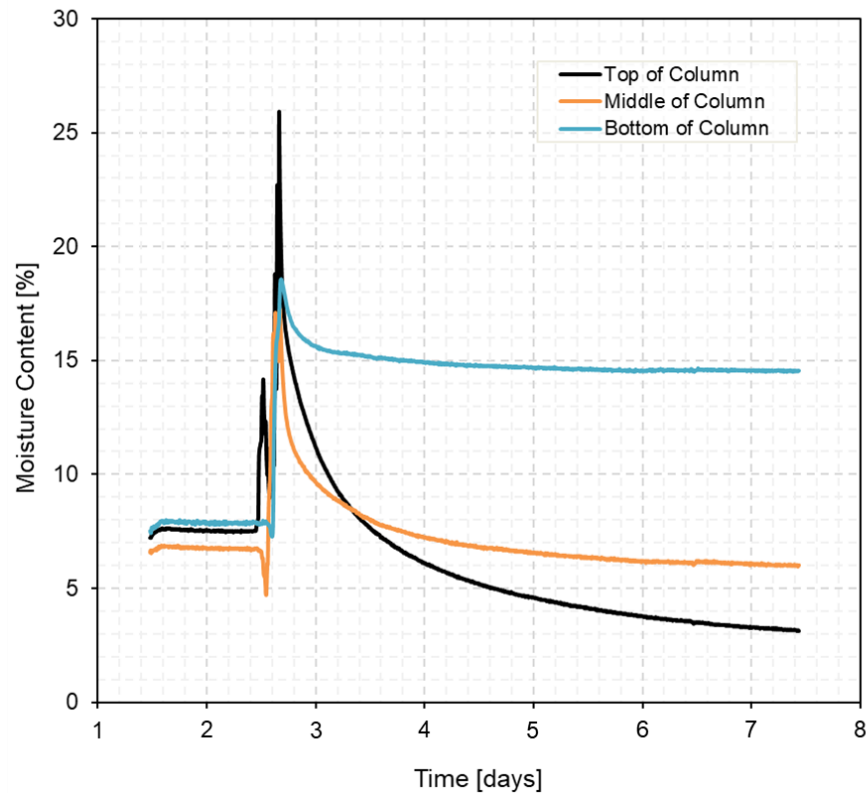


Figure 4. 43 The moisture content of Bourne Amenity topsoil during the soil column experiment. Data was collected using point sensors during Series 2.

No ponding occurred. Therefore, no surface water drainage was recorded. However, 320ml of water was drained from the base of the column over three days (see Figure 4.44). The graph shows that most stormwater was drained from the column on day 2, where 236ml was removed. On day 3, 52 ml of water was drained, and on day 4, 32 ml of water was drained. No further drainage was recorded by the tipping buckets after day 4.

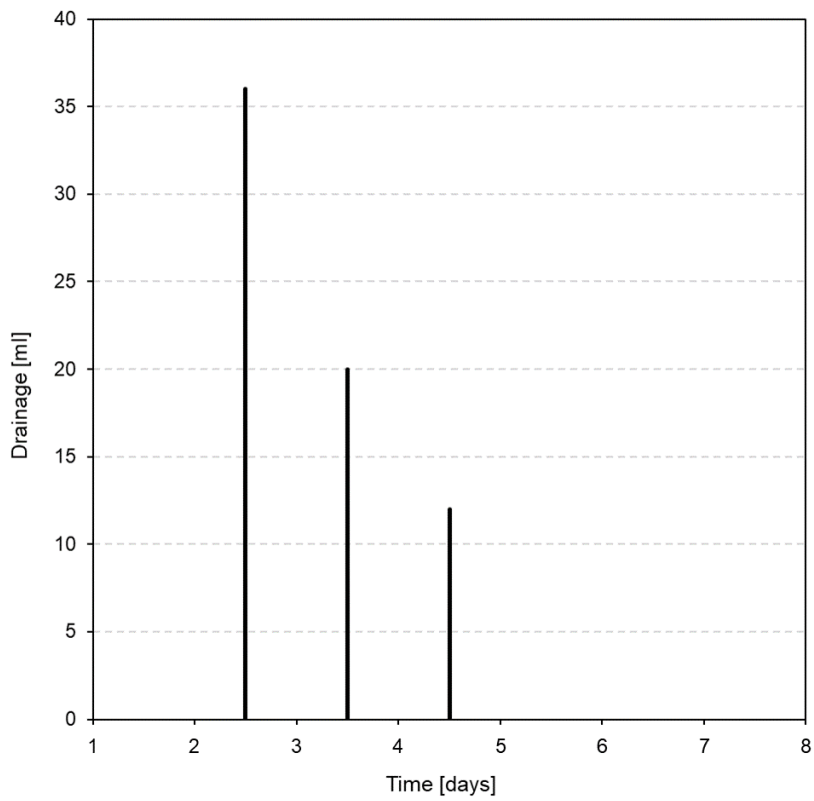


Figure 4. 44 Drainage from soil columns measured by the tipping bucket at the base of the soil column.

Figure 4.45 highlights the change in soil temperature after it was placed in the environment chamber (day 1). The temperature fell significantly from 11:30 to 16:35, decreasing from 23.43°C to 16.30°C. After 16:35, the soil temperature remained between 16.30°C and 16.28°C.

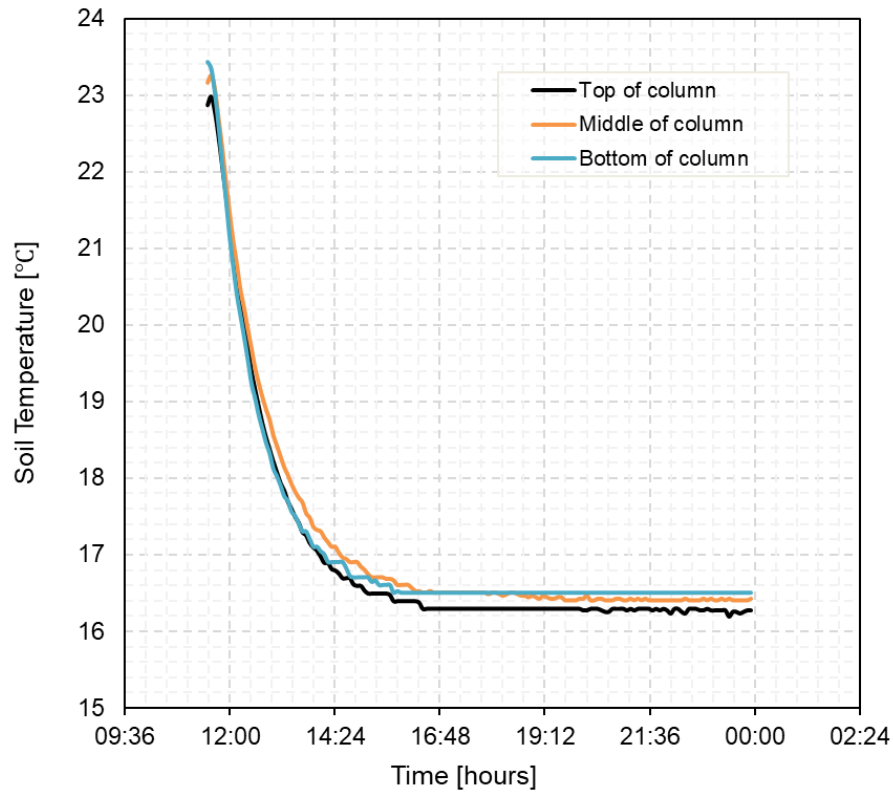


Figure 4. 45 Temperature change in topsoil-filled soil column on day 1 (one day before the simulated storm). Data shows a decrease in temperature once the soil was placed in the environment chamber.

Soil transfer resistances are compared to the change in soil temperature on day 1 when the soil was placed in the environment chamber (Figure 4.46). Like the sand-filled column, transfer resistances increase as soil temperature decreases. Analysis of the sand-filled soil column demonstrates the impact of using timesteps in the inversion process where temperature changes occur. Therefore, like the sand-filled column experiment, a baseline inversion is applied to the geoelectrical data using two sets of geoelectrical data files. (1) A timelapse survey using files where soil temperature changes were decreasing; (2) A timelapse survey using a baseline from the first measurements taken on day 2, when the temperature of the sand remained constant.

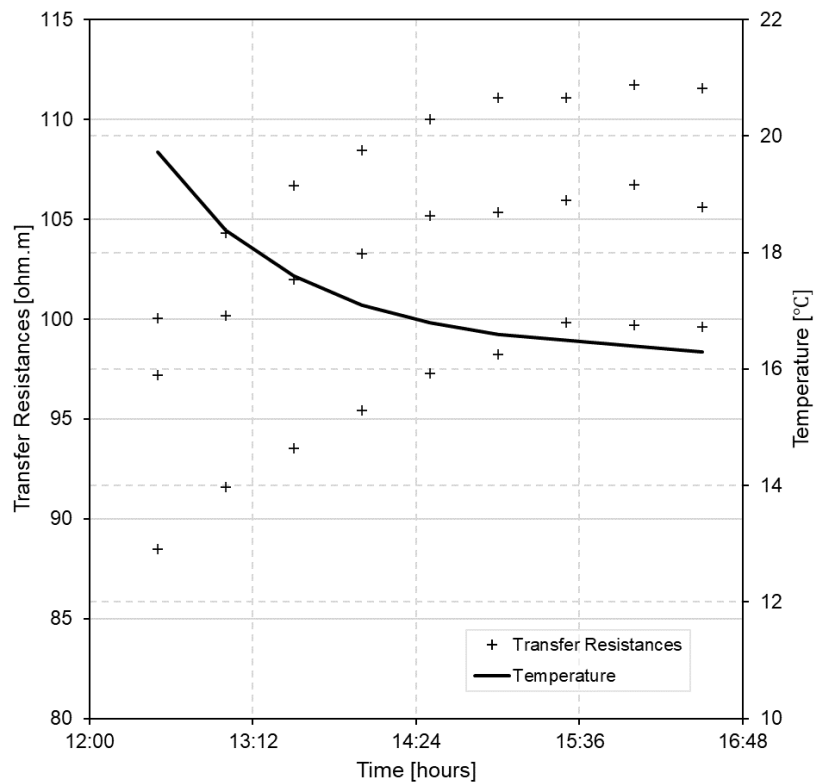


Figure 4. 46 Soil temperature versus transfer resistances of Bourne Amenity topsoil one day before the storm (day 1).

4.10.2 Timelapse ERT Surveys

Timelapse inversions from surveys (1) and (2) are shown in Figures 4.47 and 4.48. Survey (1), Figure 4.47, presents ERT imaging with modelling artefacts presenting as regions of high electrical resistivity contrast. Although the survey depicts spatial distributions in resistivity over time, little to no helpful information can be derived from the images. This is because many measurements exceeded 4600 ohm.m. Although rescaling resistivity to a custom range is possible, the original scale was provided to highlight the high range of electrical resistivity measurements modelled in the inversion. Inverting geoelectrical data from when the soil temperature decreases induces artefacts throughout the time-lapse survey. Although these electrical resistivity measurements are not actual values, they are artefacts triggered by temperature changes in the soil, and they demonstrate the impact of temperature regularisation on the inversion process. Geoelectrical files used in Figure 4.47 model changes in resistivity over a 3.4°C temperature decrease. Despite this relatively small temperature change, its effect on ERT imaging is significant. The storm was simulated at 11:25 on day 1. At 11:30, a low resistivity region (approximately 250 ohm.m, 0- -100mm depth) emerges. This is seen when looking at the percentage change in electrical resistivity. A significant decrease in artefacts is

also observed. However, some regions of high resistivity remain between -100mm and -200mm depth. From 12:00 onwards, a wetting front emerges, and resistivity from the soil surface decreases by 100%. High-resistivity contrasts develop beneath the wetting front due to the high soil moisture contrast at different depths. By 14:30, the wetting front reached the base of the soil column, and no artefacts were observed in the data.

Figure 4.48 shows a time-lapse survey of the topsoil-filled column using geoelectrical data from day 2 after stabilising soil temperatures. The resistivity scale is significantly lower in survey (2) compared to (1), where electrical resistivity does not exceed 330.4 ohm.m, unlike survey 1, where values reached 4600 ohm.m. Artefacts are still visible in the time-lapse survey, although to a lesser extent. Despite water not being added to the survey until 11:25, electrical resistivity contrasts are visible at 11:00. These artefacts look similar to those observed in the forward modelling experiment (Section 4.6), with areas of high resistivity located close to the electrodes and soil surface and base. At 11:30, an area of high resistivity (modelling artefacts) is observed extending from the soil surface to a depth of -75mm. This is likely due to the soil moisture contrast generated by starting the storm and adding water to the column. This area of high resistivity advances as more water is added to the soil (12:00). At 12:30, the extent of artefacts has decreased. The percentage difference in resistivity has returned to similar levels observed at 10:30. Between 13:00 and 13:30, as water is added to the column, electrical resistivity from the soil surface towards the base of the soil continues to decrease. This is observed in imaging the spatial distribution and percentage difference in resistivity.

Like the time-lapse electrical survey of the sand-filled soil column, ERT image quality is better when geoelectrical data influenced by soil temperature changes are excluded from the inversion. Given transfer resistances increase as temperature decreases, this, of course, makes sense. However, what is interesting is how significantly ERT image quality is affected by small (3°C) temperature changes. These findings may suggest that temperature changes during the experiment must be carefully controlled during a wetting event, or a temperature correction is applied during geoelectrical modelling to reduce the impact of temperature on a column experiment where soil moisture dynamics unimpeded by temperature variations are the research focus.

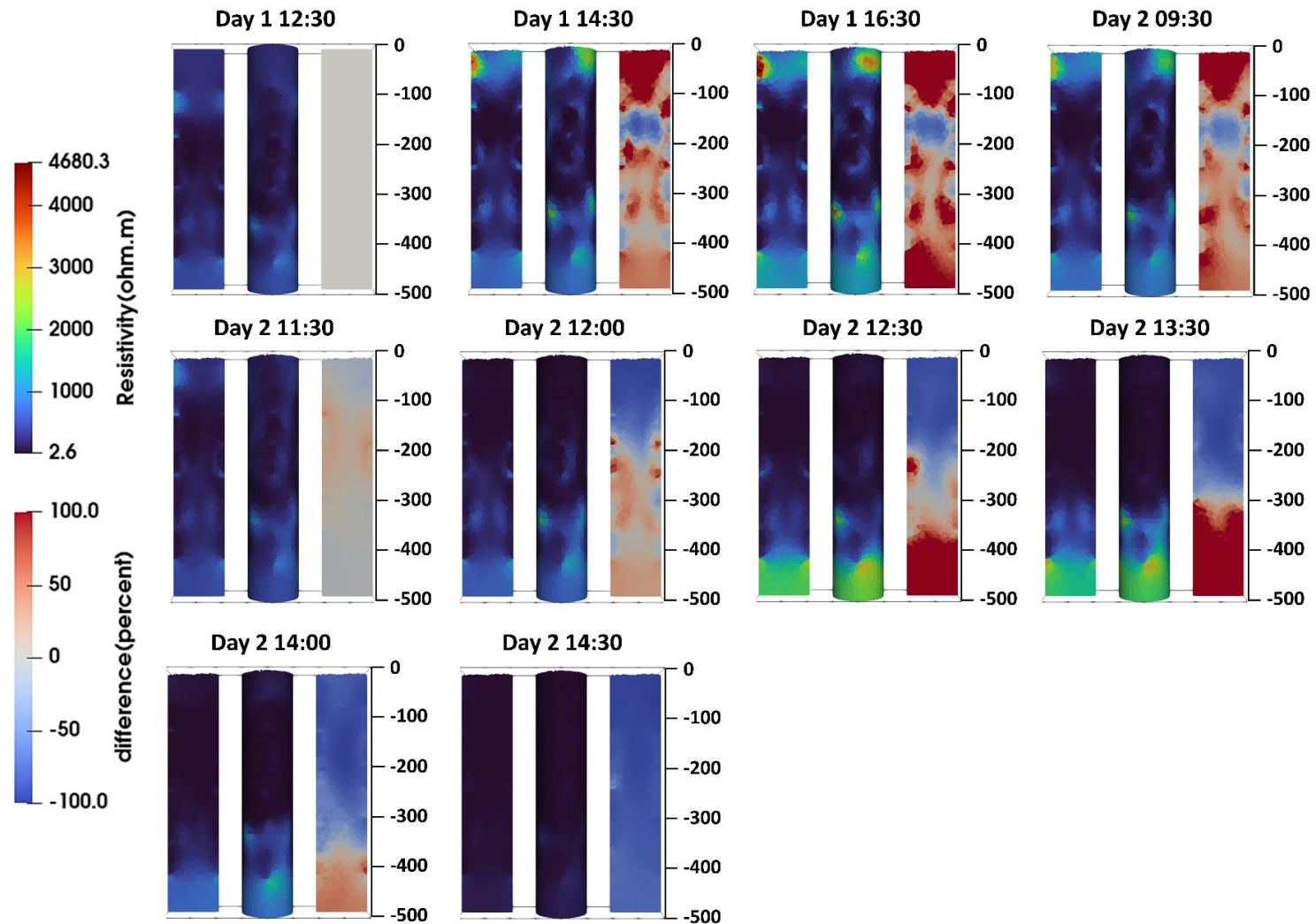


Figure 4. 47 Survey (1) a time-lapse survey of the topsoil-filled soil column, including data collected from day 1, when soil temperatures decreased. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

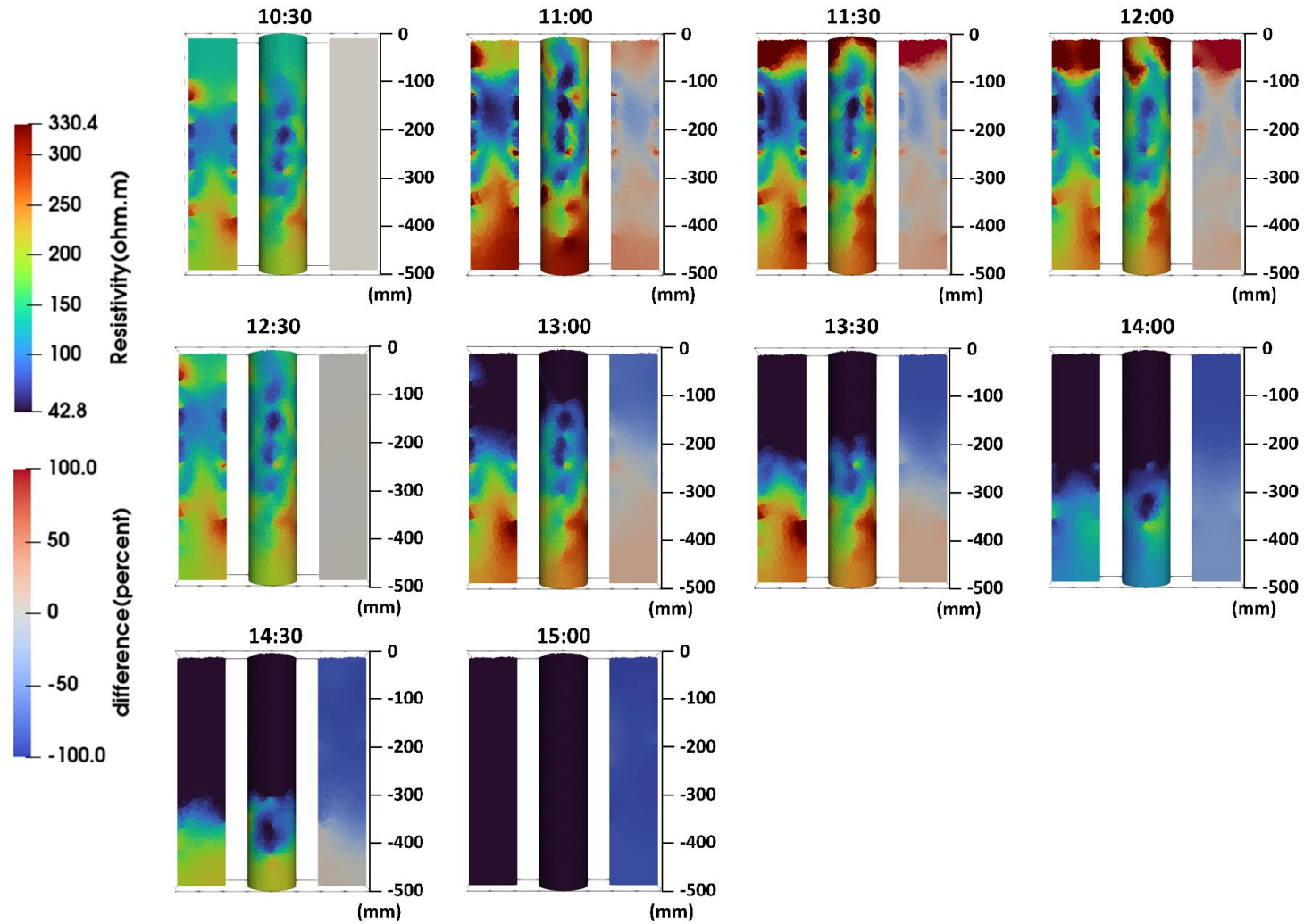


Figure 4. 48 Survey (2) a time-lapse survey of the topsoil-filled soil column during the storm, including data collected from day 2, when soil temperatures stabilised. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

4.11 Clay Topsoil-Filled Soil Column Experiment

4.11.1 Introduction

In Series 1, column experiments were performed on clay topsoil (CT) compacted to three dry densities (1.46 Mg/m^3 , 1.57 Mg/m^3 and 1.69 Mg/m^3). In Series 2, CT was added to the column loosely compacted to reduce ponding and increase infiltration. With changes made to the experiment design and method (see Section 3.6 for a complete account of these changes), alongside reducing ponding, the expectation was to improve the quality of CT ERT images in Series 2 by reducing the appearance of artefacts. Like previous Series 2 experiments (sand and topsoil), CT was oven-dried and mixed with water to achieve a moisture content of 10%. The soil was added to the column in 100mm intervals and lightly compacted to ensure good contact between the soil and electrodes. However, due to the low level of soil compaction, column experiments on CT were done twice due to the significant settlement during the storm in the first attempt (approximately $\leq 150\text{mm}$ of soil displacement). Due to settlement, the top layer of electrodes and point sensor were exposed. The soil was further compacted during the repeat experiment, and significant settlement was avoided. A time-lapse survey was produced from both experiments to determine the impacts of settlement on the electrical surveys. Additionally, changes in soil temperature were measured to further establish the effects of temperature on 4D column ERT imaging.

4.11.2 Point Sensor Measurements

Figure 4.49 shows the changes in moisture content during the first soil column experiment where settlement occurred. The graph indicates that moisture content in the soil fell beneath 0% on day 2, the day of the storm. This happened due to the air exposure of the top point sensor, located 100mm beneath the soil surface. Moisture content in the first experiment increases throughout the soil profile during the storm. Three hours later, moisture content rapidly decreases at the top of the soil due to settlement and water draining through the material. During the drying phase of this first experiment, the moisture content in the middle and bottom sections of the soil remain high (between 48.6% and 49.7%).

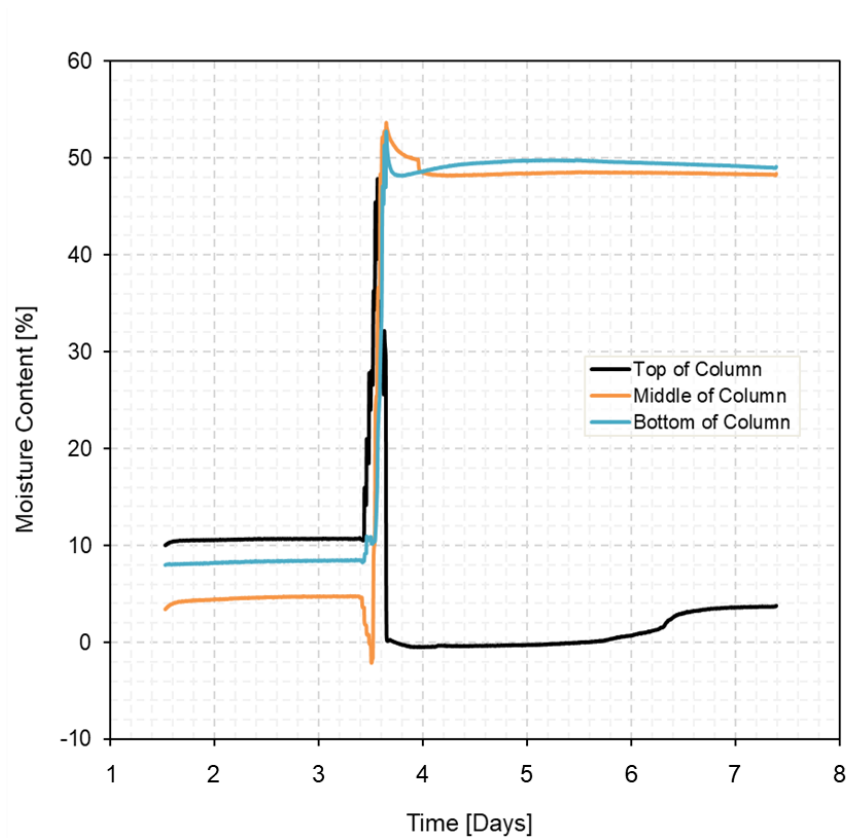


Figure 4. 49 The moisture content of clay-topsoil where significant settlement occurred during the storm simulation resulted in cavitation of the point sensor, causing moisture content to fall beneath 0%.

Point sensor data captured on day 2 of the repeat experiment (Figure 4.50) shows a rapid decrease in moisture content at the location of the middle sensor (-250 mm depth). Like point sensor measurements taken from the topsoil column experiment (Section 4.11), stormwater could be driving soil moisture through the material to increasing depths, accounting for the initial decrease in moisture content. After the initial drop, moisture levels increase throughout the soil profile, peaking at 62.6%, 51.4%, and 30.2% at the top, middle, and bottom sections of the soil, respectively. In the drying phase of the experiment, moisture content at the top of the column decreased to below recorded levels in the middle and bottom of the soil.

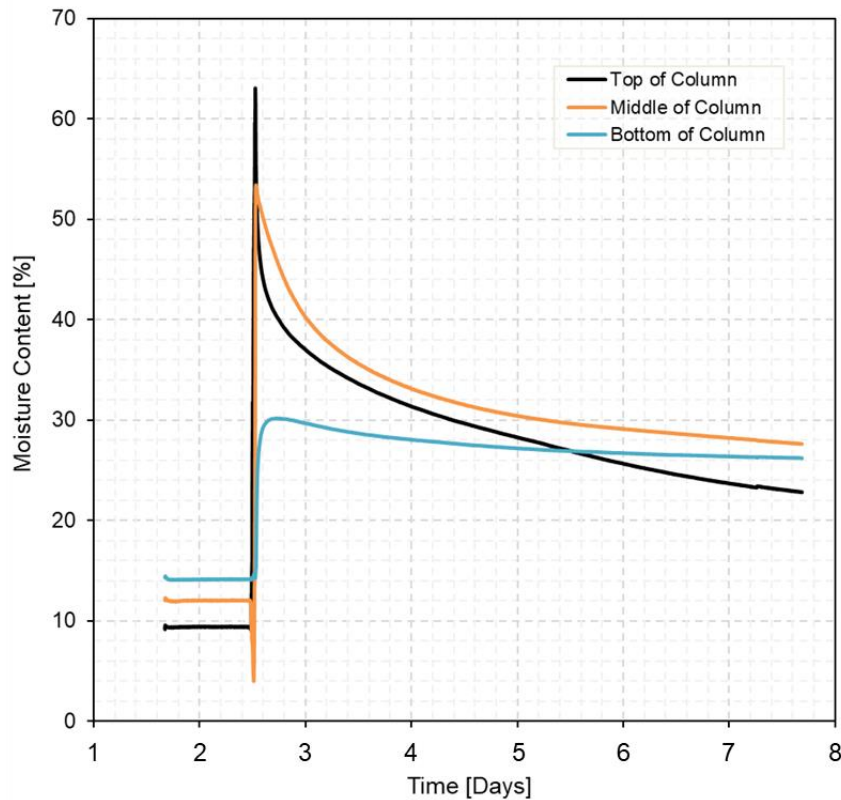


Figure 4. 50 Changes in soil moisture content during a soil column experiment (repeat experiment- clay topsoil).

4.11.3 Attempt 1 - Clay Topsoil Soil Column Experiment

As seen in the previous Series 2 column experiments (sand and topsoil), the effects of temperature on transfer resistances before a simulated storm were tested. Therefore, in the first attempted column experiment, where settlement occurred, the column was filled with soil and placed in the environment chamber. Data collected from the sand and topsoil experiments indicate that soil temperatures stabilised after approximately ten hours of being placed into the chamber. In these previous experiments, a storm event was initiated 1 day after the soil was placed in the chamber. However, fine-grained soils, such as clay topsoil (CT), have a lower thermal conductivity than coarser materials, resulting in slower heat transfer. Therefore, the CT was left for one additional day to regularise before a storm was simulated. Soil temperature changes are shown in Figure 4.51. The graph shows that, despite the soil being left for an additional day to regularise to the conditions of the chamber, soil temperatures levelled out at 16.5°C at approximately 21:00 on day 1. No further changes in temperature were measured on day 2. The transfer resistances of the soil were also analysed from days 1 and 2 and compared to the change in temperature. The data shows that as soil temperature decreases, transfer

resistances increase. There were no changes in the transfer resistances on day 2, which corresponds with stable soil temperature measurements.

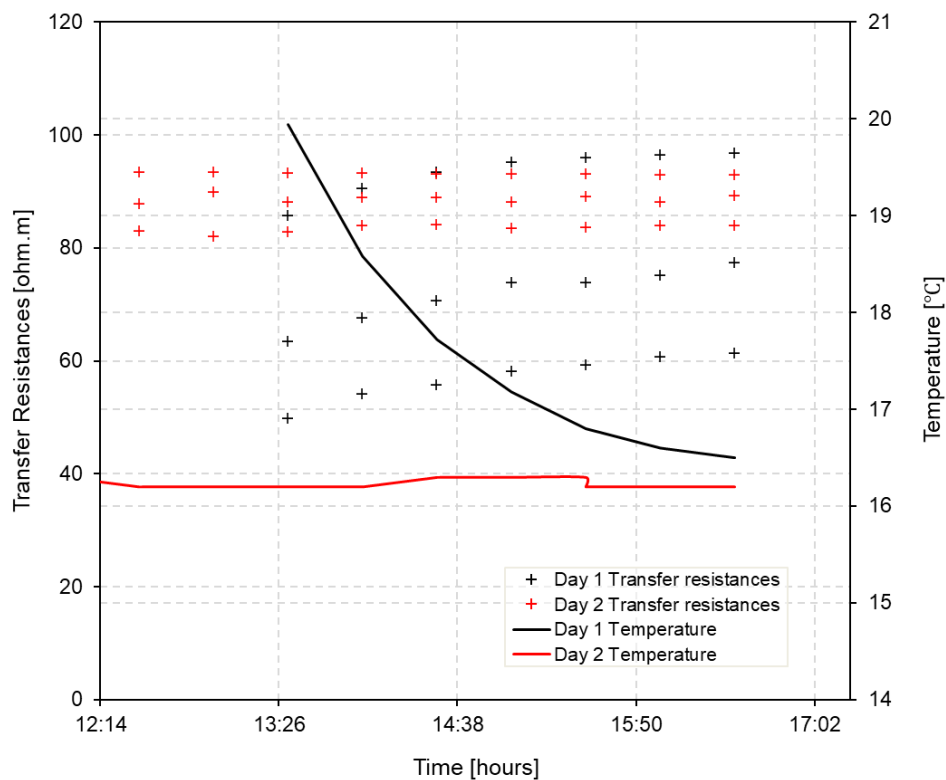


Figure 4. 51 Changes in soil temperature versus transfer resistances of clay topsoil on days 1 and 2 before a storm event.

ERT time-lapse surveys of the CT where significant settlement occurred during the storm were processed using three different sets of geoelectrical files:

1. the first time-lapse survey uses data captured on day 1 when soil temperature decreased, and transfer resistances increased accordingly (Figure 4.52)
2. the second survey uses data captured on day 2 when the PRIME system did not measure further changes in temperature and transfer resistances (Figure 4.53)
3. the final survey uses data exclusively from the day of the storm (day 3) (Figure 4.54).

4.11.4 Time-lapse Survey 1

Survey 1 (Figure 4.52) presents the spatial distribution and percentage difference in resistivity in the CT experiment on days 1 and 3. Geoelectrical data from day 1 indicates that soil transfer resistances increased throughout the day due to declining soil temperatures. However, ERT images from that day suggest the opposite, and electrical resistivity decreased between 13:30 and 17:30. Throughout this study, transfer resistances have been used to verify that the electrodes were measuring changes in electrical resistivity accurately. Therefore, it is reasonable to suggest that the ERT imaging displayed in Figure 4.52 is inaccurate. This is no surprise, given the effects of changing soil temperatures on the inversion (see Sections 4.10 and 4.11). Modelling artefacts are observed to varying degrees throughout the survey, coalescing predominately at the base of the soil column (e.g., Day 1, 14:00 and Day 3, 10:00). Day 3 marks the storm event. Water was first added to the soil column at 11:25, and the ERT imaging indicates that electrical resistivity decreased noticeably. By 12:30, no further changes in the spatial distribution or percentage difference in electrical resistivity were observed.

ERT images from Survey 1 do not accurately reflect changes in electrical soil resistivity for several reasons. Because geoelectrical data (including the baseline image) from when soil temperature changes were in effect were used, ERT imaging contains artefacts that mask actual changes in resistivity in effect. On day 3, the day of the storm, settlement occurs immediately after the first wetting event, resulting in decreased electrical resistivity throughout the soil. As a result, one hour later, electrical resistivity throughout the soil has declined by up to 100%.

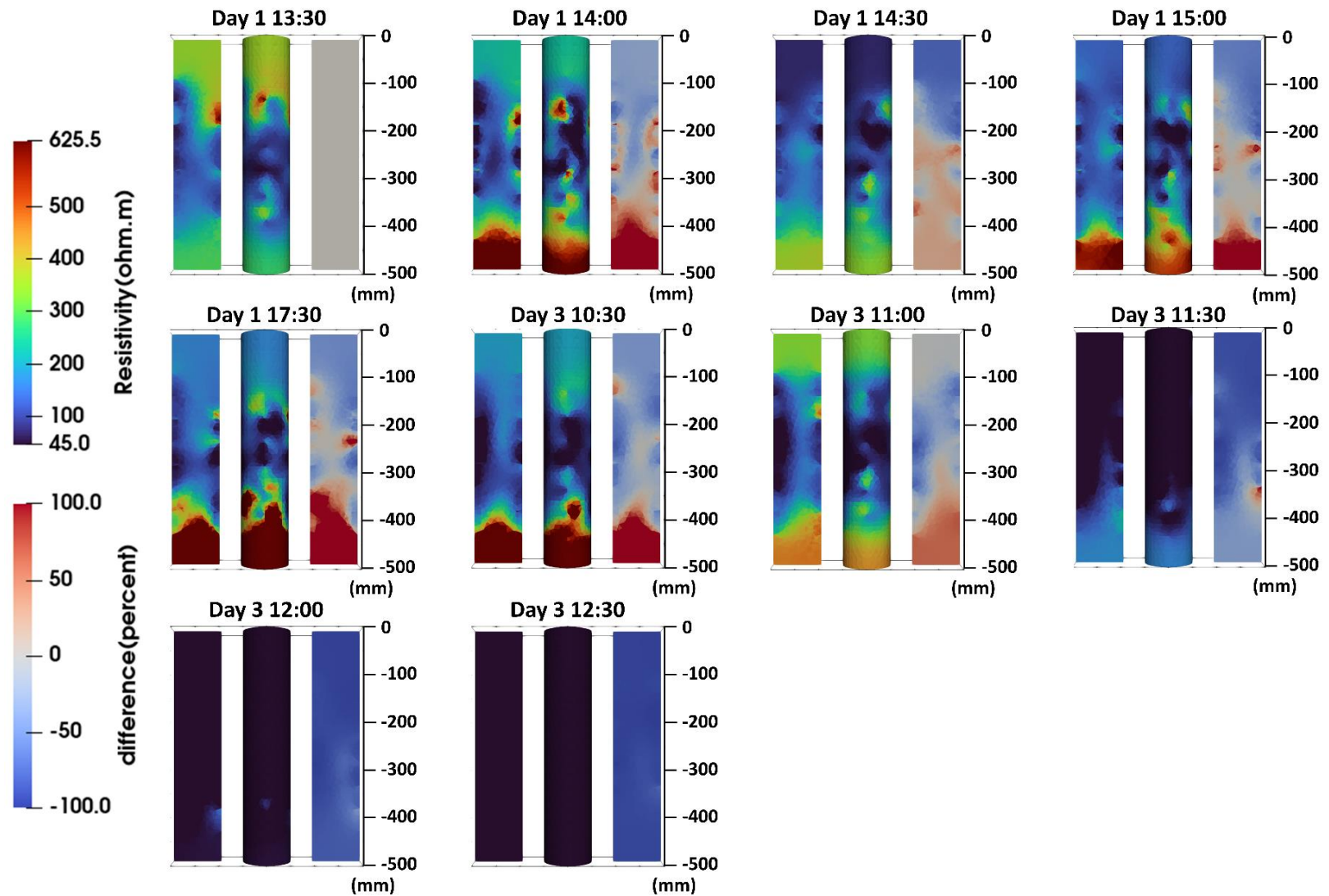


Figure 4. 52 Survey 1, a timelapse survey of clay topsoil column experiment (Series 2) where settlement occurred. The inversion uses data collected during soil temperature changes. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

4.11.5 Time-lapse Survey 2

Figure 4.53 shows time-lapse images of changes in electrical resistivity in Survey 2. The data in Survey 2 exclude geoelectrical files from day 1 (when soil temperature changes were in effect). Time-lapse surveys produced from the sand and topsoil experiments indicate that using geoelectrical data where soil temperatures are stable produces higher-quality ERT images than surveys where temperature changes are in effect. However, Survey 2 still presents significant artefacts on day 2 despite no changes in soil temperatures, transfer resistances or soil moisture content. Artefacts, presenting as high electrical resistivity contrasts, appear at the soil surface and base and extend partially towards the middle of the soil. Further, smaller areas of high resistivity are observed close to the electrodes. Similar artefact distributions were observed in the forward modelling tests (Section 4.6) and can, therefore, be attributed to the dipole-dipole array or changes to the survey volume. Survey volume changes are unlikely since no water was added to the column on day 2 (where most artefacts appear). However, if settlement occurred beneath the soil surface, this could account for the artefacts seen.

The prevalence of artefacts on day 3 (the storm simulation day) is lower than the same timesteps in Figure 4.52. However, areas of high resistance (≤ 300 ohm.m) are still observed at the base of the soil column. The storm was initiated at 11:25, and electrical resistivity decreased significantly over three hours. By 13:00, no further changes in resistivity are measured.

Modelling electrical resistivity in Survey 2 did not reduce artefacts days before the storm despite excluding geoelectrical data where temperature changes were in effect. Artefacts present in the ERT imaging similar to those observed in the forward modelling tests, suggesting that survey volume changes could have occurred. Since the soil settled significantly during the storm (day 3), soil displacement could incur survey volume changes that account for the artefacts seen on day 2. Similar to Survey 1, shortly after the storm was initiated, electrical resistivity decreases exponentially, resulting in no further changes in resistivity during the rest of the storm.

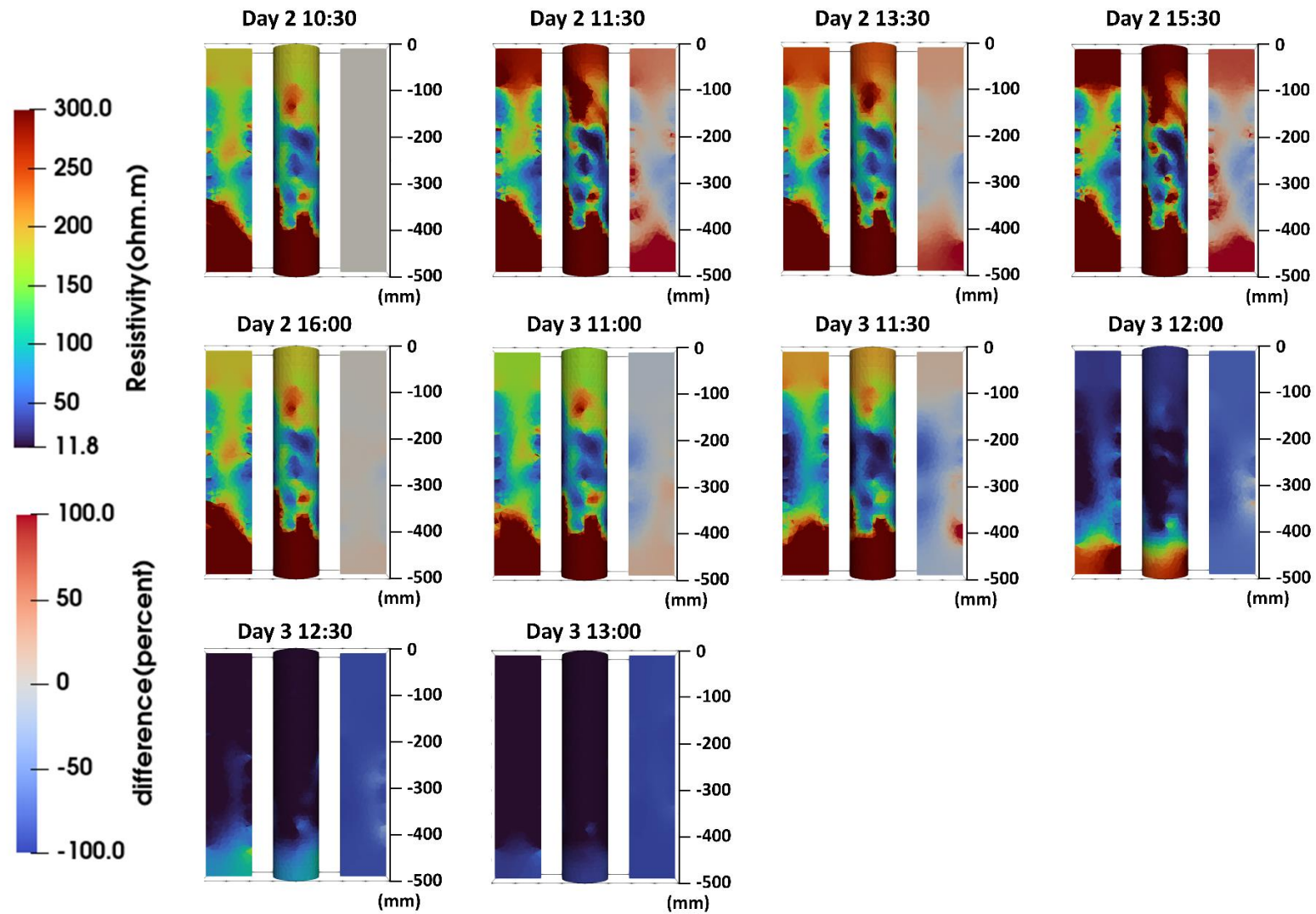


Figure 4. 53 Survey 2, ERT timelapse survey of clay topsoil column experiment (Series 2) where settlement occurred. The inversion excludes data where temperature changes were in effect before a simulated storm. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

4.11.6 Time-lapse Survey 3

In Survey 2, artefacts persisted in the ERT images despite no changes in soil temperature and transfer resistance on day 2. Therefore, a third survey (Survey 3) was processed that uses data exclusively from the day of the storm (Figure 4.54). The PRIME system began taking geoelectrical measurements from the soil column at 10:30. A region of high resistivity is observed at the base of the column (≥ 500 ohm.m). At 11:30, five minutes after the first water event, a region of high resistance is observed at the soil surface extending to 100mm depth. Initial increases in electrical resistivity after water is added to the soil are seen throughout this study and are attributed to soil moisture contrasts in the column resulting in artefacts. As more water is added to the column throughout the simulated storm, resistivity decreases, and the number of artefacts is reduced.

The presence of high-resistivity artefacts at the base of the soil before water was added to the column is unusual. The starting moisture content at the base of the soil is higher than that in the top or middle regions of the material. Research conducted by Carey et al. (2017) regarding artefacts in time-lapse ERT during rainfall simulations indicates that soil moisture contrasts can incur artificial modelled data due to a dipole-dipole array. However, the point sensors did not measure any changes in soil moisture movement before the storm was initiated on day 3, suggesting that (except for timestep 11:30) moisture contrast is not the problem. The forward modelling exercise described in Section 4.6 explains how changes to the survey volume (the soil column) could cause modelling artefacts. As previously described, the soil was loosely compacted in 100mm layers to ensure good contact between the electrodes and the material. However, as subsequent soil layers were added and compacted, the density of the bottom layer would increase over time. Density is the mass of a substance per unit of volume. Therefore, the difference in soil density between the top and bottom of the soil could have resulted in artefacts because changes in soil volume were not factored into the inversion.

Compared to the time-lapse surveys produced in Surveys 1 and 2, where geoelectrical data is used from days before the simulated storm, Survey 3 provided the highest quality survey of the three inversions undertaken as fewer artefacts were present in the time series. However, the wetting front was not well observed in any of the time-lapse surveys. Settlement during the experiment started immediately after water was added to the soil, and despite electrodes at the top of the soil being exposed, water pooling on the soil surface before percolating through the material appears to have compensated for the large amount of soil displacement that occurred.

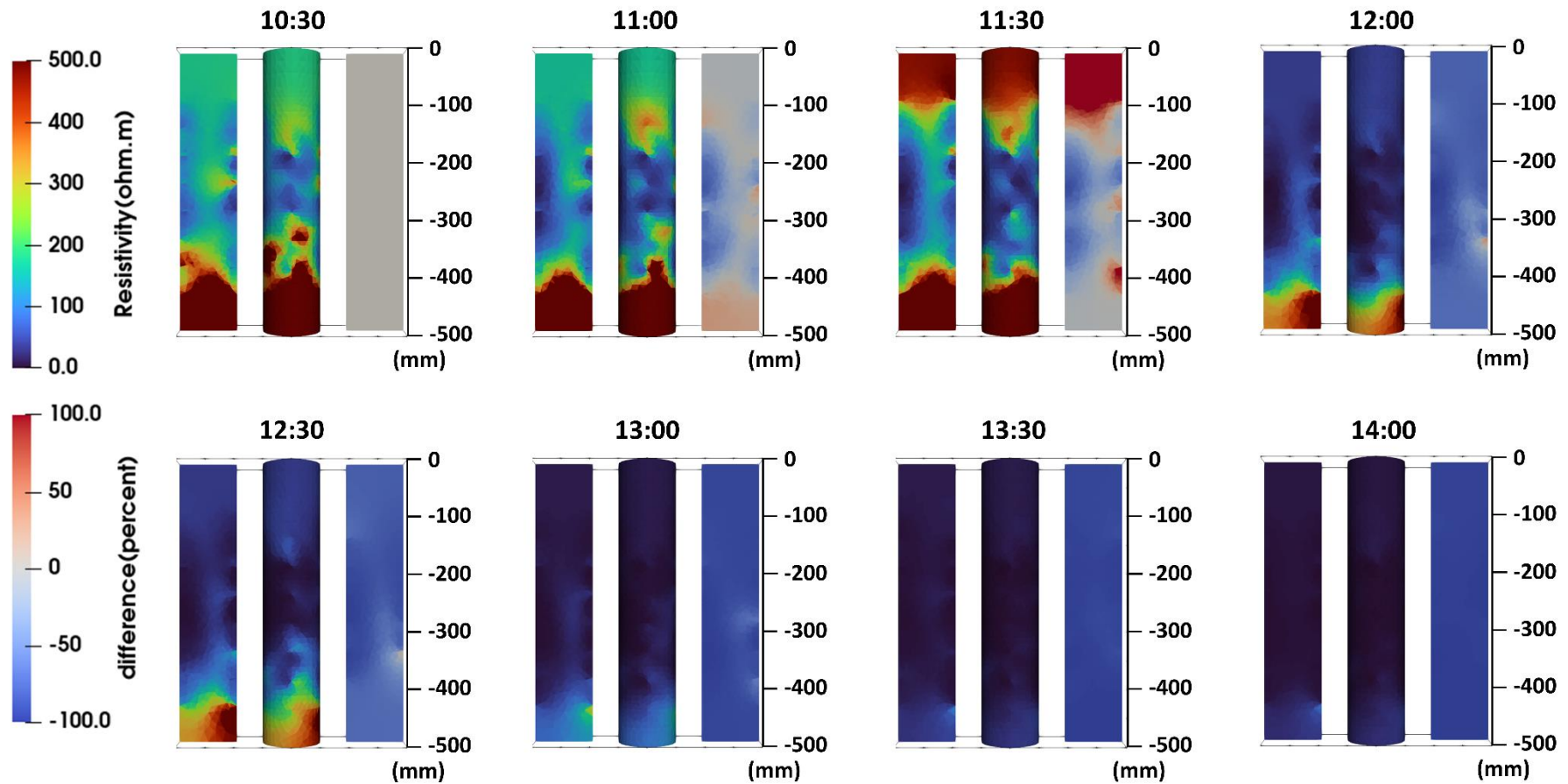


Figure 4. 54 Survey 3, a time-lapse survey of clay topsoil during a simulated storm. Data collected during the survey uses geoelectrical measurements made exclusively from day 3, where no soil temperature changes were in effect. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

4.11.7 Attempt 2 - Clay Topsoil Soil Column Experiment

Due to the settlement during the first attempted soil column experiment on CT (Series 2), the experiment was repeated (attempt 2). The soil was further compacted at 100mm intervals to avoid displacement during the simulated storm. Like the previous Series 2 experiments (sand, topsoil, and CT – attempt 1), soil temperature was monitored after the column was filled with soil and placed in the environment chamber. The soil column was filled with CT and mixed with water to achieve a soil moisture content close to 10%. It was added to the chamber on day 1. Figure 4.55 shows the change in transfer resistances as soil temperature decreases on day 1. When the clay material was placed in the chamber, the soil temperature decreased from 17.5°C to 16.3°C. Like previous materials in Series 2, transfer resistances increase as the soil temperature falls. Soil temperatures stabilised at approximately 14:00, and no changes in temperature or transfer resistances were measured after day 1.

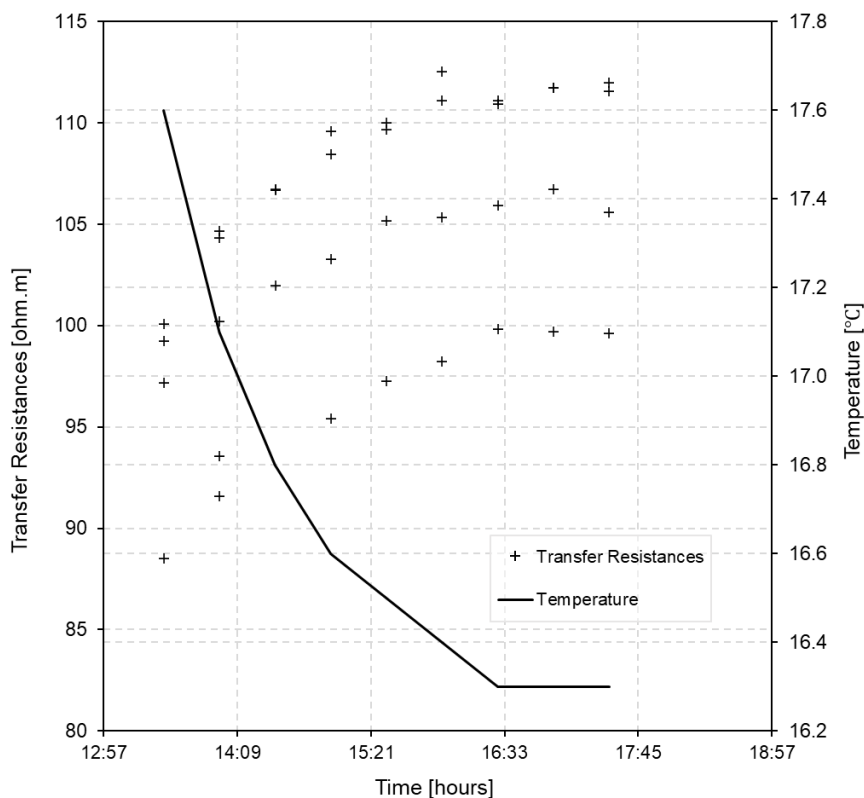


Figure 4. 55 Temperature and transfer resistance changes in clay topsoil after the soil was placed in the environment chamber on day 1 (repeat experiment).

Data collected on clay topsoil in the first attempt, as well as previous Series 2 column experiments (sand and topsoil), verifies that when doing a baseline-constrained inversion, using a reference timestep from the day of the storm provides the highest quality survey as fewer artefacts appeared in the ERT images. Therefore, geoelectrical measurements from the CT column experiment uses data exclusively from the day of the storm (day 3). Figure 4.56 shows the spatial distribution and percentage difference in electrical resistivity in the CT during the storm. The resistivity scale has a significant range owing to the presence of artefacts in the inversion. The PRIME system started taking measurements at 10:30, and despite no water being added to the soil column before 11:25, resistivity appears to decrease by approximately 10% throughout the soil column. At 11:30, five minutes after saltwater was added to the column, high resistivity artefacts appear at the top and bottom of the soil profile. This occurs due to the soil moisture contrast created when water was added to the soil or the volume change of the inversion site.

As the storm continues, the appearance of artefacts at the top and base of the column diminishes, and by 13:00, small, localised areas of high resistance are observed between -200 and -300mm depth close to the electrodes. Despite the artefacts in the inversion, by 15:00, a wetting front is visible up to -200mm, as seen by the percentage difference in resistivity imaging. From 15:00 to 16:00, as more salt water is added to the column, the percentage difference in resistivity decreases, and the wetting front extends further into the soil. At 16:30, as resistivity decreases, high-resistivity artefacts emerge in the inversion and are observed until 17:30, when the PRIME system measurements stop. Similar artefacts were observed in time-lapse surveys processed from other materials. These artefacts are likely a result of the soil moisture contrast between the drier soil at -500 to -350mm and wetter overlying material, which the inversion failed to interpret correctly. At 17:30, artefacts at the base of the soil are still present. However, as water percolates further through the soil column, artefacts are seen to diminish on the right side of the soil. Days after the storm, no further changes in the spatial distribution in electrical resistivity were observed.

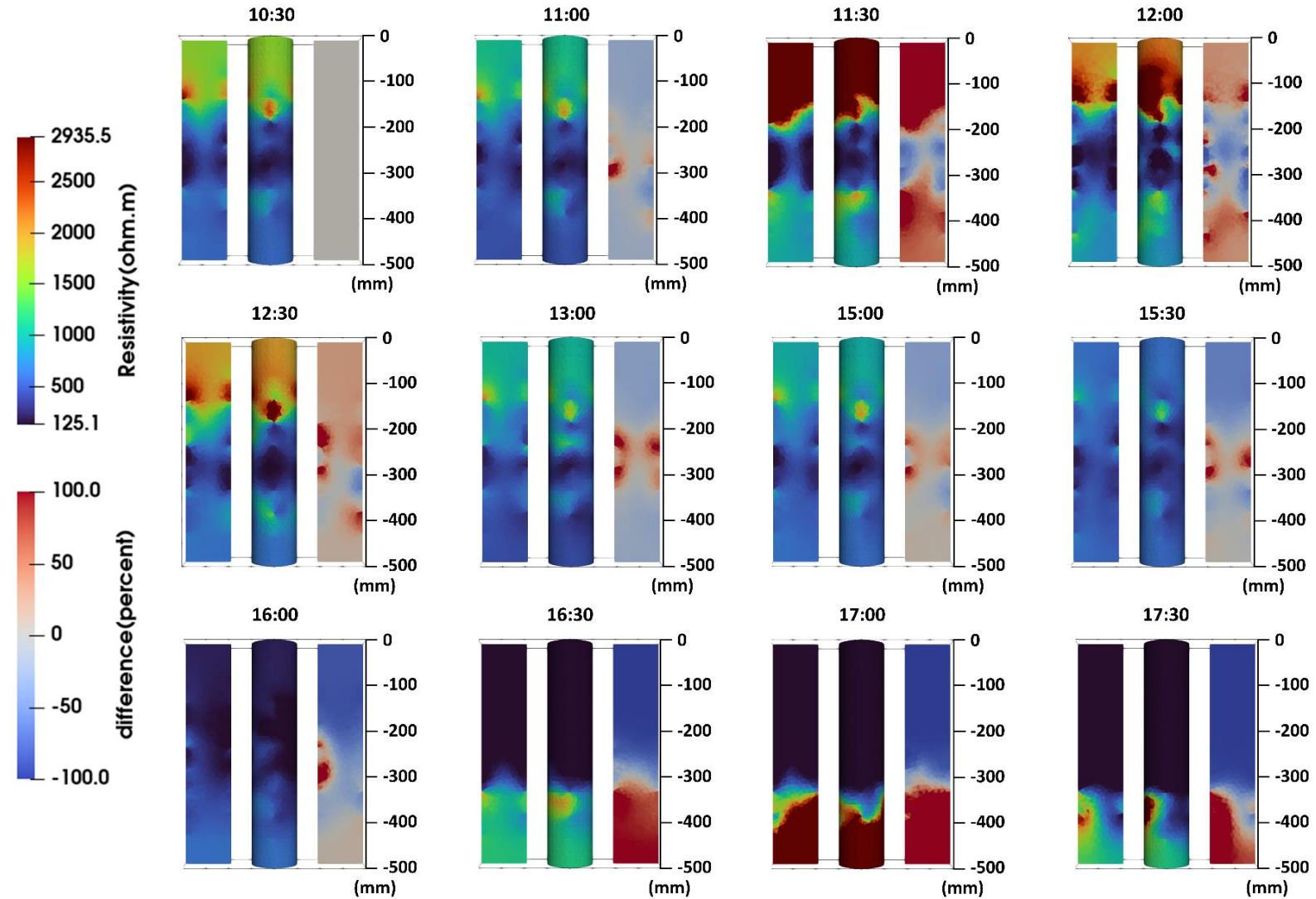


Figure 4. 56 Time-lapse survey of clay topsoil where no settlement occurred (attempt 2). Data was collected during a simulated storm on day 3. ERT images show the spatial distribution of electrical resistivity (left and centre of each timestep) alongside the percentage difference in resistivity (right).

4.12 Petrophysical Relationships

4.12.1 Series 1 Bourne Amenity Topsoil Column Experiment

In the Bourne Amenity topsoil (BAT) experiment, changes in the spatial distributions in resistivity were most noticeable during the simulated storm. Figure 4.57 shows a side-by-side comparison of changes in soil resistivity and VMC before, during and after the storm took place. ERT images show changes in VMC and resistivity at the column wall and the middle cross-section. Images of resistivity correlate well with changes in VMC. The data shows that moisture content increases from the soil surface to a depth of -250mm and that by the end of the storm (17:30), the moisture content in the column has increased, with levels being higher from the base of the soil towards the surface.

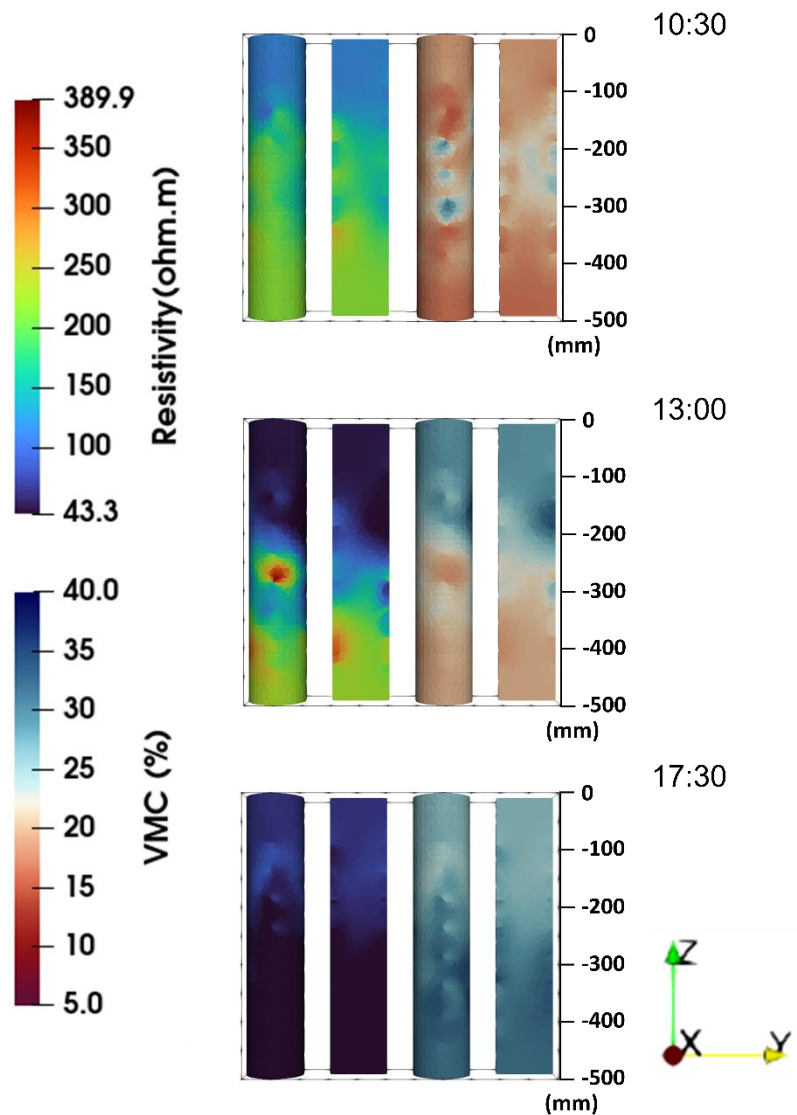


Figure 4. 57 A sample of the time-lapse survey of topsoil comparing changes in the spatial distributions in resistivity alongside changes in volumetric moisture content (VMC) at critical moments during a simulated storm. ERT images show the spatial distribution of electrical resistivity (left of each timestep) alongside the VMC (right).

The complete time-lapse survey showing changes in VMC in the BAT experiment during the storm is given in Figure 4.58. Electrical measurements taken by the PRIME system commenced at 10:30, and the simulated storm took place over six hours. At 10:30 and 12:00, small, localised regions of high VMC (approximately 25%) are observed at the site of the electrodes from -200mm to -300mm depths. This was seen in other time-lapse surveys measuring resistivity and is thought to be a product of complexities in the geosynthetic mesh. At 12:00, soil moisture content at the surface increases from approximately 15% to between 20% and 30%.

Transitioning from 12:00 to 12:30, more subtle changes in soil moisture content are viewed, which are lost in the resistivity survey produced in Section 4.5. Here (12:30), pockets of lower resistivity (approximately 10% to 15%) are observed in the near-surface and decrease in size as VMC in the upper section of the soil column (between 0 and -250mm depth) increases. By 13:00, the moisture content in the upper section of the soil column had exceeded 25% and was more uniform in its distribution.

At 13:30, the spatial distributions in VMC had changed quite drastically compared to its previous timestep (13:00) and subsequent measurements (14:00). At the soil surface to -100mm depth, a distinct boundary of comparatively lower moisture content is observed (between 20% – 22%). Before moisture content below this sharp boundary increases to approximately 25% - 30%. Furthermore, a localised area of high VMC is observed between -100mm and -200mm in the left image (13:30). It is difficult to identify if these characterisations at 13:30 are a product of modelling errors (artefacts) or actual measured distributions in VMC. The time-lapse survey from the BAT geoelectric data in Section 4.5 shows that resistivity in this section of the soil had decreased significantly, and no artefacts were observed. However, the distinct boundary between low and high moisture content present at -100mm could suggest some degree of artificial results. Additionally, the change in soil moisture dynamics between 13:30 and 14:00 occurs over a relatively short timeframe out of character with subsequent time steps.

At 14:00, any potential artefacts observed at 13:30 are gone, and the wetting front is seen to progress from -260mm to -300mm depth. In ERT images depicting changes in electrical resistivity, colour contrasts (red and blue) like those observed at 14:00 indicate artefacts.

However, despite the significant colour difference, the difference in VMC between -260mm to -300mm depth is approximately between 6% and 3%. By 14:30, moisture content at the base of the column increases from 20% to approximately between 25% and 30% as water from the storm percolates towards the base of the column.

At 15:00, a slight decrease in soil moisture content is observed. Drainage data collected from the tipping bucket located at the base of the column recorded that 10mm of water was removed from the column at 15:00, which coincides with the ERT image. At 15:30, VMC at the base of the column increases. A region with high moisture content ($\geq 40\%$) develops in the middle of the soil column (between -200mm and -300mm depth). Like the formerly discussed timestep at 13:30, it is somewhat difficult to distinguish if measurements are partially artificial. This is due to the localised areas of high VMC close to the three electrodes, where it was discussed that these areas are prone to modelling errors. However, this increase in moisture content is observed to extend into the soil in the cross-section view and was also observed at 14:00. ERT images measuring changes in soil moisture content (Figures 4.58 and 4.59) capture an uptick in moisture content at that time. However, nothing in the middle section of the soil is measured by the sensors exceeding 40%.

At 16:00, these areas of high VMC are gone from the middle of the soil column, and moisture content at the top and base of the soil are slightly higher than those in the middle region of the material. At 16:30 and 17:00, no more water was added to the soil, and despite some artefacts being observed at the wall of the column where the electrodes were positioned, this did not disrupt the overall spatial distribution of VMC at the end of the experiment.

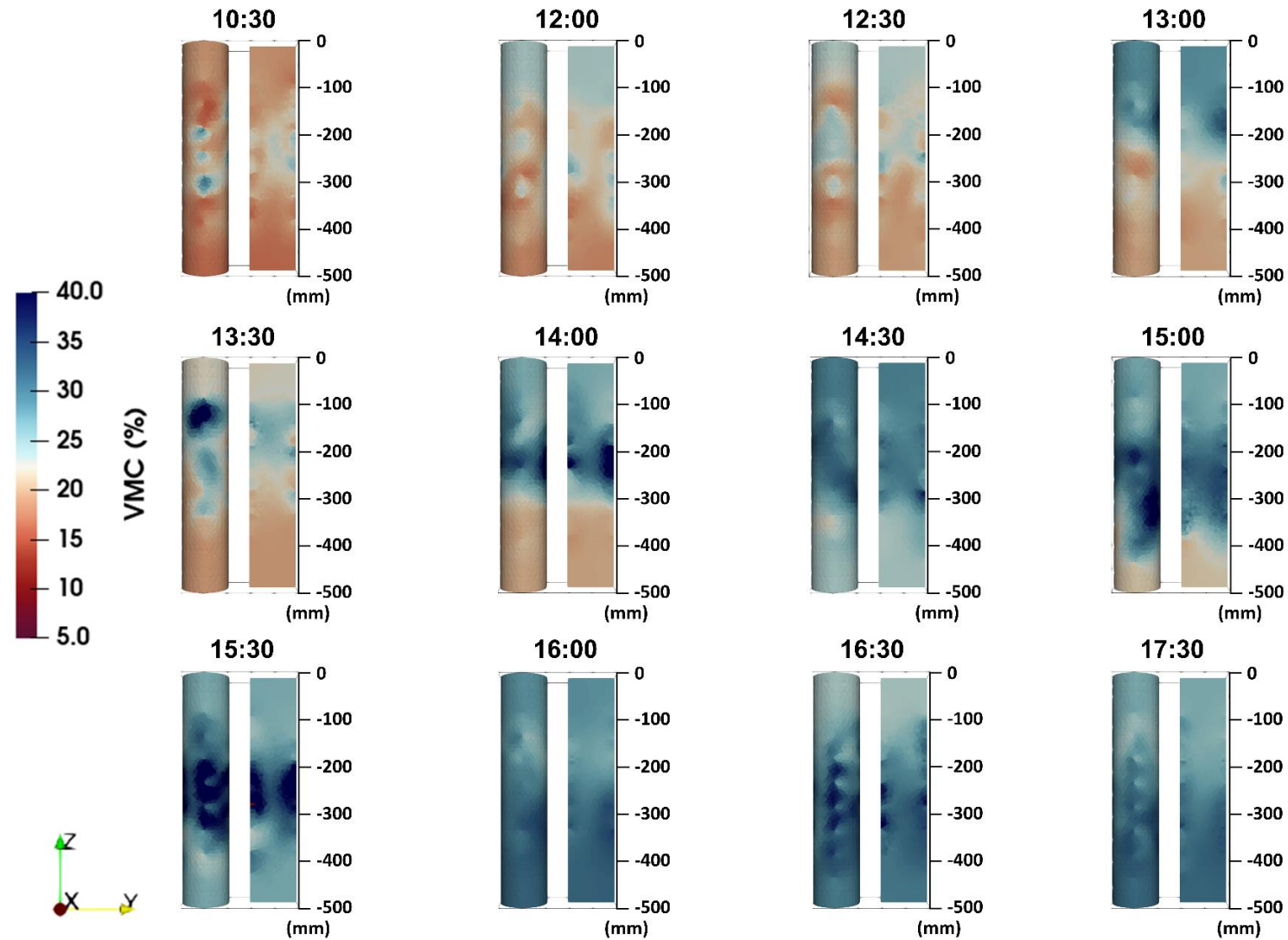


Figure 4. 58 Spatial distributions in VMC in Bourne Amenity topsoil (Series 1) during a simulated storm. Data at each timestep shows the VMC at the wall of the column (left of each timestep) and a cross-section view down the middle of the soil profile (right of each timestep).

4.12.2 Series 1 Clay Topsoil Column Experiment

A PLF model fitted the HYPROP data for the clay topsoil (CT) exceptionally well. However, due to the scheduling parameters of the PRIME system, much of the wetting front was lost outside the measurement window. Figure 4.59 shows a sample of the spatial distribution of resistivity and percentage difference in resistivity during the soil column experiment on CT. Due to low infiltration rates, significant ponding occurred during the experiment. However, at 16:30, stormwater is seen to percolate to approximately -100mm depth. The PRIME system stopped its measurement cycle at 16:30 before it started again at 09:30 on day 2. From the timelapse below, it is evident how far the water had extended into the material overnight. The electrical survey developed for CT is discussed in Section 4.4.3.

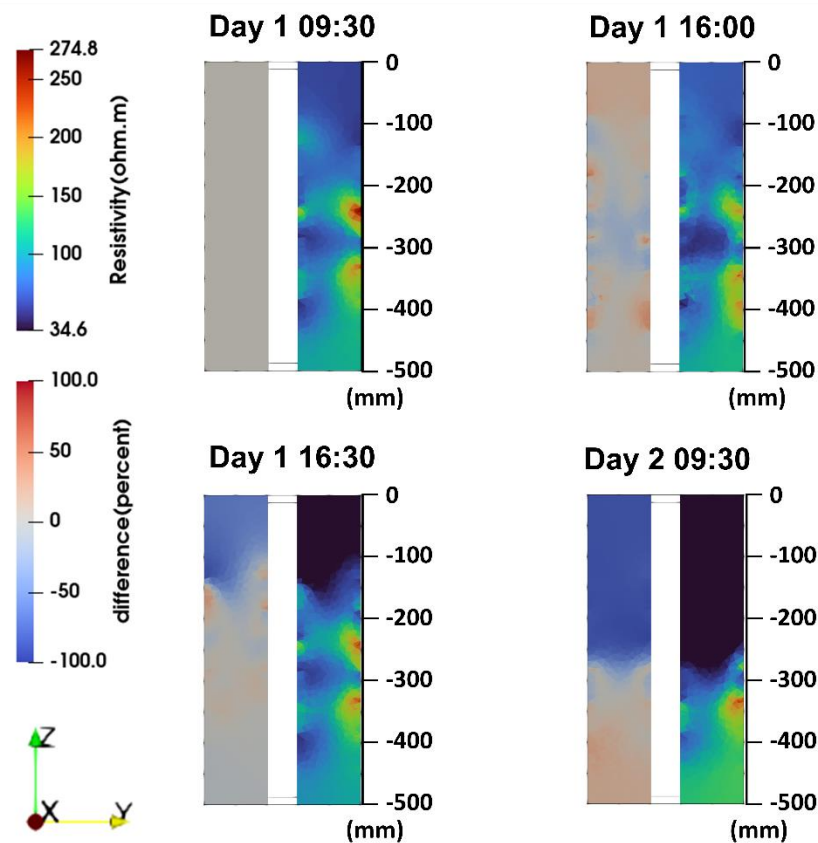


Figure 4. 59 A snapshot of the timelapse electrical survey of clay topsoil during the soil column experiment. Data shows resistivity in the upper regions of material decreasing towards the end of the storm. ERT images show the spatial distribution of resistivity (right of each timestep) alongside the percentage difference (left).

Figures 4.60 and 4.61 provide a timelapse survey of changes in VMC that occurred during the CT column experiment using a PLF calibration. ERT images are divided into two surveys to illustrate the significant changes in soil moisture content outside the PRIME systems measurement window. The time-lapse inversion given in Figure 4.60 shows changes in VMC at the beginning and end of the simulated storm event. The scale provided measures VMC from 2% - 10%, whereas the scale provided in Figure 4.61 measures changes in VMC between 3% - 78%. It was necessary to use two scales to highlight the more subtle changes in soil moisture dynamics that occurred on both days.

To achieve a dry density of 1.46 Mg/m^3 , CT was added to the soil column at a moisture content of 10.2%. Spatial distributions in VMC on day 1 at 09:30 (Figure 4.60) show that moisture levels decrease with depth, with pockets of alternating high and low moisture content between -200mm and -450mm. Between 09:30 and 16:00, despite ponding, little to no percolation had occurred. Data collected during the forward modelling exercise (see Section 4.6) indicates that changes to the survey area volume can incur artefacts in ERT images. However, despite the mass and subsequent volume changes that occurred due to progressive ponding, little change took place in the VMC profile of the material. By 16:30, as was seen in the resistivity ERT survey (Figure 4.59), a breakthrough occurs as water infiltrates through the soil, with a visible wetting front appearing in the inversion, extending from the soil surface to -190mm depth.

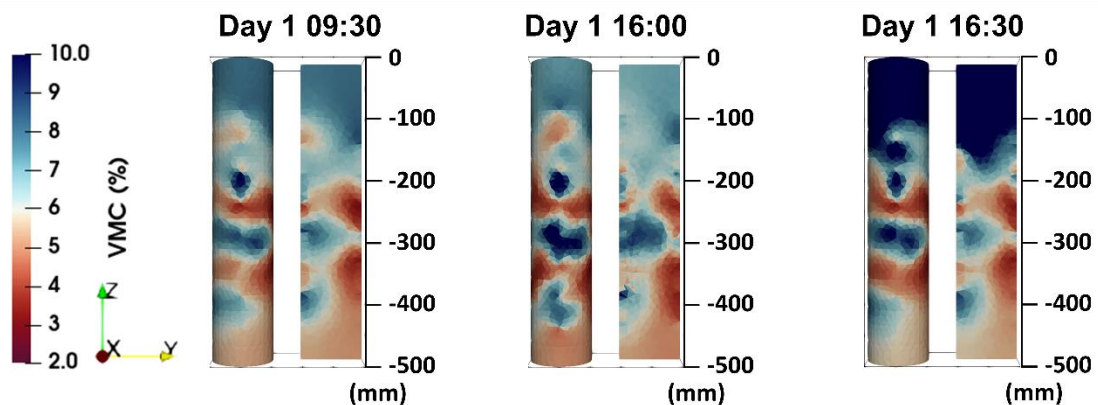


Figure 4. 60 A sample of the time-lapse survey was taken for the clay topsoil experiment. Data shows changes in VMC that occurred during a simulated storm event.

Figure 4.61 shows a time-lapse survey of changes in VMC in CT the day after the storm (day 2). The scale of VMC has been increased compared to the time series provided in Figure 4.60 to highlight the increases in MC one day after the storm. Figure 4.61a compares the final

timestep taken on the 17th to the first taken on the 18th using the same scale, demonstrating this moisture content change near the soil surface. The time-lapse survey (Figure 4.61) provides a view of the soil column at the pipe boundary (left image of each timestep) and a cross-section view down the centre of the material (right image of each timestep).

Although moisture content increases overnight, the wetting front does not progress over the following week that the material was monitored. At 11:30, clusters of red elements emerge in both the boundary and cross-section view of the soil column. These clusters indicate regions where the modelling software failed to input the moisture content of the material and are therefore allocated a MC value of 0% in ParaView. Compared to spatial changes in the VMC of the BAT (Figure 4.58), changes in the CT are less easily interpreted owing to artefacts in the modelled data. When geoelectrical data from the CT experiment (at a dry density of 1.46 Mg/m³) was inverted (see Section 4.4.3), a large region of artefacts beneath the wetting front was identified. However, despite this, the wetting front was clear. Hence, the decision was made to plot the data as spatial distributions in VMC. However, plotting the data as VMC has provided a different perspective of the underlying conditions of the inversion process that were not visualised in the ERT resistivity survey.

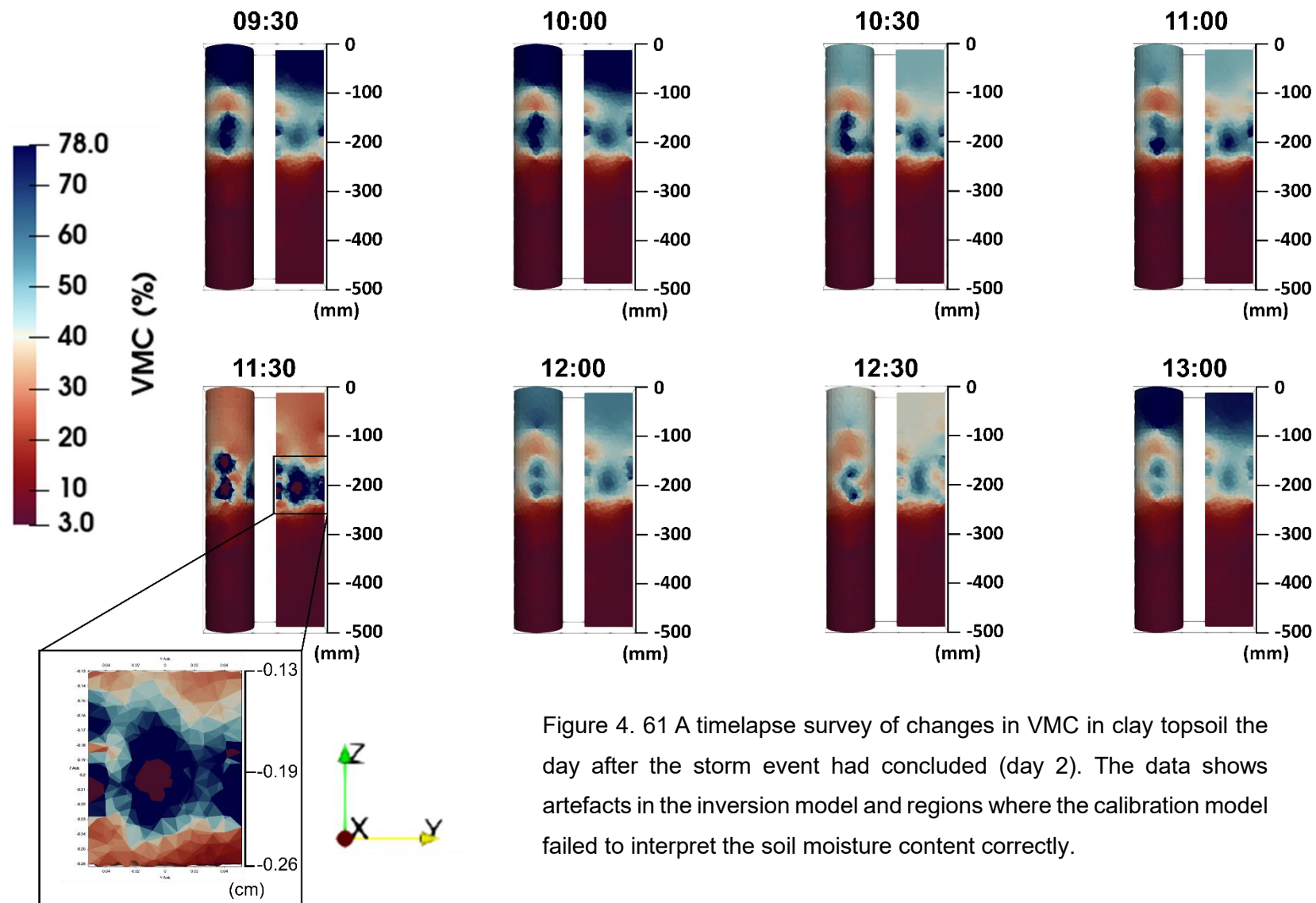


Figure 4. 61 A timelapse survey of changes in VMC in clay topsoil the day after the storm event had concluded (day 2). The data shows artefacts in the inversion model and regions where the calibration model failed to interpret the soil moisture content correctly.

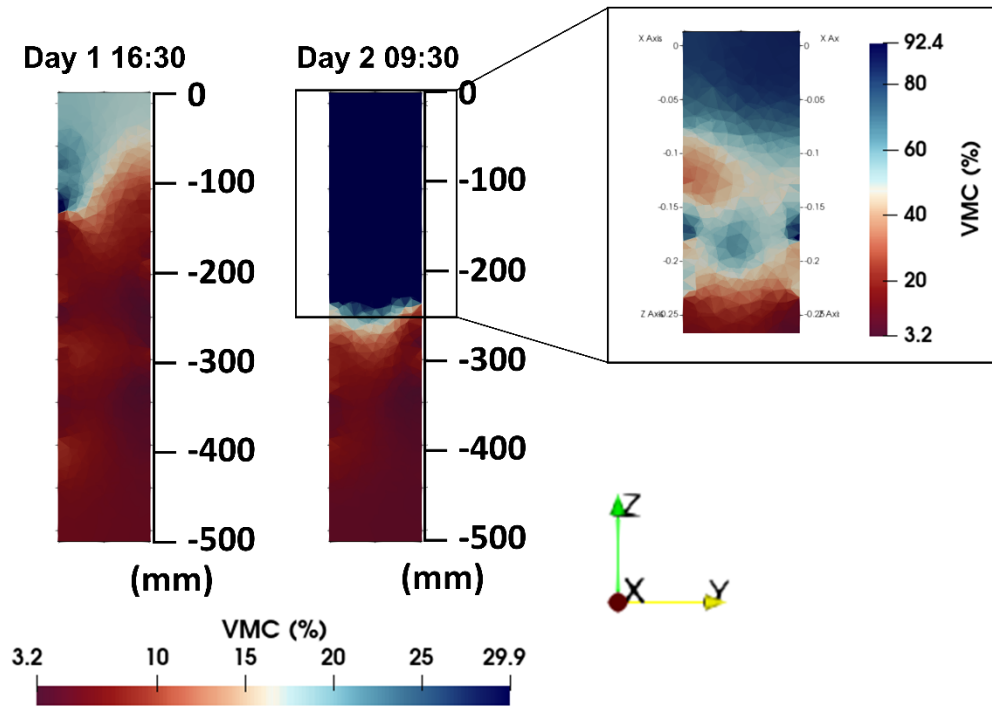


Figure 4. 61a A comparison of the spatial distribution of moisture content at the end of the storm (day 1) vs the following day (day 2) when measurements were re-commenced.

Figure 4.62 compares the spatial distributions in resistivity (left) vs the VMC (right) in the CT during a single timestep where artefacts are noted at different depths in each image. In the resistivity image, a small cluster of artefacts is seen on the right-hand side of the soil column wall, which is not observed in the image depicting VMC. This area of high resistance is situated at a depth of -350mm and close to an electrode. In contrast, in the VMC image, a region of low resistivity artefacts is identified between -120mm and -250mm, which is not observed in the resistivity image. The appearance of different artefacts being identified in either image is attributed to the fitted curve that converts resistivity to moisture content. Figure 4.62 also shows the calibration curve used in the CT experiment. The graphs highlight the wet and dry ends of the curve. Due to the gradient of the line, more measurements exist at the wetter, and therefore less resistive, end of the curve, enabling the electrical survey to better interpret the spatial distributions of VMC at a higher moisture content. Hence, information regarding potential artefacts in the inversion is observed in blue, where moisture levels are perceived to be higher. The calibration model has more data that is captured at a low resistivity. On the other hand, where moisture content is lower and resistivity is higher, the line gradient is steeper and fewer

measurements exist at the drier end of the curve. Therefore, the VMC model fails to recognise the potential high-resistivity artefacts in the left resistivity image.

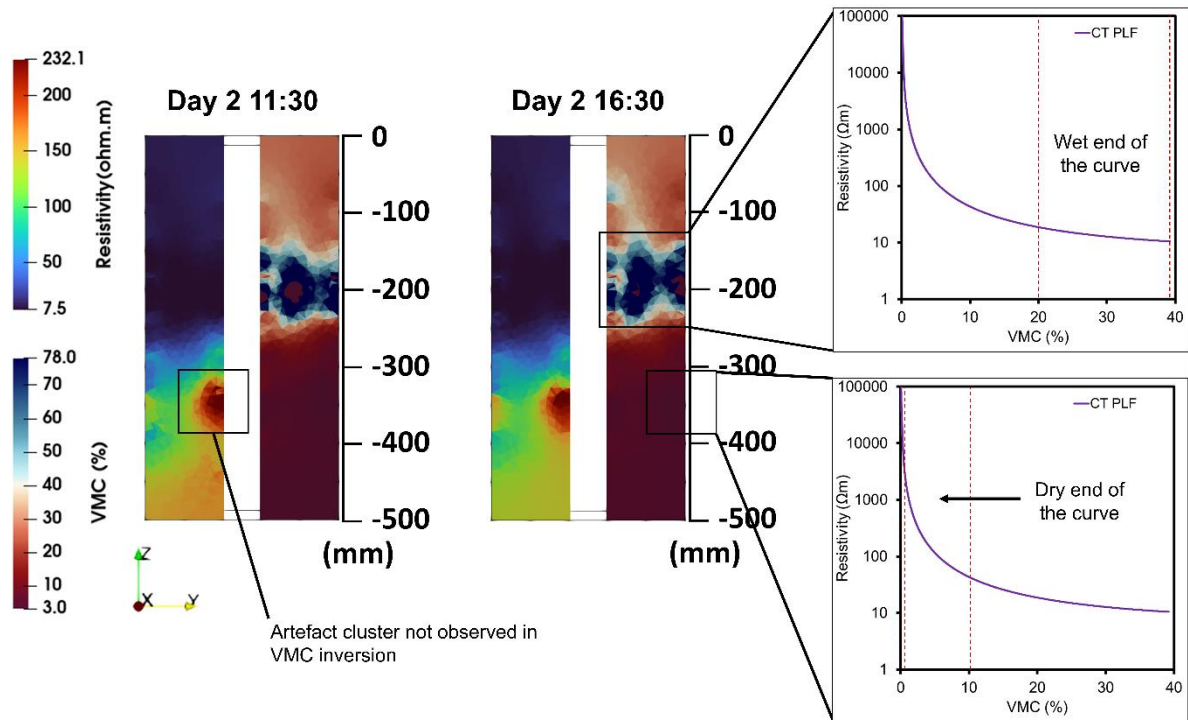


Figure 4. 62 A snapshot from the timelapse survey of the clay topsoil column experiment comparing spatial distributions in resistivity versus their VMC imaging. Data was collected one day after the simulated storm (day 2).

4.12.3 Comparing Soil Moisture Sensor Measurements and ERT Models

Alongside each ERT soil column experiment, a second column was instrumented with point sensors (TEROS 12 and TEROS 31) to measure water content and matric potential. It was not possible to instrument a single column with the ERT array and point sensors due to the interference the sensors would have on the electrical survey. The metal from the TEROS 12 would conduct electricity from the ERT array, and the sensors would also add to the complexity of the geosynthetic model. The ERT and point sensor columns were designed and filled to the same specifications. Water was added to both columns simultaneously and from the same source (CAT 5/saltwater). Despite this, there are still likely to be some differences in infiltration rates and water migration pathways that would ultimately be reflected in differences between the point sensor and ERT-derived measurements. The approximate volume of influence of the TEROS sensors is 100mm (Meter Group, 2024; Ramson et al., 2021). Using the calibrated

VMC model of each soil, timelapse surveys were visualised using ParaView. The spatial data was cross-sectioned using the box function, and the 4-D data was clipped according to the exact position and volume of influence of the three soil moisture sensors (SMS): top, middle, and bottom. These sensors, relative to the surface level of the soil at 500mm, are located at 100mm (top sensor), 250mm (middle sensor) and 400mm (bottom sensor).

Figure 4.63 shows the locations where the data was clipped using ParaView. Cell data associated with each clipped section (associated with the position of the top, middle, and bottom sensors) was exported to Excel and contained array information on VMC (%).

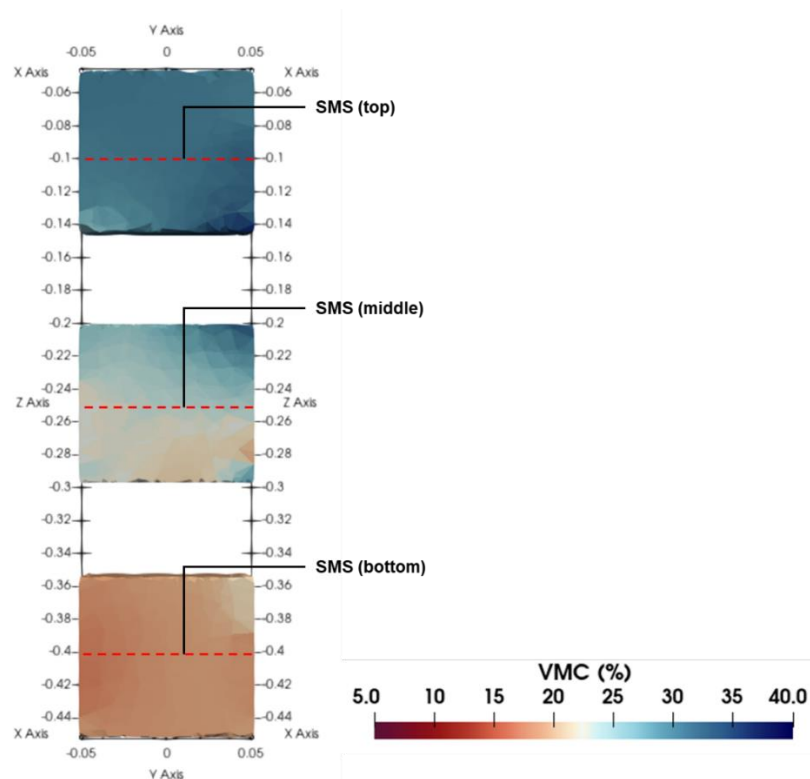


Figure 4. 63 Clipped soil column data showing the spatial distribution of VMC for a single timestep of topsoil during a storm simulation. The data has been clipped, and the positions of the soil moisture sensors are shown to demonstrate what data was analysed relative to the sensor's volume of influence.

Figures 4.64, 4.65 and 4.66 compare the VMC derived from the calibrated ERT data and soil moisture sensors (SMS) in the Bourne Amenity topsoil (BAT) and clay topsoil (CT) experiments. 34 ml of water was added to the columns every 15 minutes, and the PRIME

system took one complete set of measurements (forward and reciprocal) every 30 minutes. The range of moisture contents depicted every 30 minutes indicates the volume of elements, or cells, in each measured zone (top, middle and bottom SMSs). Given that each cell is assigned its moisture content, values will range depending on the location of the cell within that 100mm zone and the migration pathways the stormwater took during each experiment. A total of three SMSs were used to measure VMC. They were placed (relative to the soil surface level) at -100mm, -250mm and -400mm depths and are referred to as the top, middle and bottom sensors, respectively.

The data in Figure 4.64 show changes in the VMC of BAT during the simulated storm. At the top moisture sensor (SMS top) location, the calibrated VMC data derived from the ERT experiment (ERT top) is generally higher than measurements taken from the middle and bottom of the soil. This is also reflected in the data captured by the point sensors. Data collected at the ERT (top) is within range of the SMS (top). However, there are some exceptions. Data at 12:30, 15:00 and 17:00 is slightly lower than the VMC measured by the SMS but still within an acceptable range, given that data was collected from two separate columns. There is a significant contrast in the moisture content measured by the SMS (top) and the ERT (top) data at 10:30, 11:00, and 16:00. This is also reflected in data collected by the SMS in the middle of the soil column (SMS mid) and the ERT-derived VMC data collected at its location (ERT mid) but to a greater degree. Fewer measurements from the ERT (mid) align with the SMS (mid) data compared to the top column measurements. However, ERT (mid) data does capture the wetting and drying trend that is also measured by the SMS (mid), despite many of the measurements being out of range. ERT (btm) measurements correlate with the VMC at the lowest soil moisture sensor (SMS btm), except for data between 13:30 and 14:30. However, ERT VMC measurements do increase during this window to align with SMS measurements.

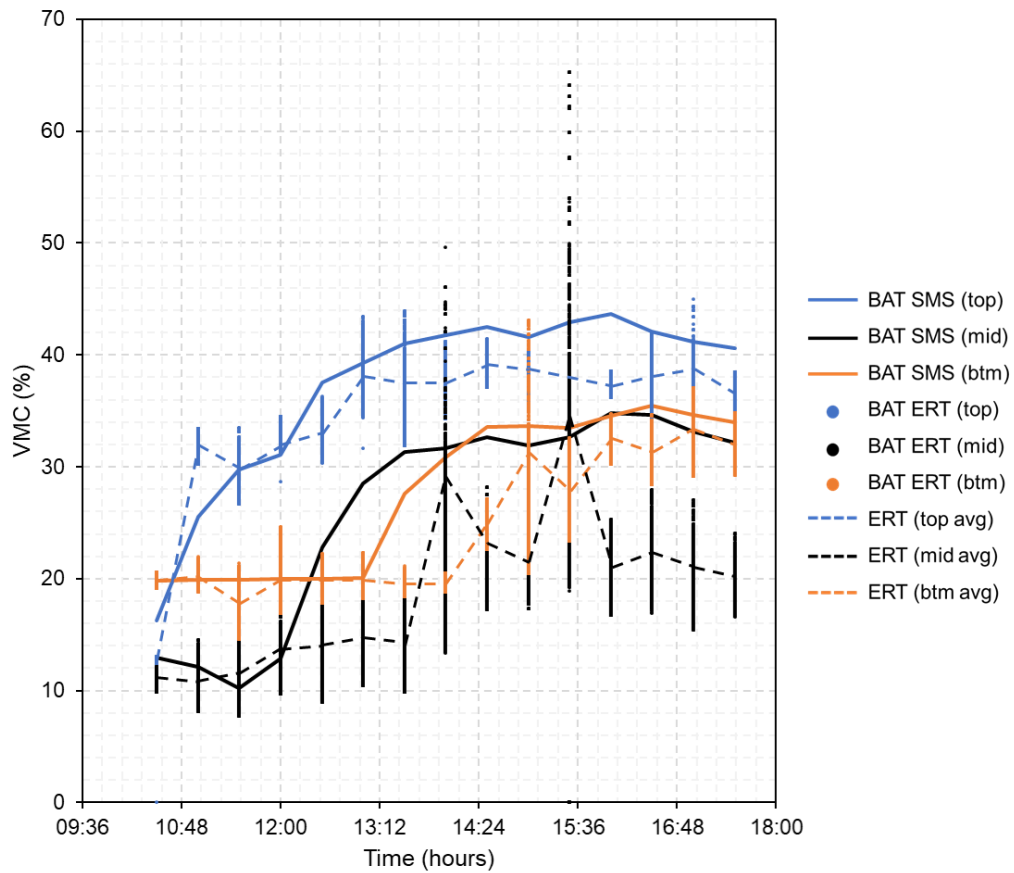


Figure 4. 64 Changes in volumetric moisture content (VMC) during a storm simulation on Bourne Amenity Topsoil (BAT). Data is measured by the soil moisture sensors (SMS) and ERT calibration at the top, middle and bottom of the soil profile.

VMC data comparing measurements taken by the point sensors and ERT calibration are plotted in two separate graphs (Figures 4.65 and 4.66). Data from Figure 4.65 shows changes in VMC that occurred on the day of the storm. Little to no changes in VMC were detected during the electrical survey until 16:30, when the ponded water could migrate through the near surface of the soil. SMS data indicates that moisture levels from the soil surface to approximately -150mm increased at 13:00. This surface water breakthrough was not captured simultaneously in the electrical survey. However, a significant uptick in moisture content was observed at 16:00 in the ERT data. Overall, the SMS data is higher than measurements taken during the ERT survey, except for data collected from the bottom of the soil column, which shows that SMS data sits within the envelope of ERT measurements.

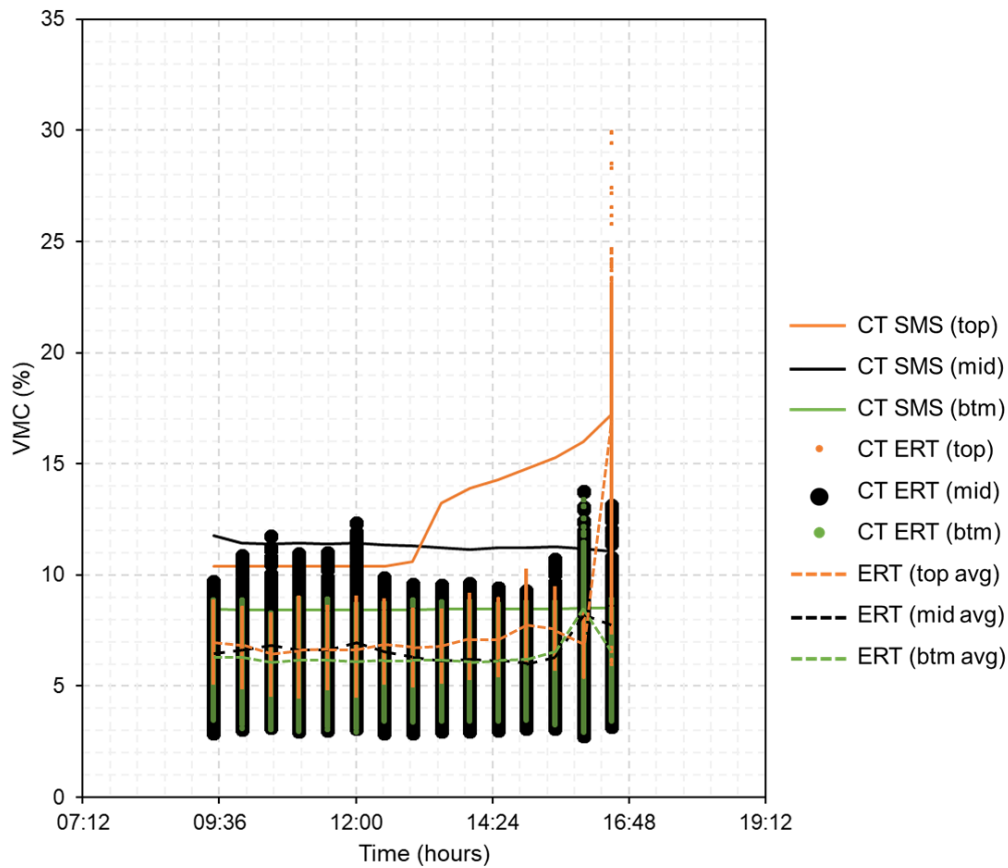


Figure 4. 65 The VMC of soil moisture sensors (SMS) located at the top, middle, and bottom of the soil profile during soil column experiments performed on clay topsoil (CT) during the simulated storm. Data compares the VMC collected from SMSs and the calibrated ERT data during the storm.

Figure 4.66 compares the changes in VMC captured by the SMS and ERT array on day 2, one day after the storm. Similar to the VMC time-lapse survey shown in Figure 4.61, there is little change in the spatial distribution of moisture content that day. This is reflected in the SMS data in Figure 4.66. There is an increase in soil moisture content in the middle of the soil profile from 12% to 26% throughout the morning until 14:30. This change in soil moisture content could account for the two spikes in VMC measured at 11:30 and 14:00. These sudden increases in VMC were observed as artefacts in the inversion. Possibly, the changes in moisture content focused on the middle section of soil incurred artefacts either due to a volume change in the survey area of a soil moisture contrast between the middle and upper/lower regions of material, causing the inversion to interpret the transfer resistances and the subsequent PLF model incorrectly. Despite this, SMS data in the middle and top of the column are within the envelope

of ERT measurements. However, ERT measurements from the middle of the column vary considerably due to the broad spectrum of MC values per cell. SMS data at the base of the soil (SMS btm) are higher than those plotted from the ERT measurements, but both still reflect the minor change in moisture content that occurred throughout day 2. When discussing the data from Figure 4.61 (VMC timelapse of CT), it was noted that some elements beneath the wetting front (towards the base of the soil column) could be artificial values. The significant difference in moisture content between the bottom SMS and bottom ERT measurements could reflect these artefacts in the results.

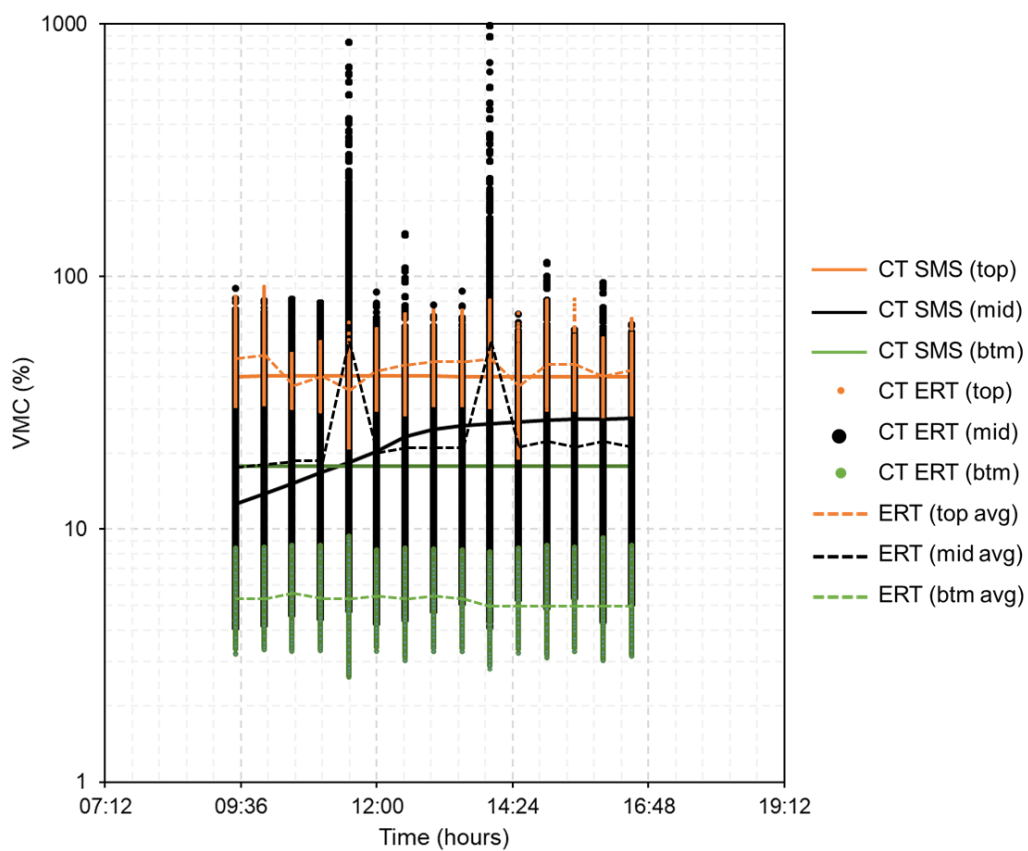


Figure 4. 66 A graph showing the VMC of soil moisture sensors (SMS) located at the top, middle, and bottom of the soil profile during soil column experiments performed on clay topsoil (CT) the day after the simulated storm (day 2). Data compares the VMC collected from SMSs and the calibrated ERT data during the daytime measurement window of the PRIME system.

4.12.4 Series 2 Bourne Amenity Topsoil Column Experiment

A time-lapse image series showing changes in volumetric moisture content (VMC) in the Bourne Amenity Topsoil (BAT) produced mixed results. Section 4.11 highlights the prevalence of artefacts that appear in the inversion due to soil moisture contrasts/survey volume changes. However, the decision was made to convert resistivity to VMC as artefacts were reduced as the wetting front progressed. Figure 4.67 compares the VMC measured by the soil moisture sensors (SMS) to cell data from the time-lapse ERT model. The range of values at each timestep from the ERT data accounts for the number of cells within the volume of influence of each SMS (located at 100mm, 250mm and 400mm within the soil profile. During the simulated storm, ERT values of VMC are lower than those measured by the moisture sensors. As water is added to the soil throughout the storm, moisture levels in the middle of the soil profile increase, resulting in cell data from the ERT survey sitting within the range of data captured by the SMS. Throughout the experiment, data from the middle of the soil columns remains within the range of measurements recorded by the moisture sensor at the middle of the column (250mm from the base/surface of the soil). However, moisture content in the middle section of the soil generally increases throughout the wetting event. At 13:00, moisture content falls slightly. This is captured in both the SMS data and ERT survey. At the top of the soil profile (between 50mm and 150mm depth), measurements from the ERT survey are lower than those recorded by the top SMS located at a depth of 100mm. However, from 13:30 to 17:30, SMS measurements are within the envelope of cell data measured in the time-lapse survey. At the base of the soil (between 350mm and 450mm), cell data from the ERT survey is lower than measurements made by the bottom SMS (400mm depth) until 15:00, where measurements are situated within range of the SMS. Averaging the ERT-derived VMC at each timestep of the storm shows that ERT data corresponds with the SMS measurements. They are not the same; however, they follow a similar trend.

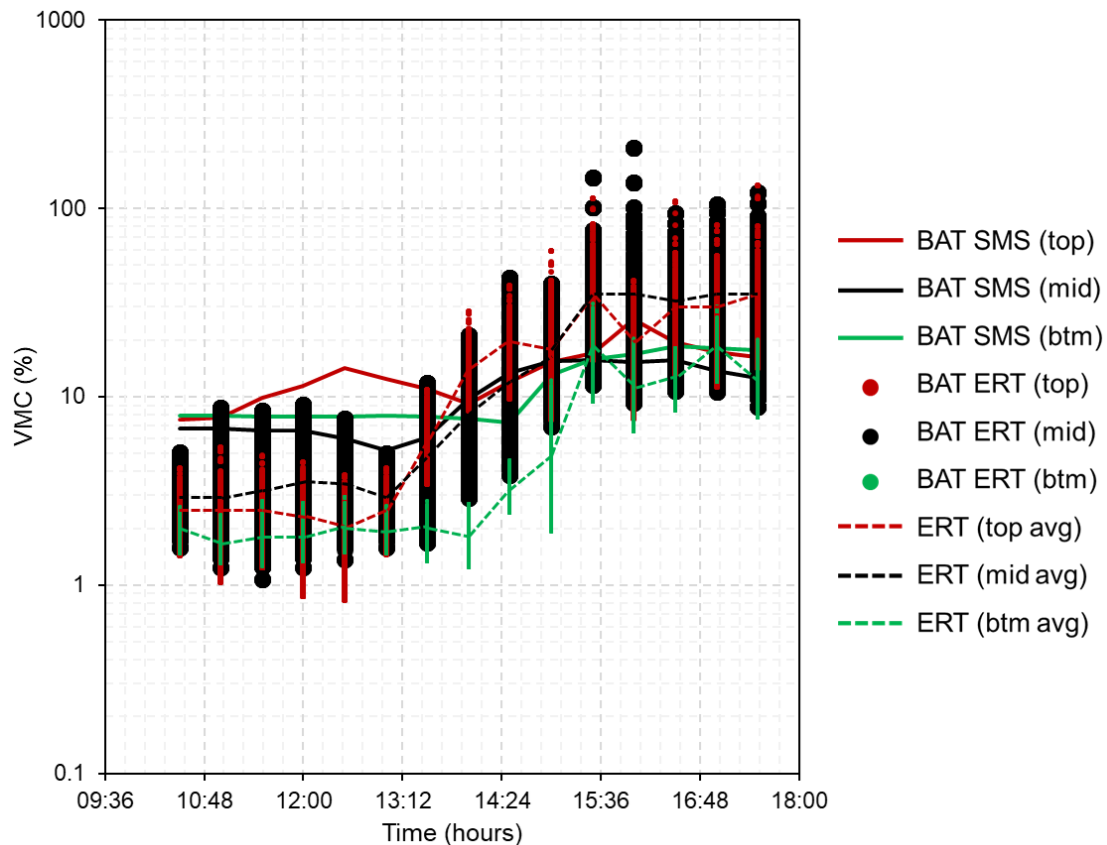


Figure 4. 67 A graph showing the VMC of the Bourne Amenity Topsoil (BAT) measured by the soil moisture sensors (SMS) located at the top, middle, and bottom of the soil profile compared to the VMC derived from the calibrated ERT data.

The time-lapse survey of spatial distributions in VMC in the BAT is shown in Figure 4.68. The survey provides a side-by-side cross-section analysis of spatial distributions in resistivity and VMC. Scaling changes in VMC to best provide a visualisation of change in moisture content/resistivity during the wetting event was challenging. Despite moisture levels exceeding 10%, a scale from 0% to 10% was used to visually indicate the progress of the wetting front. However, a second time-lapse is provided in Figure 4.69, which increases the scale to analyse changes in the soil-moisture dynamics from 15:30 to 17:30 (the end of the storm) in greater detail.

The time-lapse survey explains why moisture content at the top and base of the soil profile is lower than those recorded by the SMSs up to a certain point. At 10:30, before the simulated storm, the timestep showcases several artefacts differently. At the soil surface and base of the material, areas of high resistivity/low moisture content are observed to extend towards the

middle of the soil column. In contrast, small, localised regions of lower resistivity/higher moisture content are observed at the site of electrodes located between -180 and -300mm depth. This is shown in greater detail in caption (A) in Figure 4.68, where the scale of moisture content is reduced, and a view of the soil column wall is also provided to better observe artefacts close to the electrodes. The presence of these artefacts is discussed in Section 4.11, where analysis of transfer resistances establishes that artefacts resulted from the inversion process, likely attributed to unaccounted complexities in the geosynthetic mesh at the site of the electrodes. This is supported by the fact that these artefacts continued to become more apparent at 11:00, despite the water being added to the soil before 11:25. The presence of artefacts at the top and base of the soil accounts for why the VMC measured by the ERT survey is lower than measurements made by the moisture sensors. Given that the artefacts present as areas of high resistivity, this is captured in the calibrated ERT model, which shows that moisture levels are lower than they are. At 13:30, a significant change in moisture content from the soil surface to approximately -250mm depth is recorded. This change is also observed in the graph provided in Figure 4.68. From 13:30 to 15:30, the wetting front progresses through the soil profile to the base of the column.

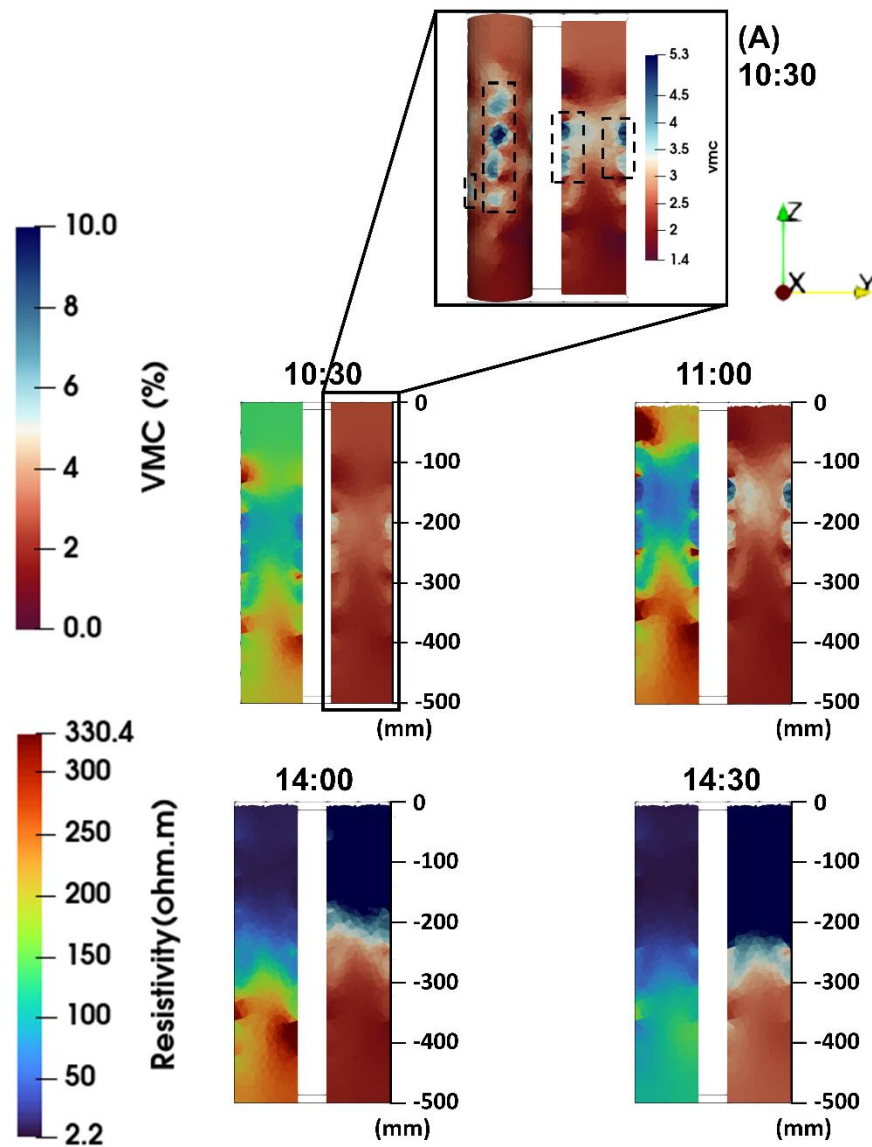


Figure 4. 68 A time-lapse survey of the spatial distribution of VMC (right of each timestep) and resistivity (left of each timestep) in BAT during a storm simulation (day 1). Caption (A) provides a scaled view of artefacts present at the start of the survey.

Figure 4.69 shows changes in VMC at a reduced scale between 0% and 10%. Much of the details regarding the spatial distribution of moisture content within the wetting front are lost after 15:30 as the wetting front at 10% moisture content has reached the base of the column. Therefore, a second time-lapse survey from 15:30 – 17:30 (the end of the simulated storm) was produced that was scaled from 0% to 40% (Figure 4.70). Increasing the scale has provided greater insight into the distribution of VMC in the column experiment. At 15:30, the data suggests that water preferentially migrates along the column wall towards the right-hand side. Moving away from the column wall leftwards, moisture levels decrease from 40% to 18% above a depth of -300mm. From -300mm to -500mm (the soil base), moisture contents are 10-15%. At 16:00, a low VMC region emerges towards -85mm from the soil surface. This is likely a product of artefacts in the inversion and not actual measurements, given that the data suggests that moisture content from 15:30 to 16:00 at the soil surface decreased from 40% to 8%-15%. By 16:30, artefacts at the soil surface are reduced, and moisture levels between -100mm and -200mm have increased. From 16:30 to 17:30, a region of high moisture content ($\geq 40\%$) forms from the right column wall, extending towards the left side between -100mm and -200mm.

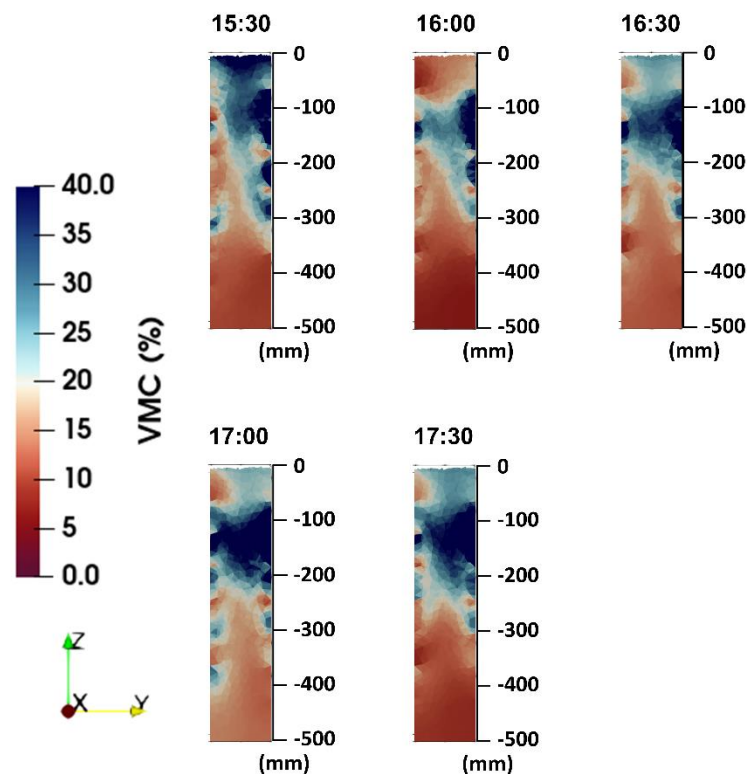


Figure 4. 69 A time-lapse survey showcasing the spatial distribution of VMC in BAT from 15:30 – 17:30 during the wetting event. The time series is a continuation of Figure 4.68 but scaled to a moisture content of 40%.

4.12.5 Series 2 Sand Column Experiment

Section 4.10 presents a time-lapse survey of the sand-filled column, depicting the spatial distribution of resistivity and the percentage change in resistance during the six-hour storm simulation. A condensed version of that survey is provided in Figure 4.70. A logarithmic scale was necessary to provide a detailed visual representation of changes in resistivity over time, as cells in the inversion exceed 5000 ohm.m due to the high contact resistances and reciprocal errors in effect during the inversion process. Despite these difficulties, a wetting front was discernible in the electrical survey. The survey shows that the percentage difference in resistivity decreases by $\geq -100\%$ throughout the soil profile once water is added to the soil column. By 11:30, modelling the percentage difference in resistivity provides very little information on the changes in soil moisture dynamics during the remaining hours of the simulated storm. Imaging of the spatial distributions in resistivity was more informative. The survey indicates that a noticeable reduction in resistivity first occurs at the base of the soil profile (at 11:30-13:00). This is in line with the conditions of the experiment, as the drainage valve at the base of the column is closed during the simulated storm. Previous ERT experiments on granular soils reveal that the PRIME system could not perform a forward and reciprocal measurement fast enough to account for a sudden change in resistivity as water drains through the sand. Therefore, throughout the experiment, the water release valve at the base of the column is closed due to the hydraulic conductivity of the sand. The valve is opened towards the end of the experiment (17:00), reflected in the survey, showing an increase in electrical resistivity between 15:00 and 17:30.

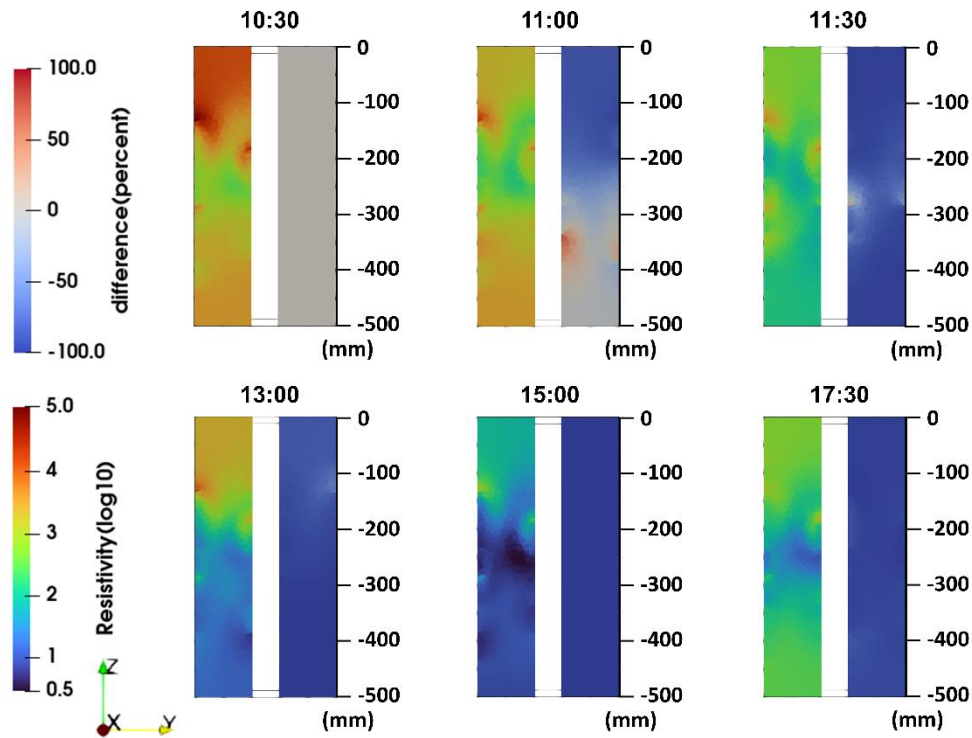
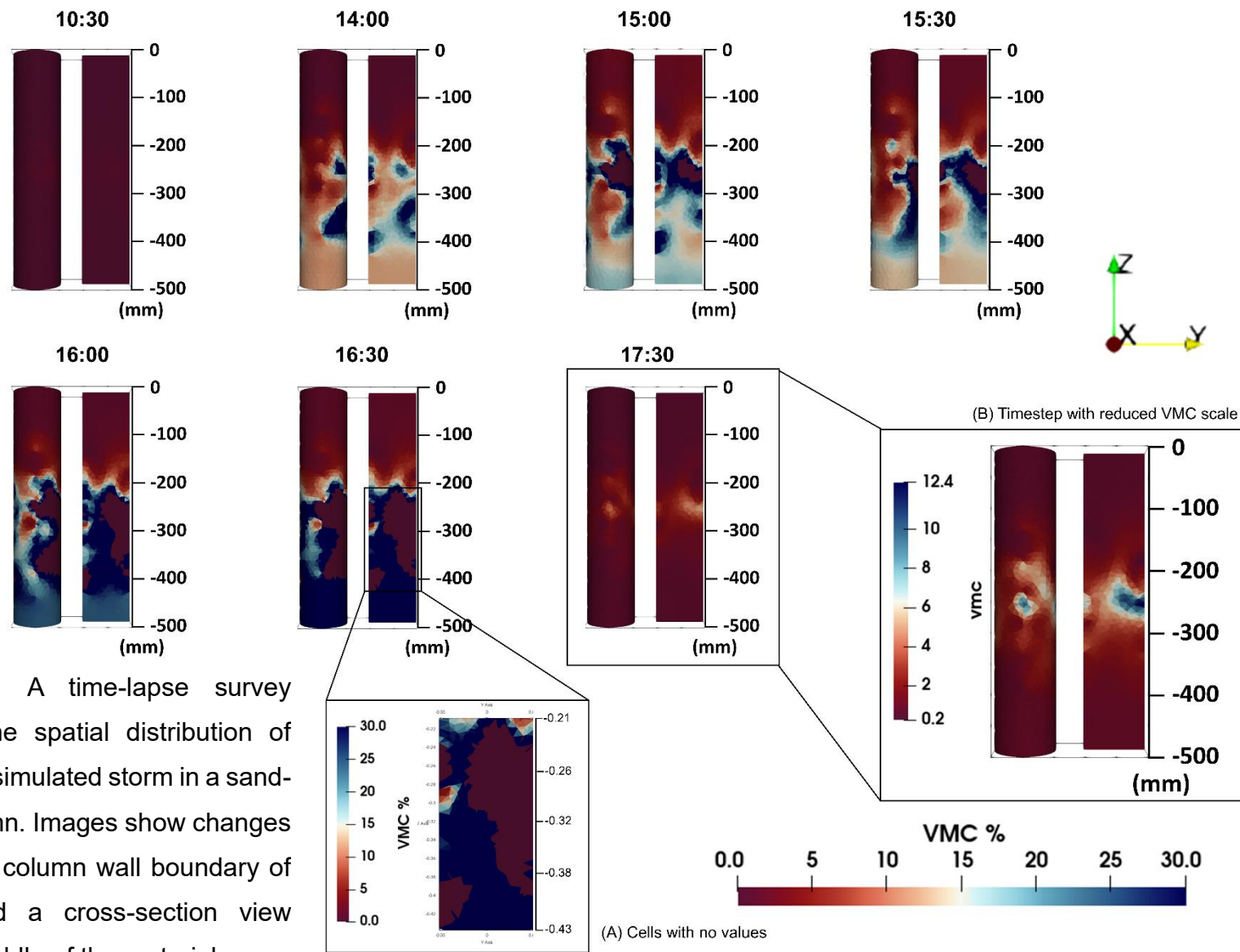


Figure 4.70 A sample of the time-lapse survey of the sand-filled soil column (Series 2) during a simulated storm. The data shows the spatial distribution in electrical resistivity (left of each timestep) alongside the percentage difference in resistivity (right of each timestep).

A PLF model converts electrical resistivity to VMC in the sand-filled column experiment (Figure 4.71). The time-lapse survey shows the change in VMC during the storm at the column wall boundary of the sand and a cross-section view through the middle of the material. The survey shows the VMC of the sand at the start of the experiment (10:30), indicating that moisture content was low (between 0% and 1.2%). No visual changes in moisture content were observed until 14:00 when moisture content from the base of the soil to -220mm depth increased between 15% and 25%. As water is added to the column during the six-hour storm, moisture content increases from the base of the column up. By 16:30, moisture content between -500mm and -200mm was $\geq 30\%$. In multiple timesteps and seen in Caption (A) in Figure 4.71, areas of dark red are observed in the inversion, which indicates cells that have not been assigned a VMC value. Like the time-lapse survey provided in Figure 4.70, timesteps taken at the end of the experiment (17:30) show a reduction in moisture content as the column is drained of water. Caption (B) provides a scaled perspective of the soil column drained of water.

By modelling the VMC of the sand during the storm event, a more detailed interpretation of changes in soil moisture dynamics can be compared to the resistivity data showcased in Figure

4.71. Due to the many cells in the inversion having resistivity values far exceeding 1000 ohm.m, it was necessary to visually represent the spatial distributions in resistivity using a logarithmic scale. However, by doing so, much of the details regarding changes in soil electrical resistivity are missing. This is also evident when looking at the percentage difference in resistivity throughout the simulated storm. By 11:00, moisture content in the column has increased to $\geq 100\%$. As a result, the percentage difference in resistivity changes is difficult to discern from the time-lapse ERT images. By modelling VMC, a more detailed analysis of changes in the soil moisture dynamics of the sand is provided, which is not seen in the resistivity and percentage difference in resistivity ERT images given in Figure 4.70 compared to Figure 4.71.



A graph comparing the VMC of the sand in the soil column experiment measured by the SMSs and the calibrated ERT model is given in Figure 4.72. Like data collected from the BAT (see Figure 4.67), measurements taken by the SMSs at the start of the experiment (before water was added to the sand) are higher than measurements derived from the electrical survey. This is likely a result of the high contact resistances between the electrodes and the sand that, therefore, did not accurately represent the resistivity of the material. As water is added to the sand, the VMC captured by the electrical survey increases and measurements coincide with those taken by the SMSs.

ERT measurements indicate that moisture levels in the middle and bottom sections of the column increase more than the top of the soil profile. These increases in moisture content are less noticeable in the sensor data. However, data collected from the electrical survey reflects the potential volume of influence of each sensor and considers the moisture content of each cell or element within that zone. Therefore, the range of potential moisture content values is significantly higher in the ERT-derived VMC data. Despite the differences between the two measurement systems (ERT and SMSs), the decrease in VMC is observed in the ERT (btm) and SMS (btm) when the drainage valve was opened to allow water to drain from the sand into the collection tray below the soil column setup.

The graph shows that at the various depths where VMC was plotted, data collected from the SMSs occasionally coincides with measurements from the time-lapse survey. However, there are evident discrepancies between the different measurement systems. These discrepancies could be attributed to several factors:

1. Artefacts in the electrical resistivity inversion ultimately resulted in the true resistivity of the sand not being correctly interpreted.
2. Not enough measurements were taken when plotting the VMC-resistivity relationship of the sand, resulting in inaccurate parameters for the fitted curve.
3. The SMSs took measurements from a separate column to the electrode array. Although the conditions of the columns were the same, there were likely differences in the soil moisture dynamics, e.g., water flow pathways.

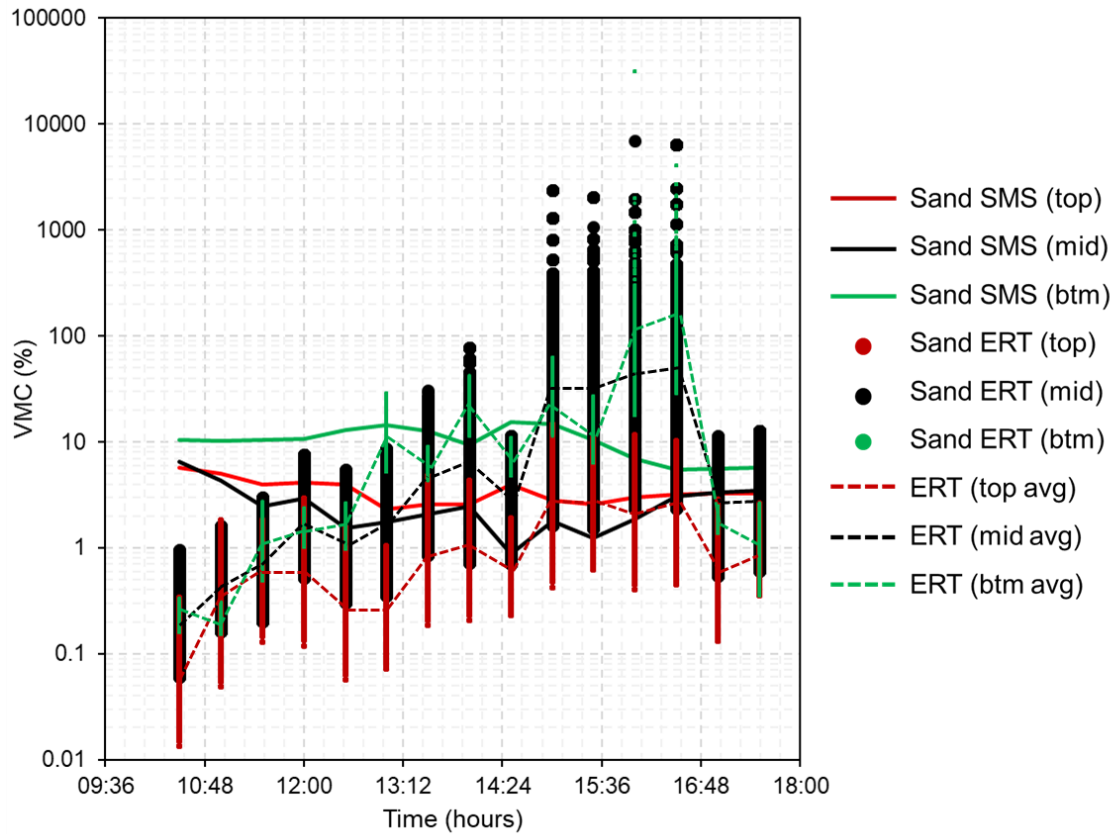


Figure 4.72 A graph showing the VMC of sand measured by the soil moisture sensors (SMS) located at the top, middle (mid), and bottom (btm) of the sand compared to the VMC derived from the calibrated ERT data.

4.12.6 Series 2 Clay Topsoil Column Experiment

Like previous time-lapse surveys (sand and BAT), artefacts are present in the 4D ERT imaging of clay topsoil (CT) during the storm. However, they subsided once moisture levels increased and a wetting front was visible in the modelled data. Figure 4.73 provides a snapshot of the electrical resistivity through time, as shown in Section 4.4.3. The data shows a cross-section of the soil column with images representing the spatial distribution in resistivity and the percentage difference in resistivity during the six-hour storm simulation. The survey demonstrates that artefacts, like those observed in the forward modelling exercise (see section 4.6), are present when water was added to the soil (see timestep 12:00, Figure 4.73). The artefacts present as regions of high resistivity extending from the soil surface and base towards the centre of the soil. It is not until 16:00 that artefacts are reduced, and a wetting front becomes visible.

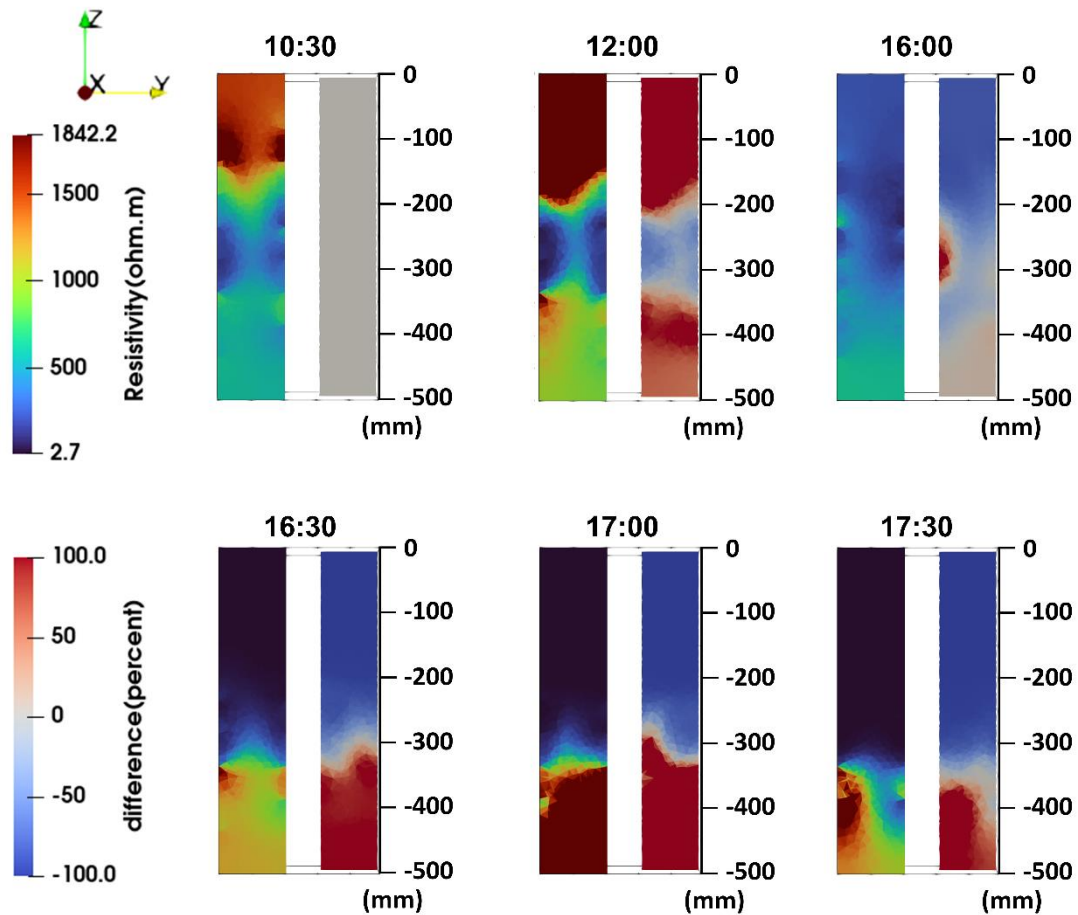


Figure 4.73 A time-lapse survey showcasing the spatial distribution of resistivity (left of each timestep) alongside the percentage difference in resistivity (right of each timestep). Data was collected from the clay topsoil experiment (Section 4.4.3) during a six-hour simulated storm.

The artefacts that appeared in the resistivity time-lapse survey were also present in the calibrated VMC imaging (Figure 4.74). Timesteps at 10:30 (before the storm) and 12:30 (during the storm) show the distinct pattern of artefacts previously observed in the forward modelling exercises and other time-lapse inversions (Section 4.6). At 16:00, many artefacts disappear from the inversion, and moisture content varies between 11% and 20.9% from the soil surface to -300mm depth and between 6% and 10% below -300mm. At 16:30, the moisture content from the soil surface to -300mm exceeded 20%. The VMC scale of the time-lapse survey is set between 0% and 20% moisture content to visualise more clearly increases in moisture content from the start of the experiment to the end of the storm. However, by 16:30, no further changes in VMC are captured at this scale.

In the ERT survey provided, images of the spatial distribution of VMC in the soil are given on increased scales between 16:30 and 17:30 to observe changes in VMC in greater detail. At 16:30, moisture content from the soil surface to -200mm depth is between 48.7% and 30%. The inversions suggest that water has percolated to a greater depth on the right side of the cross-section view of the soil column than on the left side. Between -200mm and -300mm, moisture content varies between 17% and 27%. From the base of the soil (-500m) to -300mm depth, moisture content decreases to 6.8%. At 17:00, moisture content from the soil surface towards the base of the soil decreases from 75% to 3.6%. At 17:30, moisture content from the soil surface is lower than recorded measurements at 17:00. However, the wetting front has progressed to -300mm, where previously a contrast in moisture levels had existed at -200mm, as seen in timesteps 16:30 and 17:00.

The reliability of measurements made beneath the wetting front, where VMC falls below 10%, is uncertain. In Figure 4.74, the percentage difference in resistivity imaging suggests that between 16:30 and 17:30, resistivity beneath the wetting front (seen in blue as $\geq -100\%$) has decreased by 100%. This is not possible, given that no drainage has occurred at the base of the column to account for such a significant drop in resistivity. Instead, it is far more likely that, due to the moisture contrast between the less resistive, overlying soil and the more resistive underlying material, the inversion has failed to accurately interpret the moisture content of the drier soil.

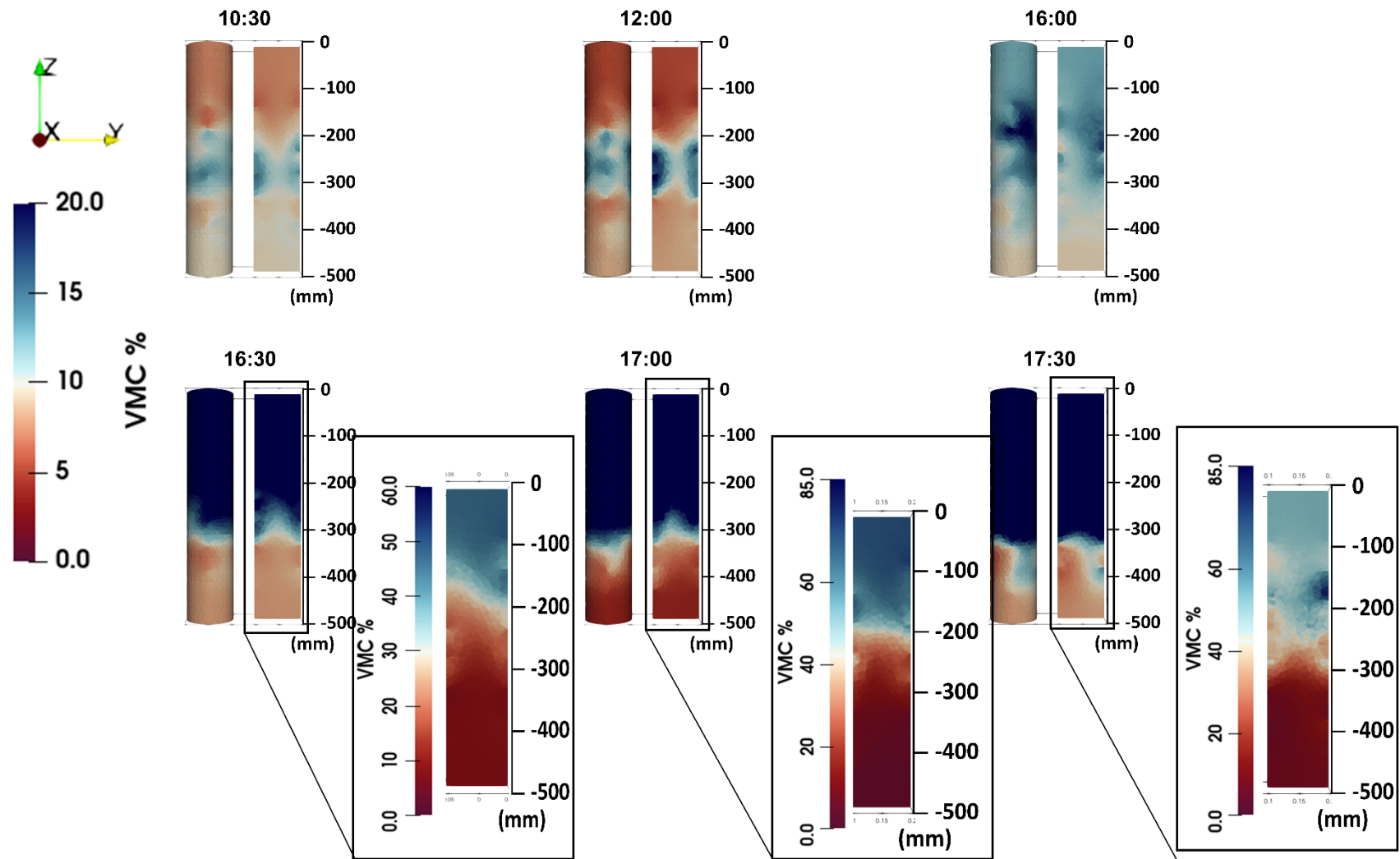


Figure 4. 74 A time-lapse survey of the spatial distributions in moisture content in CT (clay topsoil) during a simulated six-hour storm. The data shows changes in VMC at the column wall (left of each timestep) and through the middle of the soil column (right of each timestep).

The graph in Figure 4.75 shows changes in VMC during the storm event. Data shows measurements made by the SMSs and ERT array. By comparing measurements made at -100mm (top) in red by the SMSs and calibrated ERT model, the moisture sensor establishes that VMC increases throughout the wetting event. However, the ERT measurements suggest that moisture content decreases between 11:00 and 14:00 before increasing to between 37.6% and 66.4% by the end of the experiment. The ERT measurements do not correlate with the SMS measurements because artefacts were present at the top of the soil profile (-100mm) when water was added to the material.

It appears that once moisture content in the soil had reached a certain threshold, artefacts in the inversion diminish, and a more accurate record of the VMC/resistivity of the soil is depicted. This is seen in Figure 4.74, which shows that by 16:00, artefacts were no longer present in the imaging. In the middle (-250mm) of the soil column, SMS measurements between 10:30 and 12:00 are within range of each other. A reduction in moisture content is observed in the ERT data (CT ERT, mid), but it is less extreme than the decrease captured by the SMS. Between 13:30 and 15:30, moisture content increases from 4.5% to 53.2%. Again, a noticeable increase in moisture content is observed in the ERT measurements but is more gradual than measurements made by the moisture sensor.

Comparing the SMS (btm) to the ERT (btm) shows that data from the calibrated ERT model is lower throughout the experiment. The SMS measures an increase in moisture content from 13:30 to 17:30, from 15.0% to 24.3%. The ERT data shows the opposite, suggesting that moisture content decreased. Discrepancies between SMS and ERT measurements at the bottom of the soil profile (-400mm) are a product of artefacts in the inversion.

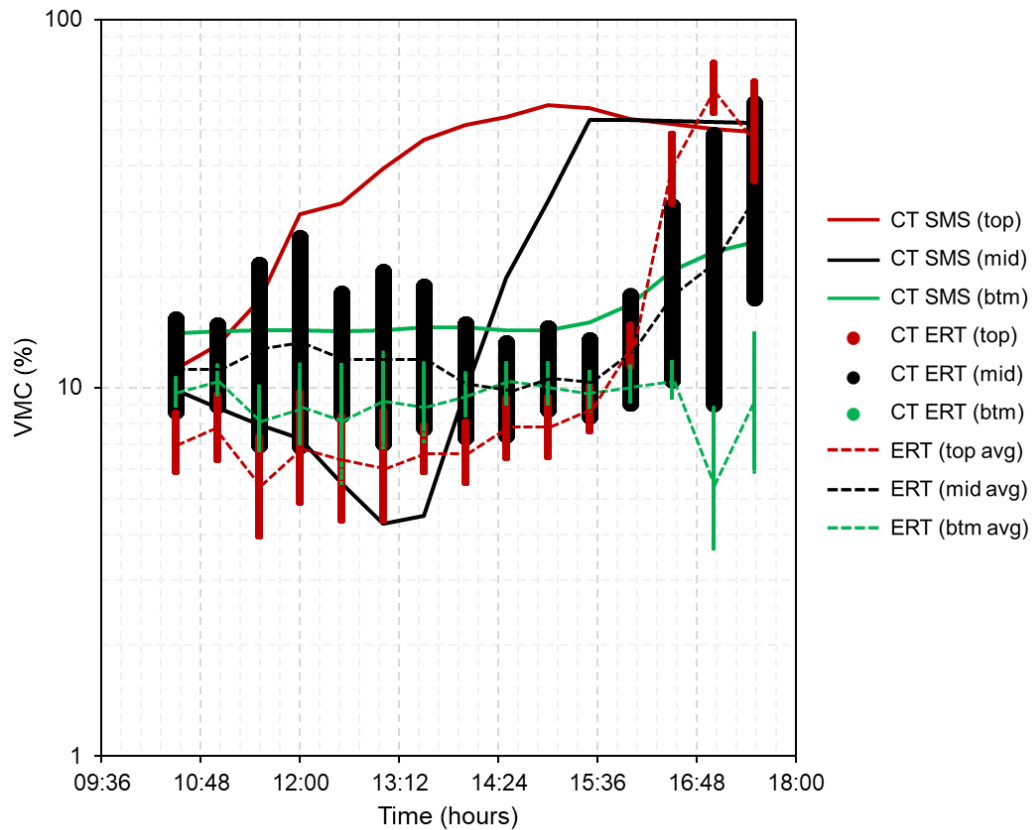


Figure 4.75 A graph showing the VMC of the clay topsoil (CT) measured by the soil moisture sensors (SMS) located at the top, middle (mid), and bottom (btm) of the soil profile compared to the VMC derived from the calibrated ERT data.

4.12.7 Soil Suction – Electrical Resistivity Relationship

Soil suction and conductivity were measured directly in the modified HYPROP 2 experiments. However, this was not the case for soils in Series 2, where a salt tracer was used during the simulated storm events. Of the Series 1 soils (sand, clay topsoil and topsoil), data from the clay topsoil (CT) and Bourne Amenity topsoil (BAT) experiments were tested to model spatial distributions in soil suction through time. Figure 4.76 plots the CT and BAT (BAT) soil suction-electrical resistivity with the fitted van Genuchten curves.

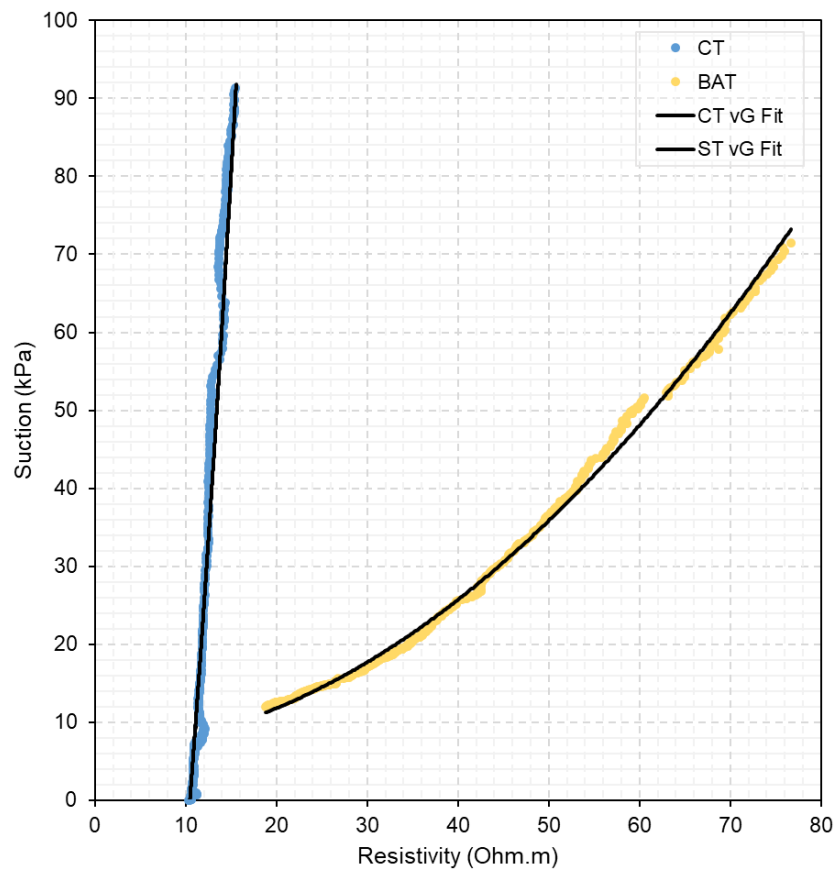


Figure 4. 76 Soil suction versus electrical resistivity and fitted curves according to Equation [19]. Clay topsoil is CT, Bourne Amenity topsoil is BAT, and vG refers to the van Genuchten fitted curve.

The calibration curves for both soils were used to convert conductivity to soil suction. However, it proved ineffective when applied to CT. Looking at the graph (Figure 4.77, CT), the data shows that soil suction changes significantly compared to electrical resistivity and, likewise, conductivity. This is not an uncommon feature of suction-resistivity curves, e.g., Figure 4.78, which shows that the SFF (Staithes Sandstone Formation), a slightly sandy clay, exhibited high suction increases over a relatively small increase in resistivity. However, this clay-rich material was procured directly from a site prone to landslides (Boyd et al., 2024). Therefore, during field observations, soil moisture content changes due to rainfall, and the resultant changes to soil suction and electrical resistivity were within the range of resistivities observed in the plotted data (Figure 4.77). This was not the case for the soil column experiment on clay topsoil. Changes in electrical resistivity far exceeded measurements derived from the HYPROP experiment owing to the simulation of a 1 in 100 storm event. This caused ParaView to assign impossible values to the calibrated suction cells.

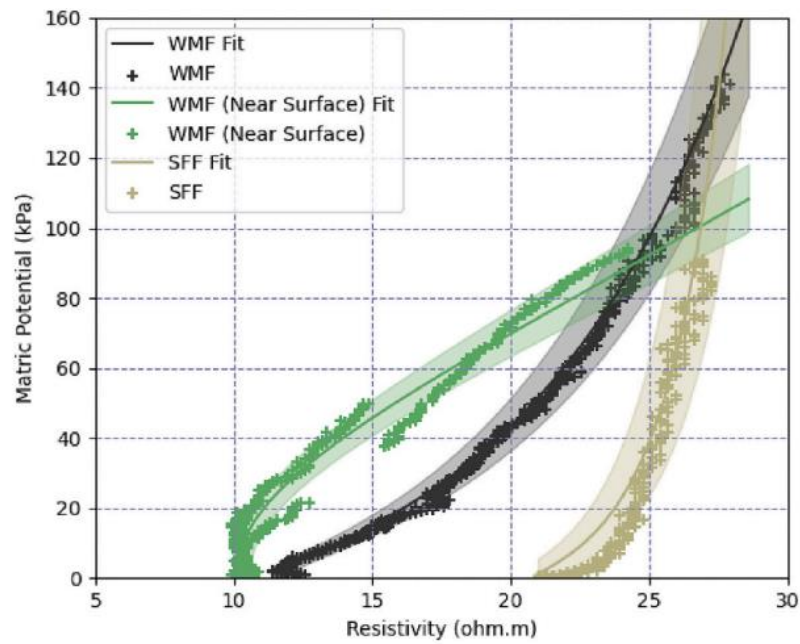


Figure 4. 77 Soil suction versus electrical resistivity and fitted curves. WMF is the Whitby Mudstone Formation, and SSF is the Staithes Sandstone Formation (Boyd et al., 2024).

Figure 4.78 gives an example of the calibration curve failing to calculate soil suction accurately. Here, two cells were selected based on their measured conductivity. The timestep was taken at hour 6 of the simulated storm. As water content increased from the soil surface to approximately -170mm depth, conductivity was measured as 54.89 mS/m. This value far exceeds the bounds of the calibration curve, which assigns a suction of 6277.76 kPa. In contrast, the second highlighted point at a depth of approximately -330mm has a conductivity of 9.09 mS/m. This value sits within the range of the fitted data and exhibits a conductivity and suction value similar to the graph.

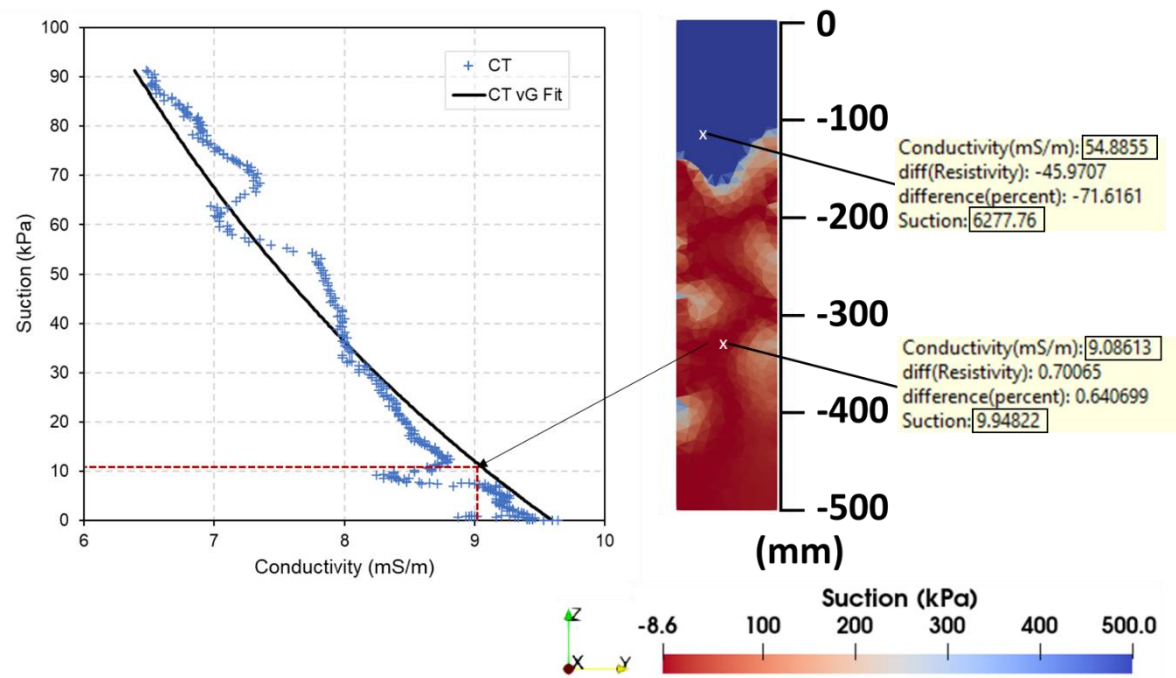


Figure 4.78 Soil suction versus conductivity of clay topsoil (CT) with fitted curve alongside an image of the spatial distribution of suction from the inversion of CT highlighting two conductivity/suction cell measurements.

In the BAT column experiment, calibrating electrical conductivity to soil suction was more successful. Figure 4.79 provides a timelapse of the column experiment during a simulated storm. Like previously showcased soil column inversions, the imaging displays regions of suspected artefacts (e.g., hour 1). However, despite this, the survey shows a relative decrease in soil suction as the wetting event progresses until hour 4 when no significant visual changes in soil suction were detected.

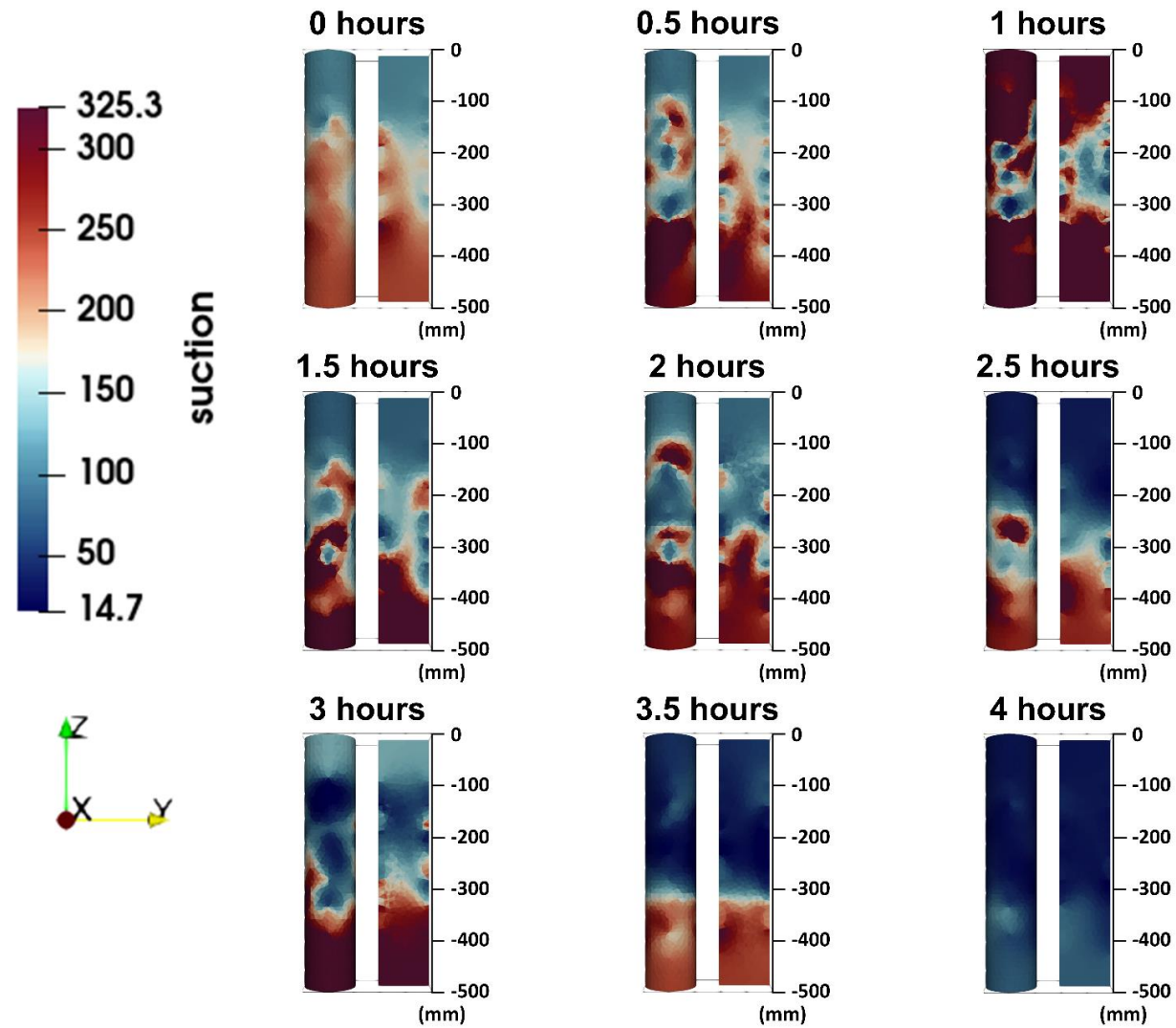


Figure 4. 79 A time-lapse survey depicting the spatial distribution of soil suction during a simulated storm. Data was collected from the BAT experiment (Series 1).

Figure 4.80 shows the changes in soil suction in the BAT column experiment during a storm simulation measured by the point sensors and ERT. Given the large amount of data collected from the ERT images, the average suction is given on the graph. Measurements made at the top of the soil by the point sensors display similarities to the ERT-derived values. At 11:30, soil suction in the column increases despite adding the stormwater to the column. This is due to modelling artefacts caused by the soil moisture contrast generated by the initial watering event. Suction returns to reasonable levels after 11:30. At the end of the storm (17:30), suction measured by the point sensor and ERT are similar.

In the middle of the column, soil suction measurements made by the point sensor are similar to those in the ERT survey. Average ERT measurements demonstrate that values are close to or cross with SMS data. Unlike ERT top measurements, unusual suction changes do not occur that would suggest artefacts. This is also seen in the ERT images in Figure 4.79, which show that high soil suction contrasts are not present at 250mm (the location of the middle SMS).

At the bottom of the soil column, ERT values are noticeably higher than point sensor measurements at the start of the experiment (10:30) to 14:00. ERT images in Figure 4.79 indicate that modelling artefacts are present throughout the survey in the bottom section of the column which would explain the high suction readings expressed in the data below. At 14:30, as artefacts diminish, ERT suction values are similar to those observed in the point sensor data and fall beneath them until 17:00. By 17:30 (the end of the storm), ERT and point sensor measurements are similar.

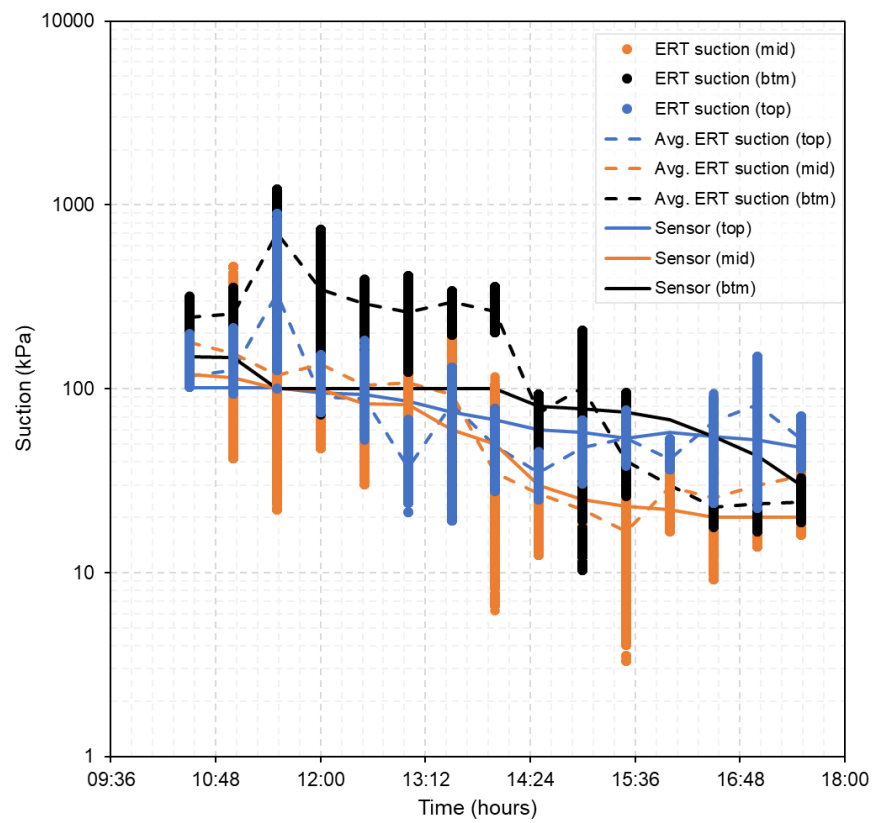


Figure 4. 80 Changes in soil suction in the BAT during a simulated storm. The data compare measurements made by the point sensors with ERT-derived values.

Chapter 5 Discussion

ERT data collected between December 2022 and August 2023 (referred to here as Series 1) are from (1) the gravel-filled Capillary Barrier System (CBS), (2) sand-filled CBS, (3) compacted clay-topsoil (CT), and (4) Bourne Amenity topsoil (BAT) columns. In Section 3.5 of the methodology, two methods of soil column tests are provided. This was due to learning from initial tests (Series 1), which showed that changes to the soil column and experimental conduct were required to improve the quality of time-lapse imaging results for subsequent tests (Series 2). Section 3.5.2 provides time-lapse images of a topsoil-filled soil column demonstrating the effects of adding water to the modelled data and outlining the subsequent changes to the experimental parameters. A total of 12 soil column experiments were completed, and artefacts from the inversions appeared in the modelled data at various stages of each experiment. These artefacts would appear as highly resistive elements that did not accurately portray the expected (or realistic) spatial distributions in resistivity. When conducting each soil column experiment, the origin and cause of these artefacts were unknown. Therefore, informed decisions were made regarding the column design, data processing and modelling to reduce or eliminate the occurrences of artefacts.

Given the presence of these artefacts, a second set of column experiments (Series 2) were performed on sand, CT, and BAT. In Series 2, changes were made to the methodology to reduce modelling errors during pre-processing (see Section 3.6). Furthermore, the soil column design was adjusted to include a surface water runoff tube to prevent ponding during the experiments.

Alongside time-lapse surveys, point sensor data was collected to assess the reliability of the 4D ERT imaging in accurately showing changes in spatial distributions of resistivity. Therefore, moisture data is also analysed to inform the soil moisture dynamics throughout each experiment and then compared to the results of the electrical surveys. Appendix B contains a sample of point sensor data specific to changes in moisture content during a simulated storm event in a sand-filled soil column experiment. Owing to the significant amount of data gathered and processed throughout these experiments, it was not feasible to submit all measurements from the point sensors. Therefore, data was uploaded to data.ncl.ac.uk, where the data can be viewed in its entirety.

A baseline-constrained inversion is applied to all the soil column geoelectrical data. This was selected over a difference inversion as the appearance of artefacts in a time-lapse survey would

vary from timestep to timestep. Therefore, comparing changes in electrical resistivity to the baseline image was more suitable than modelling resistivity off subsequent timesteps. Capturing an increase in electrical resistivity in the drying phase of the experiments proved ineffective because a baseline-constrained inversion was used. The reference images used in these experiments typically have high transfer resistances. Therefore, the soil would have to dry significantly after the storm before visual changes in electrical resistivity are observed in the time-lapse survey. Given the number of column experiments and the time limitations of the study, there was not sufficient time for the soils to dry out to record increases in electrical resistivity after a storm. Furthermore, modelling geoelectrical data >30 days would have required superior computational power than what was available.

A reciprocal error filter of 5% is applied to all the data in both series, except for the gravel and sand-filled CBSs in Series 1 and the Sand-filled soil column in Series 2. Given the occurrence of high contact resistances at larger grain sizes, efforts to filter the data at 5% would result in software crashes. In Series 2, the sand-filled column is filtered at 25%, with some timesteps filtered at 50% due to software crashes. However, for the CBSs, no reciprocal filtering was applied to the data, as any attempt to reduce the error probability would result in programme failure. Software crashes and systematic failures to model the data due to exceptionally high error probability distributions demonstrate the importance of reciprocal filtering and the necessity to consider percentage error when conducting 4D electrical surveys in soil columns. Not including reciprocal filtering is highly inadvisable when conducting an electrical survey as it significantly increases the inaccuracy of modelled data. Given this, the CBS data demonstrates the problems when producing time-lapse resistivity surveys of granular material in soil columns.

The presence of artefacts in the data was assumed to be a product of sub-optimal soil conditions before testing, leading to high CRs. Theoretically, if the soil in the columns was fine-grained and had a high starting moisture content, CRs would be low, and artefacts would be reduced. However, even at lower starting CRs, artefacts were observed in soil column experiments conducted on clay topsoil and topsoil. To identify if the artefacts observed in the ERT measurements resulted from modelling errors or actual resistivity values measured by the electrodes, the transfer resistances (i.e. raw data) from each experiment were analysed. Transfer resistance is the measured electrical resistance between two electrodes in an ERT setup (Daily et al., 2005). In contrast, modelled resistivity (ERT imaging) is the calculated distribution of resistivity values within the subsurface obtained through inversion of the measured transfer

resistances (Loke, 1999). Although modelled resistivity cannot be directly compared to transfer resistances, they (transfer resistances) should show similar trends in resistivity change to the 4D images (i.e. a decrease in resistance or resistivity during wetting, and an increase in resistance or resistivity during drying). A forward modelling exercise was also done to investigate the source of artefacts in the ERT imaging. Forward modelling predicts the expected resistivity measurements based on the subsurface model, thereby simulating the soil column experiment.

Petrophysical relationships for each soil were calculated using a Waxman Smits model (Waxman & Smit, 1968) and a Root Mean Square (RMS) numerical approach. Soil moisture content, suction, and conductivity were directly measured in each material using a modified HYPROP 2 to produce 4D hydrological surveys derived from their time-lapse resistivity equivalents. Where artefacts persisted in the soil column experiments, applying the petrophysical data proved ineffective. However, petrophysical relationships were applied to the results from the sand, CT, and BAT column experiments.

In Appendix D, a sample of the data collected from the modified HYPROP2 experiments is provided. The data is specific to the sand experiment and shows the raw values for changes in moisture content, suction and resistivity as the material dries with both Waxman Smits and Power Law Fit plots and equations to derive these relationships. Like Appendix B, it was not possible to submit all the data from every experiment as an appendix. Therefore, full records from each experiment are available at data.ncl.ac.uk.

5.1 Series 1 Soil Column Experiments

Series 1 marks the first suite of 4D ERT soil column experiments on soils with different characteristics (e.g., grain size, dry density, starting moisture content, etc.). They provide valuable information on refining and developing the experimental method and ERT-integrated soil column design (summarised in Table 11). Experiments performed on the sand and gravel-filled CBSs indicate that low starting soil moisture contents and large grain sizes increase contact resistances, which made inverting the geoelectrical data challenging. Reciprocal errors (portrayed in the error probability distributions) were also found to be exceptionally high due to the high permeability/hydraulic conductivity of the gravel and sand layers. This also prevented an error threshold from being applied to the data, therefore reducing the accuracy of the ERT imaging.

Column Experiment	Notable design/method limitations	Experiment Impact
Gravel-filled CBS	Soil starting conditions were too dry Storm drainage occurred too quickly	High contact resistances High reciprocal errors
Sand-filled CBS	Soil starting conditions were too dry Storm drainage occurred too quickly	High contact resistances High reciprocal errors
Compacted CT	Low permeability	Storm water did not percolate quickly enough to produce a notable change in resistivity
	Surface water accumulation	Distorted the geoelectrical model causing artefacts
	Intermittent surface drainage with fitted runoff tube	Generated a strong soil moisture contrast causing artefacts
	Challenging to fill and empty between experiments	Due to compaction and the confining geometry of the column experiment setup times were high
BAT	Ponding reached the column lip	challenging to complete the 1 in 100 storm simulation
	Significant soil settlement	Contrasted with the geosynthetic model causing some artefacts
	Low compaction	Elevated reciprocal errors

Table 11 Summary of technical challenges associated with the first suite of ERT soil column experiments.

Considering these discoveries, subsequent experiments were performed on clay topsoil (CT) compacted at different dry densities (1.46 Mg/m³, 1.57 Mg/m³, and 1.69 Mg/m³). Ponding occurred throughout column experiments on CT, a problem that was not experienced during tests on the CBSs. Ponding changes the boundary conditions of the electrical survey and distorts the electric field, causing artefacts to appear in the ERT images. Therefore, the soil column design was changed to incorporate a surface water runoff tube to limit ponding. However, surface water drainage was intermittent because of soil settlement during storm simulations and the washing of fines into the tube, causing blockages. Intermittent surface water drainage appears to worsen the appearance of modelling artefacts in the repeated column experiments.

It was challenging to locate the exact cause of the modelling artefacts. Testing soils of different densities, grain sizes and starting moisture contents has led to artefacts in each time-lapse survey for seemingly different reasons (e.g., high contact resistances, ponding, surface water drainage, etc.). As a result, finding commonalities between each experiment (regarding the cause of artefacts) was exceptionally difficult. However, several factors regarding ERT image quality were apparent:

1. Contact resistances and reciprocal errors must be low to permit an error threshold of 5% and enable the inversion to converge.

2. Ponding should be avoided to maintain the electric field and prevent artefacts.
3. To observe a wetting front over time, soil dry density could not be too high to ensure water could percolate through the soil during the storm or within one week of the storm's conclusion.

Regarding (3), this is a limitation of the research as opposed to a problem with the soil column design. For time-lapse ERT column experiments where the design is optimised, the length of the experiment would not be limited by the function of the column itself. For these experiments, visualisation of a wetting front would inform whether resistivity is being measured effectively. Therefore, if the dry density is too high and water cannot percolate, changes in electrical resistivity will be low, and little information on the efficacy of 4D ERT column experiments will be gathered.

Topsoil was used in the final Series 1 soil column experiment. Contact resistances and reciprocal errors were kept low throughout the experiment, enabling the inversion to converge in less than 20 iterations and a reciprocal error threshold of 5% to be applied. Ponding was avoided during the storm to maintain boundary conditions and point sensor data indicates that stormwater percolated towards the base of the soil column. ERT imaging from the topsoil column experiment shows a significant reduction in artefacts compared to experiments performed on the CT and CBSs. However, some artefacts are still observed in the time series.

Inspired by Carey et al. (2017), a forward modelling experiment was conducted to understand better why artefacts appear in the time-lapse surveys. The model simulated an event whereby 100mm of surface water had accumulated before it was drained from the soil surface. The findings made by Carey et al. (2017) on what causes modelling artefacts, alongside forward modelling of the soil column compared to laboratory geoelectrical data, indicate that soil moisture contrasts and deployment of a dipole-dipole array could lead to modelling artefacts. Indeed, the forward modelling time-lapse results revealed many artefacts that look remarkably similar to those observed during the laboratory experiments. However, before commencing Series 2 of the column experiments, the influence of the electrode array and soil moisture contrasts was not fully realised.

5.2 The Forward Modelling Process

Due to artefacts resulting from time-lapse ERT during simulated storms, forward modelling is used to identify the cause and distribution of resistivity contrasts that did not accurately reflect actual moisture dynamics in the column experiments. Experiments performed on sand and gravel-filled columns revealed that artefacts arose due to high CRs and REs. However, experiments performed on clay topsoil (with reduced CRs and REs) still displayed inversion artefacts. Carey et al. (2017) discovered that artefacts were prominent when soil moisture contrasts were high during rainfall simulations and when ERT surveys deployed a dipole-dipole array. Column experiments in this study use a dipole-dipole array as other array types (e.g., pole-dipole), which Carey et al. (2017) identified as better for reducing inversion artefacts, are poorly suited to column experiments due to space limitations. Forward modelling, where a synthetic model identical to the dimensions of the column experiment, is used to imitate a time-lapse sequence where ponded water is removed from the surface of the soil. Imaging depicting the percentage difference in resistivity confirms that artefacts in the inversion are attributed to soil moisture contrasts and surface water accumulation and drainage, likely exacerbated by the dipole-dipole electrode configuration – although different electrode arrays were not tested. Forward modelling also identified that some artefacts occur at the walls of the soil column close to the electrodes. The exact reason for this is unknown. However, it is speculated that these resistivity contrasts are due to an oversimplification of the synthetic mesh that does not account for geometric complexities between the column wall and the flush electrodes.

5.3 Water-based Soil Column Diagnostic Experiments

After completing Series 1 of the column experiments, the source of the modelling artefacts was not fully established. Early notions of reducing soil grain size and increasing moisture content before a simulated storm successfully reduced contact resistances and reciprocal errors, aiding in a smoother inversion process. However, decreasing soil grain size decreased porosity, which led to ponding. This caused artefacts to appear in the electrical surveys. Adding a surface water runoff tube reduced ponding, but moisture contrasts at different soil depths coupled with deploying a dipole-dipole array still incurred artificial data. However, the role of the array type and moisture contrasts were not considered when planning Series 2 of the soil column experiments. Additional soil column experiments were planned (Series 2) after processing time-lapse surveys of the previous column experiments (Series 1), which revealed modelling artefacts in each experiment.

After completing Series 1 and before soils (sand, CT and BAT) were retested with a revised set of conditions (Series 2), diagnostic tests on the ERT columns were performed to identify the source of the modelling artefacts. Transfer resistance measurements suggest that resistivity increases during simulated storms due to modelling errors. However, before Series 2, it was essential to test the components of the experiment to identify if the equipment or another, yet unknown factor, was contributing to the appearance of artefacts. The wired connections between the electrodes and the PRIME system were checked using a Multimeter. All the electrode-PRIME system connections were robust, ruling out a potential connection issue of increasing resistivity.

The results provided in Section 4.8 indicate that the electrode array style (dipole-dipole), soil column design, and material temperature could influence artefacts in the results. Liu et al. (2022) investigated the correlation between temperature and soil electrical resistivity in clayey sand. Soil samples were placed in enclosed containers in an environment chamber, and two pairs of ERT electrodes were used to measure electrical resistivity (Figure 5.0) by deploying a Wenner four-electrode method. A freeze-thaw cycle was simulated between 5°C and -20°C and then back to 5°C.

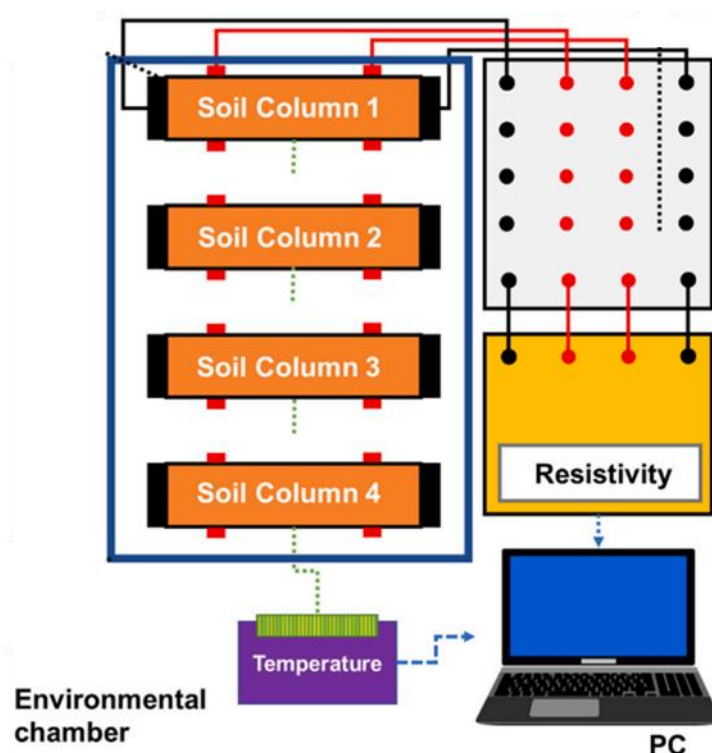


Figure 5. 0 The experiment setup used to measure changes in soil temperature and electrical resistivity using ERT and an integrated multi-switch, which enabled simultaneous measurement from multiple columns (Liu et al., 2022).

Liu et al. (2022) found that electrical resistivity negatively correlates with soil temperature (Figure 5.1). The graph shows that electrical resistivity is higher at lower temperatures. Liu et al. (2022) note that when soil column temperatures stabilise, so does the electrical resistivity value at that temperature.

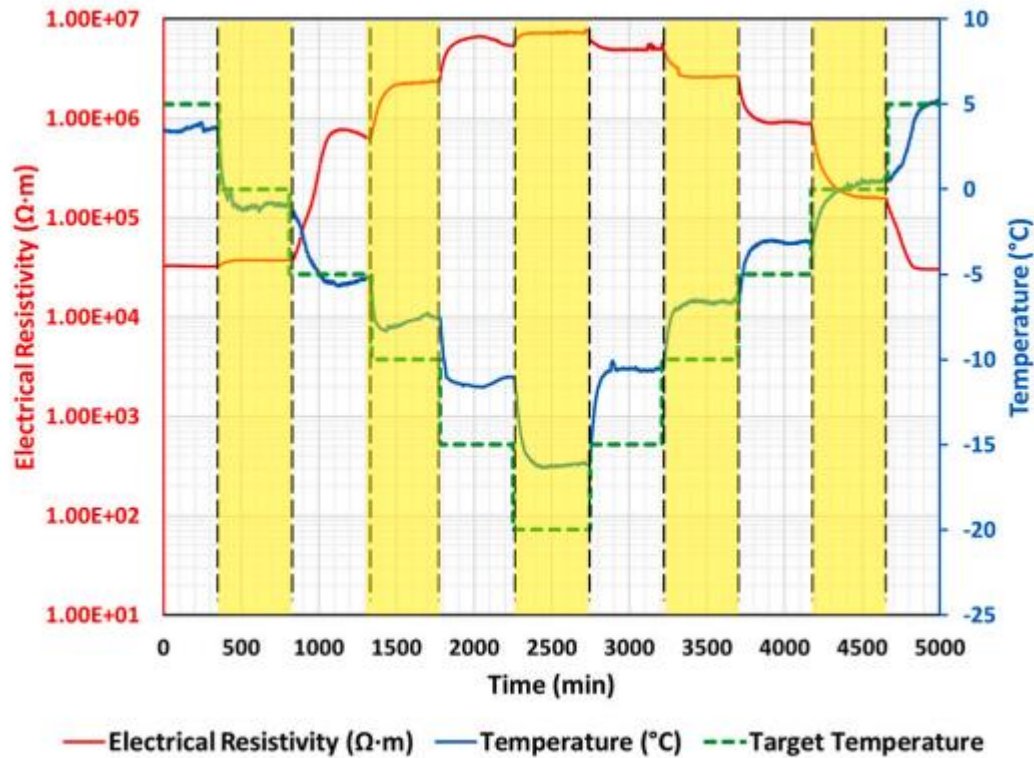


Figure 5. 1 Changes in electrical resistivity and temperature over time in clayey sands during a freeze-thaw simulation (Liu et al., 2022).

In the soil column experiment performed on water, tap water was added at 21.2°C. The temperature of the environment chamber remained at 16.6°C throughout the soil column experiments. Therefore, the water temperature decreased over time. The water temperature was checked one day after being placed in the chamber and was recorded as 17.6°C. Measurements were taken from the centre of the column using a thermometer. Recorded changes in temperature coupled with the initial increase in transfer resistances when water was added to the column provide further credence to the effect of water temperature fluctuations on the inversions from the soil column experiments. In light of this information, during Series 2, after the soil was mixed to a specific moisture content, it was left to regularise to the conditions of the environment chamber for a minimum of 24 hours before a storm was simulated.

5.4 Series 2 Soil Column Experiments

Geoelectrical results from Series 1 suggest that electrical resistivity increases when water is added to the soil during a simulated storm. Sections 4.6 and 4.8 explain that modelling artefacts stem from a number of sources (soil moisture contrasts, electrode array deployment, soil temperature regularisation, etc.). However, upon completing Series 1, the reason artefacts appeared in the time-lapse surveys was not understood. Diagnostic tests performed using a water-filled column highlighted that water temperature fluctuations could affect the resistivity of the survey area. Therefore, when soil was added to the columns during Series 2, the material was left in the environment chamber for a minimum of 24 hours before a simulated storm. The injected current was also increased to 10 mA to improve the signal-to-noise ratio (SNR), and ERT imaging of the water-filled column (Section 4.8.4) indicated that modelling artefacts decreased. Additionally, further changes were made to the methodology in Series 2 to reduce the appearance of appearance.

Soil column experiments undertaken in Series 1 informed column experiments in Series 2. Due to artefacts in the ERT images (Series 1), changes were made to the soil column design and methodology to reduce artefacts. These changes included:

1. Increasing the injected current from 2 mA to 10 mA to improve the SNR.
2. Adding stormwater outside of forward and reciprocal measurement sequences to improve error probability distributions.
3. Reducing the complexity of the tested materials by not examining multilayer soils (CBSs).
4. Adding damp soil (approximately 10% moisture content) to reduce contact resistance at the start of the experiment.
5. Using a high resistivity contrast salt tracer during the storm to ensure a wetting front would be visible in the ERT imaging.
6. Allowing the soil to regularise to the conditions of the environment chamber to ensure soil temperatures are stable.

Prior to starting Series 2, the effects of soil moisture contrasts and the deployment of a dipole-dipole array on modelling artefact incursions were unknown. This was only established after a forward modelling test (Section 4.6). Therefore, artefacts were still present in the Series 2 time-lapse surveys. Despite artefacts in Series 2, the changes implemented above did aid in improving the ERT images and permitted smoother geoelectrical modelling (fewer software crashes and converging in fewer iterations).

Water-filled column tests using 4D ERT (Section 4.8) indicate the negative correlation between temperature and electrical resistivity. Research by Liu et al. (2022) investigated the effects of temperature on resistivity in soil by simulating freeze-thaw cycles. Although temperature changes in those experiments were extreme (temperature changes of 25°C), the potential implications of temperature on the soil column experiments could not be ignored. Therefore, in Series 2, the relationship between soil temperature and electrical resistivity was measured by plotting changes in temperature alongside transfer resistances. In each soil (sand, clay topsoil and topsoil), transfer resistances increased as temperature decreased. This relationship (resistivity-temperature) was taken further by inverting geoelectrical data affected by temperature changes with data collected during a simulated storm in each column experiment. Even in cases where temperature changes were small ($>3.5^{\circ}\text{C}$) ERT images in each experiment showed that artefacts were significantly more prevalent when data affected by temperature change was used, despite these variations being far lower than those tested by Liu et al. (2022).

5.5 Petrophysical Relationships

5.5.1 Soil Moisture Content – Electrical Resistivity Relationship

Section 3.8 of the methodology gives a method for determining the variable spatial distribution of soil moisture content and suction. A modified HYPROP 2 is used to measure electrical conductivity, soil suction and moisture content simultaneously in a given soil, and the data is fitted using a calibration curve (e.g., Waxman-Smits or an Inverse Power Law Fit). With the exception of gravel, modified HYPROP 2 tests were carried out on each material examined in the soil column experiments (sand, clay topsoil, and topsoil). Due to the large grain sizes of the gravel used in the capillary barrier system (CBS) experiment, determining suction and resistivity using this technique was not possible.

As geoelectrical measurements were collected from the soil column tests, it became evident that developing time-lapse surveys showing moisture content in each column experiment would not be possible due to the high number of modelling artefacts in many inversions. Artefacts were present in the sand and gravel CBS surveys, but even if this were not the case, due to the columns being comprised of two layers (granular material and topsoil), producing 4D ERT images that assessed changes in suction or moisture content would not be possible owing to the difference in material properties. In field surveys, this would not have been problematic. However, the column experiments utilised a dipole-dipole array that measures

resistance over a depth that would conflict with material boundaries. A potential solution would be a reconfiguration of the synthetic mesh geometry. However, this went beyond the scope of the experiments.

Modified HYPROP tests were performed in the clay topsoil (CT) experiments at a dry density of 1.46 Mg/m^3 only. Concerning the CT column experiments, data described in Section 4.4 demonstrates that, artefacts were prevalent throughout these timelapse surveys except for clay topsoil at 1.46 Mg/m^3 , where a wetting front during the storm was most pronounced. Translating resistivity to moisture content where artefacts in the data are abundant would only mask the actual soil moisture dynamics in effect during a storm simulation, as was observed in many of the resistivity surveys throughout Chapter 4. Therefore, in Series 1, timelapse surveys of moisture content were developed for the Bourne Amenity topsoil (BAT) and clay topsoil (CT) (1.46 Mg/m^3) column experiments only.

5.5.2 Waxman Smits Model Versus a Power Law Fit

In previous studies where a modified Waxman-Smits model was fitted to resistivity and moisture content data (e.g., Holmes et al., 2022 and Boyd et al., 2024), a GMC-resistivity relationship was derived from the Waxman-Smits equation, see Section 3.9. Figure 5.2 demonstrates that a Waxman-Smits model does not fit the data but that a PLF model is a better fit.

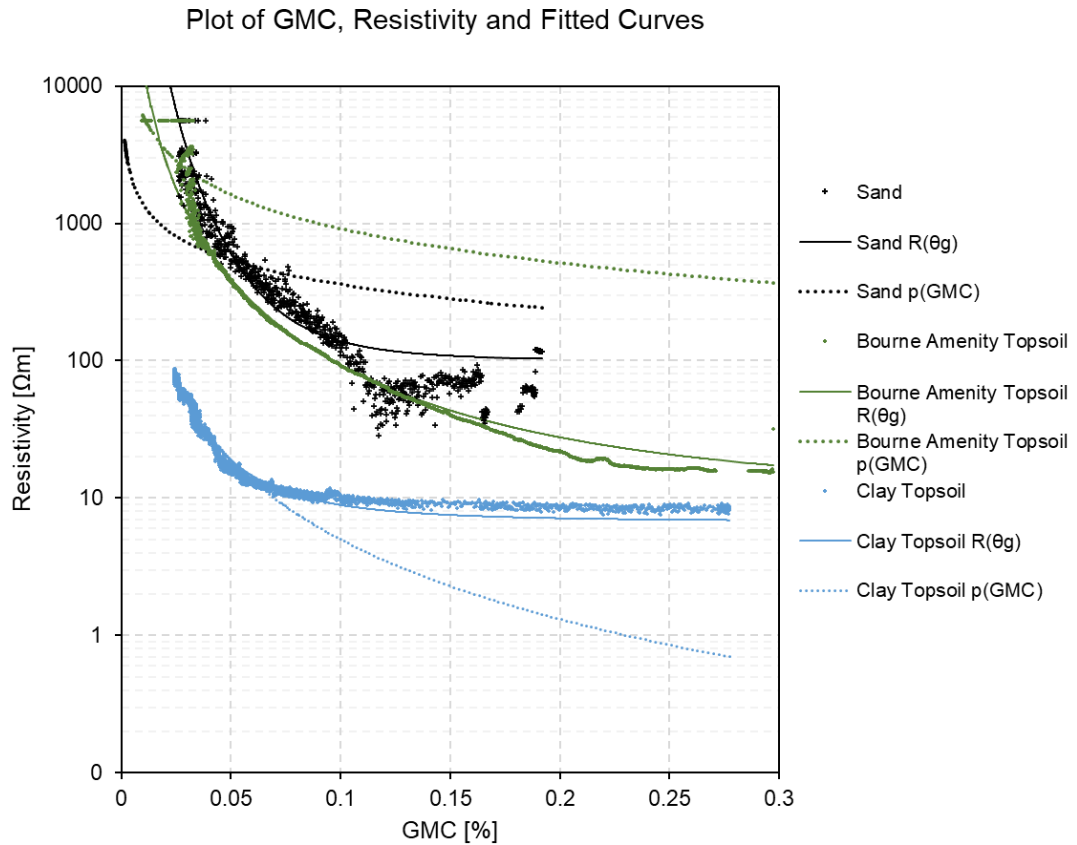


Figure 5. 2 Graph showing GMC, resistivity and fitted curves of sand, Bourne Amenity Topsoil and clay topsoil used in column experiments (Series 1). Where $R(\theta_g)$ is fitted resistivity using power law, and $p(GMC)$ is resistivity when using a Waxman-Smits curve.

In light of using a numerical approach to derive the resistivity and moisture content relationship for the soils, a PLF was applied to the volumetric moisture content (VMC) measured during each Modified HYPROP2 experiment instead of continuing with GMC. VMC accounts for changes in hydrological parameters (e.g., permeability, shrinkage, gravimetric deformation, and bulk density, etc.), which would alter pore spaces and hydraulic conductivity. Furthermore, modelling spatial distribution in VMC would allow comparisons to be made to the soil moisture sensor (SMS) data captured during simulated storms in a separate soil column. Figure 5.3 shows the relationship between electrical resistivity and VMC in the soils (sand, CT and BAT) by applying a power law fit.

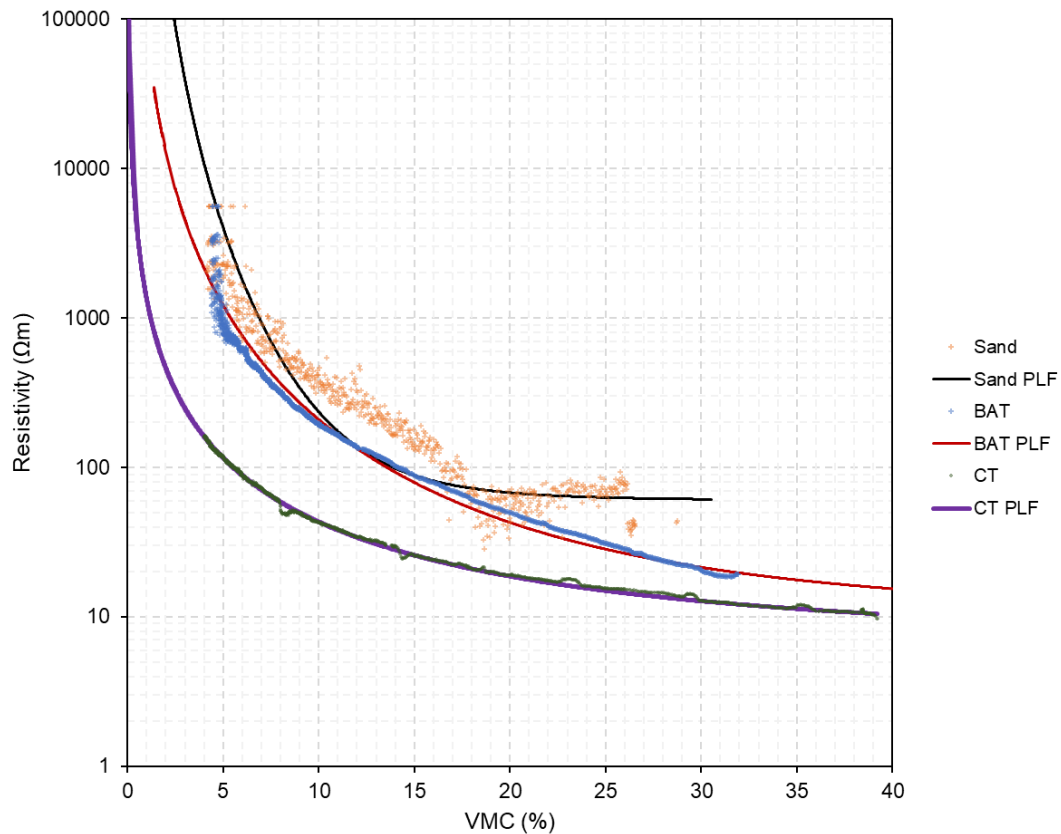


Figure 5. 3 Volumetric moisture content (VMC) versus electrical resistivity for the sand, Bourne Amenity topsoil (BAT) and clay topsoil (CT), with a power law function (PLF) used to fit the data.

A modified HYPROP 2 setup was deployed for soils examined in Series 1 (the first suite of soil column experiments) to convert electrical resistivity to soil moisture content and suction. The modified HYPROP 2 enabled soil moisture content, suction, and electrical resistivity to be measured simultaneously. Calibration curves were developed for the Bourne Amenity topsoil (BAT) and clay topsoil (CT) only due to the prevalence of artefacts observed in other Series 1 ERT time-lapse surveys. A Waxman Smits model was used to convert electrical resistivity to volumetric moisture content (VMC). However, this did not fit the data well, as the equation did not account for variable porosity. Instead, an inverse power law is used, which can fit the data.

During simulated storms, the VMC ERT data is compared to measurements made by the SMSs at the top, middle, and bottom of the soil columns. Although ERT and SMS values were not identical in the BAT, averaging the ERT data shows that moisture content increased similarly to measurements made by the SMSs. Significant discrepancies between the ERT and SMS data in the BAT are due to artefacts in the ERT images.

A different method for converting electrical resistivity to VMC is used for soils tested in Series 2 (sand, CT and BAT) because the column experiments were done using tap water mixed with salt. Instead of using a modified HYPROP 2, the soil was mixed with salt water to a specific moisture content and the electrical conductivity was measured. The data was fitted using a power law fit (PLF) by measuring conductivity at different moisture contents. Comparing SMS and ERT VMC data showed a reasonable correlation between the two. However, where modelling artefacts are observed in the ERT images, ERT VMC measurements differ considerably from those of the SMSs.

Converting electrical resistivity to volumetric soil moisture content highlights the challenges of displaying 4D ERT surveys as figures. Simulating a 1 in 100 storm is an example of an extreme rainfall event. Therefore, moisture content can increase significantly in a short period. As a result, this can induce artefacts due to a soil moisture contrast, and it is challenging to showcase the ERT images using one scale. Multiple surveys throughout Section 4.14 (e.g., Figure 4.61) display time-lapse surveys over multiple figures due to the need to adjust the VMC scale to ensure changes in moisture content are observed due to sudden increases.

It was not possible to model soil suction for Series 2 soils (Sand, CT and BAT) as this data was not collected when acquiring resistivity and VMC measurements. Additionally, due to saltwater being used in the storm simulations, suction could be affected by salt particles. Instead, 4D ERT surveys modelling changes in suction were produced for CT and BAT in Series 1 (where tap water is used). The data was calibrated using a van Genuchten model. Modelling changes in suction during a storm in the CT was not possible because the calibration curve was too steep. However, in the BAT, changes in suction were modelled. Sensor and ERT data were compared and were found to be similar. Like examples in Section 4, where artefacts occur in the ERT images, there are more significant discrepancies between the sensor values and ERT measurements.

Chapter 6 Conclusion

6.1 ERT Soil Column Design and Construction

When considering 4D ERT soil column experiments, the original expectations for the research were to evaluate soil moisture dynamics in vegetated soils to ascertain the effects of roots/plants on soil hydrological properties (e.g., infiltration, hydraulic conductivity, and water retention, etc.) during and after extreme weather events. However, geoelectrical modelling of water-filled soil columns and capillary barrier systems (CBS) indicated that the design and method of the column experiments required significant improvement to reduce the appearance of modelling artefacts in resulting inversions. Therefore, the application of 4D ERT in a laboratory setting was prioritised instead of focusing on the vegetation aspect of the experiment.

To improve ERT image quality, several columns were constructed that adopt different design features:

1. Different electrode materials (stainless steel and carbon graphite).
2. Machine building versus hand-built soil columns
3. Wire-electrode connection types
4. Electrode geometries

The first soil column was built by hand, and stainless-steel electrodes were connected to wires via single-pin male-female connectors. Electrodes were held in adjustable glands that allowed them to be easily removed between experiments and enabled soil-electrode penetration to be changed per experiment. This design was very robust, and wires rarely detached from the electrodes between experiments – a tendency given the number of electrodes (32) and the need to remove the electrodes from the column between experiments for safety reasons. However, modelling artefacts were exceptionally high when analysing ERT images from the column filled with tap water. It was assumed that elements of the soil column design were at fault. Minor discrepancies between the geosynthetic model and actual placements of some of the electrodes were discovered that, in other settings, could lead to artefacts. In a field survey, deviations of less than 5 mm are unlikely to affect geoelectrical measurements, but these minor differences could significantly impact results at a laboratory scale. The soil column was hand-built, including the holes for the electrodes, hence the differences between the column and the geosynthetic model. The PVC pipe and electrode holes were machined when redesigning the

ERT soil column, providing a high degree of accuracy. Additionally, electrode glands/material were changed in favour of carbon graphite in a fixed position flush to the column interior. This reduced the complexity of the geosynthetic model.

Geoelectrical measurements were gathered from the second soil column (column 2), and modelling artefacts were reduced. However, despite changes to the design, many artefacts were still observed in the time-lapse surveys. Subsequent geoelectrical modelling of the water revealed that the standard 20 mA injected current used in field surveys was too high, which led to voltage clipping, and this was reduced to 2 mA, which significantly improved 4D ERT imaging by removing most modelling artefacts from the survey. However, some artefacts, appearing close to the electrodes at the column wall, persisted in the images despite simplifying the electrode geometries. Although voltage clipping primarily caused modelling artefacts (according to the water-filled column experiments), ERT images were slightly improved in soil column 2 compared to 1 prior to reducing the injected current. Therefore, experiments on soils were carried out using the updated design.

Column experiments on different materials/asset management regimes further informed the design of 4D ERT soil columns. Tests on granular soils (gravel and sand) led to high contact resistances (CRs) and reciprocal error (RE) percentages that severely impeded geoelectrical modelling. When REs are too high, the inversion fails, and any attempts to apply an error threshold on geoelectrical measurements would cause programme failure. In these experiments (CBSs), it is thought that using the adjustable glands from soil column design 1 and positioning the electrodes further into the soil instead of flush to the column interior (column 2) could have reduced CRs by increasing the electrode area in contact with the granular material. This could have reduced REs despite the high hydraulic conductivity of the soil. However, inserting the electrodes into the soil would likely increase the complexity of the array, which would need to be accurately portrayed in the geosynthetic model; otherwise, artefacts could be worsened.

The dimensions of the soil column were 500 mm in height and 110 mm in diameter. This was selected to accommodate the size of the environment chamber. If the columns were larger, water would take longer to percolate through the material, which may decrease REs. Indeed, a larger column would have been desirable for these experiments, given that the simulation of an extreme weather event meant that changes in soil moisture content would occur quickly, leading to discrepancies between the forward and reciprocal measurements.

Column experiments on fine-grained soils (clays and topsoil) revealed that ponding is likely due to low infiltration during a storm simulation. Therefore, a surface water runoff tube was fitted at surface level (500 mm). The tube was connected to a tipping bucket to measure runoff, and the tube aperture was equipped with a mesh to prevent fines from washing into the tube, leading to blockages. However, mixing water with clay particles blocked the mesh, leading to ponding. Furthermore, as settlement occurred during a storm, the distance between the aperture and soil surface increased, leading to ponding. This particular design challenge is difficult to overcome. Perhaps using something finer than a mesh (e.g., gauze) would allow water to pass whilst blocking the soil more effectively. A potential solution would be to place multiple surface water runoff tubes at the column walls at different heights. These could be kept closed until the soil has settled to the height of a specific runoff tube, reducing the effects of settlement on ponding. Alternatively, using a sloped upper soil boundary would promote runoff and reduce the complexity of the column design, which could have implications for the complexity of the geosynthetic model. Additionally, the extent of ponding during the experiment could be measured throughout, and the geosynthetic model could be adapted to account for changes in the boundary conditions during the storm. However, this particular strategy is quite cumbersome. It would require the researcher to check the height of the water regularly or use a camera that monitors changes in the near-surface and assign a new height to the geosynthetic model at specific timesteps to match the degree of settlement.

Experiments on topsoil show significant improvements in ERT imaging concerning modelling artefact prevalence. However, error probability distribution (EPD) analysis indicates high error percentages before the storm. CRs were relatively low (≤ 500 ohm.m); therefore, it was assumed that a higher injected current (≥ 2 mA) was necessary to reduce the distribution of REs. If the current is not high enough to register a consistent potential signal on the potential electrodes, then array sensitivity will be low. Therefore, the injected current was increased to 10 mA. Given the impacts of voltage clipping on column ERT imaging, soil transfer resistances were analysed after the current increase, and no deviations in geoelectrical measurements were found that indicated clipping had occurred. The impact of the injected current on soil column experiments utilising time-lapse ERT technology is clear, and it is suggested that for future experiments, different injected currents are applied to tested materials (starting from a high injected current and decreasing) to gauge which supply proffers the highest quality 4D ERT imaging.

6.2 Time-lapse ERT Imaging of Soil Column Experiments

6.2.1 Series 1

Section 6.1 discusses results from column experiments performed on tap water, CBSs, clay topsoil (CT), and Bourne Amenity topsoil (BAT). By testing different materials during a 1 in 100 simulated storm event, the ERT soil column design could be improved to meet the challenges associated with time-lapse ERT for laboratory-scale imaging of soil moisture dynamics. As previously stated, experiments on gravel and sand-filled CBSs indicated that high REs and CRs made geoelectrical modelling exceptionally challenging. High CRs were unavoidable due to the large grain sizes of the drainage layers. REs were also difficult to control owing to the simulation of an extreme weather event coupled with the high hydraulic conductivity of the coarse-grain soils. As a starting point for column experiments (the CBSs), it was a poor suite of reference experiments as few geoelectrical measurements were collected that could be modelled. If soil-based experiments had been first performed on a simpler soil regime (fine-grained, homogenous topsoil), geoelectrical modelling might have been possible, and it would have provided more valuable information regarding the design and conduct of the column experiments. Although understanding the effects of high REs and CRs was highly valuable, their influences on time-lapse ERT overshadowed yet unknown concerns over the cause of artefacts in ERT imaging (soil moisture contrasts, injected current input, etc.).

Soil column experiments on clay topsoil (CT) were done to mitigate the impacts of high REs and CRs, which were indeed reduced. However, a new design challenge was met in the form of ponding during a simulated storm. Ponding changes the boundary conditions of the electrical survey, increasing the known volume of the inversion, which can cause modelling artefacts. This was known before the experiments, and a surface water outflow tube was fitted to mitigate ponding. However, intermittent surface water drainage (as discussed in Section 6.1) increases the prevalence of modelling artefacts. Furthermore, a more significant soil moisture contrast developed between the top, middle and bottom sections of material that further exacerbated artefact intrusions by not allowing the surface water to infiltrate through the soil.

In retrospect, it is recognised that shifting tests from soils with a high drainage potential (gravel and sand) to low-permeability clay topsoil unavoidably created new challenges associated with integrating time-lapse ERT owing to the vast differences in soil properties (e.g., porosity and density). Upon completing experiments on both the CBSs and clay topsoils, soil column tests on topsoil (BAT) were performed, which provided somewhat of a middle ground between the formerly tested soils and further highlighted the complexities of the investigation. ERT images

portraying spatial distributions in resistivity during the storm were improved compared to the CBSs and CTs. EPDs and CRs were improved, and modelling artefacts were reduced. However, artefacts persisted, especially in the first few hours of the storm, which meant crucial moments during the advancement of the wetting front were lost until soil moisture content overcame these high resistivity contrasts.

6.2.2 Water-filled Soil Column Diagnostics

Geoelectrical measurements in Series 1 demonstrate that ERT image quality was far from exemplary owing to modelling artefacts. Before commencing Series 2, geoelectrical data was gathered from the ERT column filled with tap water (CAT 5). ERT images displayed artefacts despite the homogeneity of the water. These artefacts were also unstable and appeared to fluctuate during the array measurement timeframe. Something that was not observed during the soil column design phase, where a water-filled column was also utilised. Changes in how the artefacts were distributed were unexpected as it suggested that some artefacts present in soil tests may have been actual events during the experiment and not only high resistivity contrasts generated due to errors during the inversion. The relationship between temperature and electrical resistivity was considered and found that transfer resistances increased as the water temperature decreased. The effects of soil temperature on resistivity are well documented, particularly the impact of freeze-thaw weather cycles on ERT. However, water temperatures decreased in the column by 3.6°C, a comparatively smaller temperature shift than ERT soil column studies like Liu et al. (2022), which tested changes over 25°C. Nevertheless, measured changes in transfer resistances were captured as temperature decreased. This indicated that experiments on soils in Series 2 needed sufficient time to regularise to the environment chamber before initiating a storm event.

6.2.3 Series 2

Using a combination of ERT results from Series 1 and geoelectrical measurements made during the water-filled column tests, several changes were made to the design and conduct of the ERT column experiments for Series 2:

1. Increasing the injected current from 2 mA to 10 mA to improve the SNR.
2. Adding stormwater outside of forward and reciprocal measurement sequences to improve error probability distributions.

3. Reducing the complexity of the tested materials by not examining multilayer soils (CBSs).
4. Adding damp soil (approximately 10% moisture content) to reduce contact resistance at the start of the experiment.
5. Using a salt tracer during the storm to ensure a wetting front would prevail in the ERT imaging.
6. Allow the soil to regularise to the conditions of the environment chamber to ensure stable soil temperatures.

Column experiments in Series 2 were met with varying success. Across all tested materials (sand, clay topsoil and topsoil), CRs and REs were reduced compared to Series 1. ERT imaging in the sand improved significantly compared to the CBS experiment, and very few modelling artefacts were observed. Although the list of changes made (1-6) all likely contributed to reducing artefacts, it is thought that adding water outside of array measurement sequences (forward and reverse) helped reduce REs considerably, enabling an error threshold to be applied to the geoelectrical measurements.

In the clay topsoil and topsoil experiments, artefacts persisted in the ERT images to a greater degree compared to the sand-filled column experiment. However, modelling artefacts were overcome when soil moisture content increased towards the middle of the storm. The cause of the artefacts is attributed to soil moisture contrasts generated when the storm commenced.

Series 2 also considered the impact of soil temperature changes. Findings from the water-filled column experiments indicate that as temperature decreases, resistivity increases. This was not considered in Series 1, and as a result, storm events were often done shortly after the soil was added to the chamber, which likely contributed to modelling artefacts. This is reinforced by measurements made in Series 2, which highlights the impact of including geoelectrical measurements affected by soil temperature changes in the inversion modelling process. As apparent as this is, it was no less valuable to quantify the extent to which temperature-affected geoelectrical data has on soil column ERT imaging compared to measurements unimpeded by this relationship. Had soil temperature changes been considered in Series 1, ERT images might have been of higher quality and less hampered by artefacts.

6.3 Forward Modelling Analysis

In Chapter 4, results from the forward modelling experiment were provided after the CT column experiments to account for modelling artefacts during the time-lapse surveys. After

Series 1 and 2 were concluded, forward modelling was used to investigate resistivity contrasts during simulated storms. The subsequent time-lapse of the forward model indicated that artefacts occur for several reasons:

1. High resistivity contrasts close to the electrodes are attributed to unaccounted-for complexities in the geosynthetic mesh.
2. Soil moisture contrasts during the storm.
3. Intermittent drainage of surface water leading to survey volume changes due to variable ponding.
4. Compared to other array types (e.g., pole-dipole), a dipole-dipole array has a higher tendency to model artefacts.

Considering the role of a dipole-dipole array incurring more artefacts than other array types, had this been understood in the project design phase, efforts to devise a different electrode configuration would have been made. This could have taken the form of testing different numerical configurations in the column by altering the potential and current electrodes in different soils and materials (e.g., topsoil or water—filled columns) and comparing artefact appearance in the modelled data and plotting changes in transfer resistances over time to find a satisfactory array type.

The potential role of soil moisture contrasts during a storm and the role of the array deployed were not considered when investigating artefacts during soil column experiments. As discussed in Section 4.6, using a different array type to reduce artefacts is desirable; however, it is challenging to implement because of the space limitation of the soil column. Soil moisture might have been reduced by adding water to the column at a reduced rate. However, the storm was simulated over six hours, and lengthening this further (given that water was added manually) was not possible without increasing the time the PRIME system measured from the columns or building an automatic watering system that added water to the columns at a significantly reduced rate to allow soil moisture content to increase slowly.

6.4 Petrophysical Tests

A modified HYPROP 2 setup simultaneously measured soil moisture content, suction, and electrical resistivity. For soils investigated in Series 2, a modified HYPROP was not applied because salt water was used during storm events. Different calibration models were applied to the petrophysical measurements, and it was found that using a modified Waxman-Smits model

was ineffective as it failed to fit the data. Instead, an inverse power law was used. Although this fits the data well, the PLF does not apply measured soil properties and instead uses a numerical approach to fit the data. A van Genuchten –style fitting model was used to derive the best-fit electrical resistivity-soil suction relationship.

In the sand, CT, and BAT, volumetric moisture content (VMC) is modelled in four dimensions. Changes in soil moisture content measured by the moisture sensors compared to the ERT measurements display some similarities. However, disparities between the two measurement techniques (ERT versus SMSs) are seen where artefacts are observed in the ERT images. Due to high permeability and low suction in the sand, changes in soil suction were not shown in the sand ERT images. In the CT, modelling change in suction was not possible as changes in electrical resistivity far exceeded measurements derived from the HYPROP experiment owing to the simulation of a 1 in 100 storm event. In the BAT, changes in soil suction were successfully modelled, and sensor measurements were compared to those of the ERT data. The plotted measurements show a strong correlation, demonstrating that variable spatial distributions in soil suction can be modelled using time-lapse ERT in soil column experiments.

6.5 The development of 4D ERT for Laboratory-Scale Imaging of Soil Moisture Dynamics

This research presents the technical challenges associated with integrating time-lapse ERT in soil column experiments by analysing 4D ERT measurements acquired by the PRIME system in detail. These technical challenges (different electrode materials and dimensions, measurement settings, geophysical modelling techniques, columnar geometries, etc.) were tested to develop 4D ERT column experiments. Geoelectrical measurements highlight the sensitivity of the array to technical challenges, and potential solutions on how the method and design can be improved to reduce modelling artefacts are provided. Investigating different engineered fills (clay topsoil, sand and topsoil) and asset management regimes (CBSs) sets the foundation for broader use of the PRIME system and time-lapse ERT technology in small-scale laboratory experiments (e.g., soil-water-root dynamics), yet unexplored beyond field investigations.

Further advancements in 4D ERT soil column design are required to improve ERT imaging by reducing modelling artefacts. A standardised injected current of 20 mA was first used. However, due to voltage clipping, this was adjusted to 2 mA and later 10 mA. To the

researcher's knowledge, field applications of the PRIME system do not change the injected current. Therefore, in future small-scale laboratory experiments using PRIME technology or other time-lapse ERT methods, testing different levels of injected current for various materials is advised to calculate optimal current inputs.

A larger soil column than the one used in this study (500 mm height, 110 mm diameter) is recommended to monitor soil moisture dynamics during simulated storm events. This may reduce reciprocal errors by increasing the time the wetting front takes to percolate through the soil. Experiments on granular materials (gravel and sand) highlight the challenges associated with ERT column experiments where hydraulic conductivity is high. In low porosity soils (clay topsoil), ponding can occur, and failure to prevent this effectively can exacerbate potential problems with modelling artefacts. Ensuring soil temperatures are stable before rainfall simulations is essential to ensure changes in electrical resistivity are not attributed to changes in temperature. Furthermore, geoelectrical data affected by soil temperature changes can increase the prevalence of modelling artefacts.

Although many changes to the ERT soil column design and methodology were made throughout the experiments (Series 1 and 2), it was only when the data from all the experiments were processed and forward modelling was used that the various sources of artefacts were fully realised. A dipole-dipole array was deployed. However, it is recommended that another array type be used (e.g., pole-dipole) instead to reduce modelling artefacts. Geoelectrical measurements suggest that significant soil moisture contrasts can cause artefacts. Therefore, column experiments that simulate a severe climatic event (e.g., 1 in 100 storm event) may not be appropriate for 4D ERT column experiments. However, if the array type is changed, and the technical challenges addressed in this research are fully considered, then investigating soil moisture dynamics using 4D ERT in small-scale laboratory experiments can provide a unique insight into transient soil moisture conditions in different soils.

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APPENDIX A

Python Code for Forward and Reciprocal Date Merging

```

1. #-*- coding: utf-8 -*-
2. """
3. Created on Mon Feb 6 17:01:51 2023
4. Merge SUDs command files

5. """
6. import os
7. from datetime import datetime
8. import numpy as np
9. import pandas as pd

10. #%% setable parameters
11. source_directory = r'D:\Prime_Files\Series_2_ClayTopsoil\Experiment2\29-30\unmerged'
    # this is the directory where you keep your PRIME files
12. target_directory = r'D:\Prime_Files\Series_2_ClayTopsoil\Experiment2\29-30\merged' #
    this is where you want to save the merged PRIME files
13. fwd_id = 2001 # COMMAND ID of forward measurements
14. rev_id = 2002 # COMMAND ID of reverse measurements
15. max_delay_time = 30*60 # in seconds, so we allow for the reciprocals to start within 30
    minutes
16. # outside of this time any reciprocal measurements will be unpaired and ignored.

17. #%% functions

18. def date2id(date):
19. """
20. Change python datetime into a unique id number in the format YYYYMMDDhhmmss.

21. Parameters
22. -----
23. date : datetime
24. Python datetime object.

25. Returns
26. -----
27. id: int
28. id number (int)

29. """
30. template = '{:4d} {:0>2d} {:0>2d} {:0>2d} {:0>2d} {:0>2d}' # YYYYMMDDhhmmss
31. fid = template.format(date.year, # populate template with numbers
        i. date.month,
        ii. date.day,
        iii. date.hour,
        iv. date.minute,
        v. date.second)
32. return int(fid) # converts id number to int (from str) and returns it #

33. def getCmdId(fname,order=['cmdid','abbrev','date','time']):
34. """

```

```

35. Extract CMD id from file name.

36. Parameters
37. -----
38. fname : str
39. Name of file (must not include path).
40. order: list, optional
41. Defines how the prime file has been structured, e.g if cmdid number
42. comes first or second.
43. Returns
44. -----
45. cmdid: int
46. cmd id
47. date: python datetime
48. Datetime stamp of file
49. fid: int
50. file id number

51. """
52. # define the formatting of the prime naming scheme
53. if 'cmdid' in order:
54.     cmd_idx = order.index('cmdid')
55.     bracket_flag = False
56. elif '(cmdid)' in order: # line needed to deal with the older prime formats
57.     cmd_idx = order.index('(cmdid)')
58.     bracket_flag = True
59.     abbrev_idx = order.index('abbrev')
60.     date_idx = order.index('date')
61.     time_idx = order.index('time')
62. # reverse engineer expected file names
63. parts = fname.replace('.tab','').split('_') # splits file name into constituent parts
64. cmdid = parts[cmd_idx]
65. abbrev = parts[abbrev_idx]
66. date_str = parts[date_idx]
67. time_str = parts[time_idx]

68. def str2dt(date_str,time_str):# convert time strings into python datetime object
69.     date_info = [int(s) for s in date_str.split('-')] # convert string information to ints
70.     dt = datetime(date_info[0],date_info[1],date_info[2],
71.                   i. int(time_str[0:2]),int(time_str[2:4]))
72.     return dt # return datetime object

72. date = str2dt(date_str,time_str)
73. # construct unique file ids with this formatting using date2id
74. fid = date2id(date)
75. if bracket_flag:
76.     cmdid = cmdid.replace('(',')').replace('(','(')

77. return cmdid, date, fid

```

```

78. def readPrime(fname):
79. """
80. Read in PRIME measurement file.

81. Parameters
82. -----
83. fname: str
84. File path to prime file
85. Returns
86. -----
87. metadata: dict
88. Structure contains metadata about the parsed file
89. df: pd.DataFrame
90. Pandas dataframe with the survey measurement data.
91. """

92. def str2dt(date_str,time_str):# convert time strings into python datetime object
93.     date_info = [int(s) for s in date_str.split('-')] # convert string information to ints
94.     time_info = [int(s) for s in time_str.split(':')] # (split by delimiter)
95.     dt = datetime(date_info[0],date_info[1],date_info[2],
                     i. time_info[0],time_info[1],time_info[2])
96.     return dt # return datetime object

97. # read in metadata first
98. metadata = {}
99. fh = open(fname,'r')
100.     # read in header lines
101.     for i in range(23):
102.         line = fh.readline()
103.         parameters = line.split()
104.         metadata[parameters[0].replace(':',')] = parameters[1:]

105.     fh.close()

106.     # read in bulk of data using pandas (returns a dataframe)
107.     df = pd.read_csv(fname,header=26,delimiter='\t')

108.     # get the number of measurements
109.     nmeas = len(df)
110.     # filter out error lines (would be flagged up as first column being string types)
111.     if isinstance(df['pt_line_number:'][0],str):
112.         idx = []
113.         for i in range(nmeas):
114.             a. if isinstance(df['pt_line_number:'][i],str): # check that last measurement was not
115.                 made in error
116.             b. if 'Error' in df['pt_line_number:'][i]:
117.                 i. continue # an error line
118.             c. else:
119.                 i. idx.append(i)
120.             d. else:

```

```

        e. idx.append(i)
114. else:
115.     idx = [i for i in range(nmeas)]

116.     if len(idx) == 0: # then are no lines to be processed and hence all measurements are
        corrupted
117.         raise Exception('All measurements appear to be corrupted')

118.     # forward fill all missing current electrode ids if missing (only relevant for older PRIME
        files)
119.     if any(np.isnan(df['pt_c1_no:'])==True):
120.         df[['pt_c1_no:', 'pt_c2_no:']] = df[['pt_c1_no:', 'pt_c2_no:']].fillna(method='ffill',
            axis=0)

121.     # we also want to check how long it took the system to run the measurements
122.     # therefore check the time the last measurement was made (information is in a string)
123.     end_time_str = df['pt_time:'].values[idx[-1]].split('T') # split by T as that delimits the
        date and time information
124.     date_str = end_time_str[0]
125.     time_str = end_time_str[1]
126.     dt1 = str2dt(date_str,time_str)

127.     # we can also find the actual start time in the meta data to compute a duration
128.     start_time_str = metadata['set_actual_start_time'][0].split('T')
129.     date_str = start_time_str[0]
130.     time_str = start_time_str[1]
131.     dt0 = str2dt(date_str,time_str)

132.     # compute duration in minutes
133.     delta = (dt1 - dt0).seconds/60

134.     metadata['set_duration'] = delta # float with the actual time taken to do the
        measurements
135.     metadata['set_est_meas_duration'] = float(metadata['set_est_meas_duration'][0]) #
        predicted time to take the measurements
136.     metadata['datetime'] = dt0 # the start of the file
137.     metadata['filename'] = os.path.split(fname)[-1] # file name
138.     metadata['nmeas'] = nmeas

139.     # compute measurement times and check resistance values are not string
140.     meas_time_str = df['pt_time:'].values[idx[0]].split('T')
141.     date_str = meas_time_str[0]
142.     time_str = meas_time_str[1]
143.     dt1 = str2dt(date_str,time_str)
144.     mtime = (dt1 - dt0).seconds
145.     # note that the last measurement time needs to be done on the basis of cmd line
146.     last_cmd_line = 1
147.     df['pt_meas_duration'] = np.zeros(len(df), dtype=float)
148.     df.loc[idx[0], 'pt_meas_duration'] = mtime
149.     for j in idx[1:]:

```

```

150. cmd_line = df['pt_cmd_line_no:'].values[j]
151. if isinstance(df['pt_time:'].values[j],float): # failsafe if column value is empty
    a. mtime = float('nan')
    b. df.loc[j, 'pt_meas_duration'] = mtime
    c. continue
152. meas_time_str = df['pt_time:'].values[j].split('T')
153. #set last dt0 for channel
154. if last_cmd_line != cmd_line:
    a. dt0 = dt1
    b. last_cmd_line = cmd_line
155. date_str = meas_time_str[0]
156. time_str = meas_time_str[1]
157. dt1 = str2dt(date_str,time_str)
158. mtime = (dt1 - dt0).seconds # compute duration in seconds
159. df.loc[j, 'pt_meas_duration'] = mtime

160. # note that data types are not forced in the parser, those will be handled by the station
    class in data filtering
161. return metadata, df

162. def writePrime(dirname, meta, df):
163.     """
164.     Write PRIME meta data and dataframe to file.

165.     Parameters
166.     -----
167.     dirname : str
168.     Directory where to save file.
169.     meta : dict
170.     Meta data
171.     df : pandas dataframe
172.     Measurement scheme in dataframe format.

173.     Returns
174.     -----
175.     None.

176.     """
177.     suffix = '_merged'
178.     nmeas = len(df)
179.     meta['set_no_of_meas'] = ['%i'%nmeas]
180.     meta['set_est_meas_duration'] = [str(meta['set_est_meas_duration'])]
181.     text = "
182.     for key in meta.keys():
183.     if isinstance(meta[key],list):
        a. #slightly hacky way to reconstruct the original prime headers, but anything in
            the meta data which is a list is original
        b. text += '{:36}'.format(key+':')
        c. for e in meta[key]:# add list entries
        d. text += '{:} '.format(e)

```



```

        e. text += '\n'
184. text += '#UnitsOhm  Tenths %    -    -    -    -    mV    Tenths %
    mV    Tenths %    Degrees    Tenths %    mA    Tenths %    V
    Tenths %    Ohm    mV    -    Minutes    -    -    YYYY-MM-
    DDTHH:MM:SS -\n'
185. text += '#%d %g %g %d %d %d %d %g %g %g %g
    %g %g %g %g %g %g %g %g %g %.3f %d %d
    %u%c%u%c%u%c%u%c%u%c%u%c%u %x\n'
186. text += 'data:\n'

187. columns = []
188. for key in df.keys():
189.     if key.endswith(':'):
        a. columns.append(key)

190. fname = meta['filename'].replace('.tab',suffix+'.tab')
191. fpath = os.path.join(dirname,fname)
192. fh = open(fpath,'w')
193. fh.write(text)
194. df['pt_line_number:'] = np.arange(len(df))+1
195. df.to_csv(fh, sep='\t',columns=columns,index=False,line_terminator='\n')
196. fh.close()

197. #%% program
198. if not os.path.exists(target_directory):
199.     os.mkdir(target_directory)

200. ffiles = []
201. fdates = []
202. rfiles = []
203. rdates = []

204. for f in os.listdir(source_directory):
205.     if not f.endswith('.tab'):
206.         continue
207.     cmdid, date, fid = getCmdId(f)
208.     if int(cmdid) == fwd_id:
209.         ffiles.append(f)
210.         fdates.append(date)
211.     if int(cmdid) == rev_id:
212.         rfiles.append(f)
213.         rdates.append(date)

214. for i,rf in enumerate(rfiles):
215.     deltas = [rdates[i] - fdate for fdate in fdates]
216.     for j,delta in enumerate(deltas):
217.         if delta.days < 0: # ignore if negative
            a. continue
218.         if delta.seconds < max_delay_time:

```

- a. `# found a match!`
- b. `ff = ffiles[j]`
- c. `pair = [rf,ff]`
- d. `print('%s matched with %s'%(ff,rf))`

- e. `metaf, dffwd = readPrime(os.path.join(source_directory,ff))`
- f. `metar, dfrec = readPrime(os.path.join(source_directory,rf))`

- g. `df = pd.concat([dffwd,dfrec])`

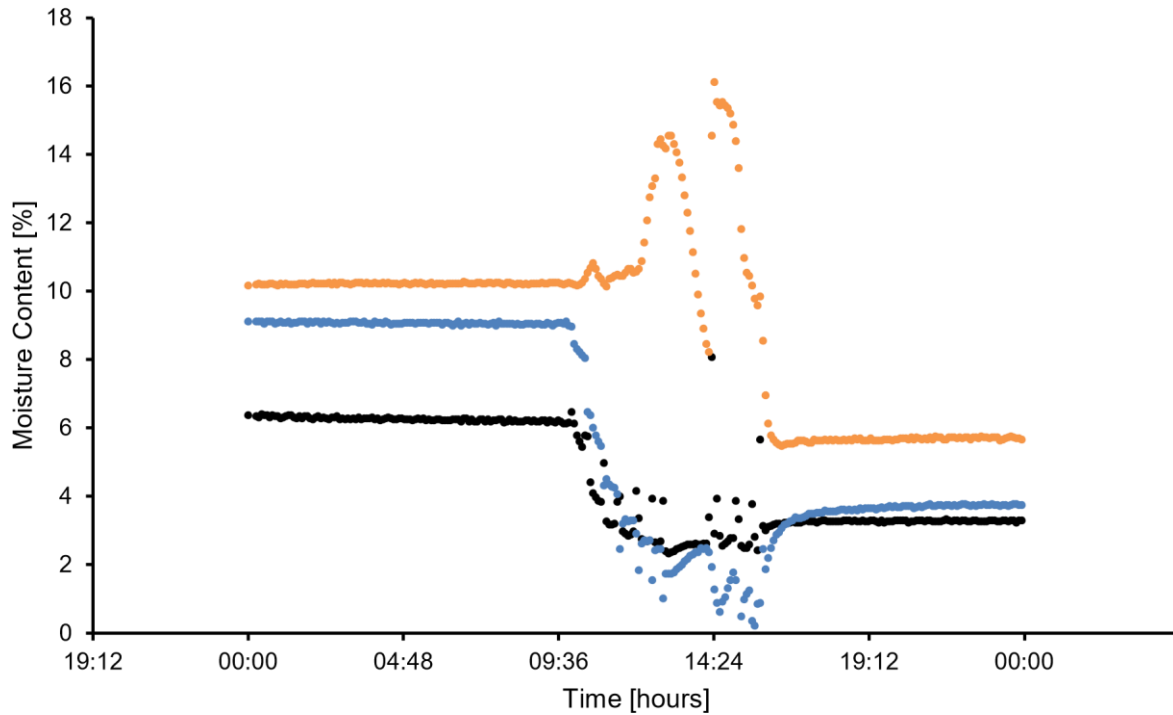
- h. `writePrime(target_directory,metaf,df)`

APPENDIX B

Sample of Point Sensor Measurements

SAND SOIL COLUMN EXPERIMENT - MEASUREMENTS FROM DAY OF STORM

Moisture content of second iteration sand-filled column



during the watering event

• Top of column • Middle of column • Bottom of column

Timestamp Top Middle bottom

00:00:00	6.368856	9.106604	10.15875
00:15:00	6.338142	9.106604	10.18773
00:20:00	6.307414	9.106604	10.2167
00:25:00	6.399557	9.106604	10.18773
00:30:00	6.368856	9.047642	10.18773
00:35:00	6.368856	9.106604	10.18773
00:40:00	6.307414	9.106604	10.2167
00:45:00	6.368856	9.106604	10.2167
00:50:00	6.338142	9.047642	10.18773
00:55:00	6.338142	9.07713	10.15875
01:00:00	6.276672	9.106604	10.2167
01:05:00	6.307414	9.07713	10.18773
01:10:00	6.338142	9.07713	10.2167
01:15:00	6.368856	9.106604	10.18773
01:20:00	6.368856	9.047642	10.18773

01:25:00	6.307414	9.07713	10.18773
01:30:00	6.276672	9.07713	10.18773
01:35:00	6.338142	9.106604	10.2167
01:40:00	6.276672	9.106604	10.2167
01:45:00	6.338142	9.106604	10.2167
01:50:00	6.338142	9.047642	10.18773
01:55:00	6.276672	9.106604	10.2167
02:00:00	6.245917	9.07713	10.24565
02:05:00	6.307414	9.106604	10.2167
02:10:00	6.338142	9.106604	10.2167
02:15:00	6.276672	9.047642	10.2167
02:20:00	6.307414	9.106604	10.2167
02:25:00	6.276672	9.07713	10.2167
02:30:00	6.245917	9.106604	10.24565
02:35:00	6.307414	9.07713	10.18773
02:40:00	6.307414	9.047642	10.24565
02:45:00	6.338142	9.07713	10.18773
02:50:00	6.245917	9.047642	10.24565
02:55:00	6.276672	9.07713	10.24565
03:00:00	6.245917	9.07713	10.2167
03:05:00	6.276672	9.07713	10.2167
03:10:00	6.245917	9.106604	10.18773
03:15:00	6.276672	9.106604	10.2167
03:20:00	6.245917	9.106604	10.24565
03:25:00	6.307414	9.07713	10.24565
03:30:00	6.245917	9.07713	10.24565
03:35:00	6.276672	9.106604	10.2167
03:40:00	6.276672	9.047642	10.24565
03:45:00	6.276672	9.047642	10.2167
03:50:00	6.307414	9.01814	10.2167

03:55:00	6.245917	9.106604	10.24565
04:00:00	6.276672	9.07713	10.2167
04:05:00	6.215148	9.07713	10.2167
04:10:00	6.245917	9.047642	10.24565
04:15:00	6.276672	9.106604	10.2167
04:20:00	6.307414	9.07713	10.24565
04:25:00	6.276672	9.01814	10.2167
04:30:00	6.245917	9.047642	10.2167
04:35:00	6.245917	9.047642	10.2167
04:40:00	6.276672	9.047642	10.18773
04:45:00	6.276672	9.047642	10.2167
04:50:00	6.245917	9.07713	10.24565
04:55:00	6.245917	9.07713	10.2167

05:00:00	6.245917	9.07713	10.18773
05:05:00	6.215148	9.07713	10.2167
05:10:00	6.245917	9.047642	10.24565
05:15:00	6.276672	9.07713	10.2167
05:20:00	6.245917	9.07713	10.24565
05:25:00	6.276672	9.07713	10.2167
05:30:00	6.215148	9.07713	10.18773
05:35:00	6.245917	9.047642	10.2167
05:40:00	6.215148	9.07713	10.24565
05:45:00	6.215148	9.07713	10.18773
05:50:00	6.245917	9.07713	10.2167
05:55:00	6.245917	9.07713	10.2167
06:00:00	6.215148	9.01814	10.2167
06:05:00	6.215148	9.07713	10.18773
06:10:00	6.215148	9.07713	10.2167
06:15:00	6.215148	9.047642	10.2167
06:20:00	6.245917	8.988625	10.2167
06:25:00	6.245917	9.047642	10.2167
06:30:00	6.245917	9.106604	10.2167
06:35:00	6.184364	8.988625	10.2167
06:40:00	6.276672	9.047642	10.27459
06:45:00	6.276672	9.07713	10.24565
06:50:00	6.184364	9.01814	10.2167
06:55:00	6.245917	9.07713	10.2167
07:00:00	6.184364	9.047642	10.2167
07:05:00	6.184364	9.047642	10.24565
07:10:00	6.245917	9.07713	10.24565
07:15:00	6.245917	9.047642	10.2167
07:20:00	6.184364	9.047642	10.2167
07:25:00	6.245917	9.01814	10.24565
07:30:00	6.184364	9.047642	10.24565
07:35:00	6.215148	9.07713	10.2167
07:40:00	6.215148	8.988625	10.24565
07:45:00	6.245917	9.106604	10.24565
07:50:00	6.245917	9.047642	10.2167

07:55:00	6.153568	9.047642	10.18773
08:00:00	6.184364	9.047642	10.24565
08:05:00	6.245917	9.047642	10.24565
08:10:00	6.184364	9.047642	10.2167
08:15:00	6.215148	9.01814	10.18773
08:20:00	6.184364	9.047642	10.2167
08:25:00	6.184364	9.01814	10.2167
08:30:00	6.184364	9.01814	10.18773

08:35:00	6.215148	9.047642	10.2167
08:40:00	6.215148	9.047642	10.18773
08:45:00	6.184364	9.047642	10.2167
08:50:00	6.215148	9.01814	10.2167
08:55:00	6.184364	9.047642	10.2167
09:00:00	6.184364	9.047642	10.2167
09:05:00	6.215148	9.01814	10.24565
09:10:00	6.215148	9.01814	10.2167
09:15:00	6.153568	9.07713	10.2167
09:20:00	6.215148	9.047642	10.24565
09:25:00	6.184364	8.988625	10.24565
09:30:00	6.153568	9.047642	10.24565
09:35:00	6.215148	9.07713	10.24565
09:40:00	6.184364	9.07713	10.2167
09:45:00	6.122757	9.047642	10.18773
09:50:00	6.122757	9.106604	10.2167
09:55:00	6.153568	8.988625	10.24565
10:00:00	6.460916	8.959097	10.2167
10:05:00	6.122757	8.455047	10.18773
10:10:00	5.782927	8.306054	10.15875
10:15:00	5.596859	8.216495	10.18773
10:20:00	5.441421	8.126814	10.24565
10:25:00	5.782927	8.037012	10.36133
10:30:00	5.75195	6.460916	10.53444
10:35:00	4.406803	6.368856	10.67834
10:40:00	4.090278	5.999376	10.82191
10:45:00	3.963275	5.782927	10.64959
10:50:00	3.867875	5.596859	10.44794
10:55:00	3.836047	5.472536	10.36133
11:00:00	4.973023	4.311993	10.2167
11:05:00	3.260733	4.501488	10.12976
11:10:00	3.164403	4.34361	10.36133
11:15:00	3.164403	4.280361	10.39021
11:20:00	3.196527	4.248716	10.44794
11:25:00	3.836047	4.058548	10.47679
11:30:00	3.995047	2.454087	10.44794
11:35:00	2.971361	3.196527	10.44794
11:40:00	2.9069	3.324883	10.53444
11:45:00	2.842383	3.260733	10.64959
11:50:00	2.874649	3.292815	10.64959

11:55:00	2.971361	3.292815	10.53444
12:00:00	4.153695	2.9069	10.56325
12:05:00	3.356936	1.835095	10.64959

12:10:00	2.745501	2.616125	10.87924
12:15:00	2.713178	2.713178	11.42127
12:20:00	2.680841	2.680841	12.07105
12:25:00	2.713178	2.713178	12.74169
12:30:00	3.931489	1.54009	13.0742
12:35:00	2.648491	2.421637	13.29484
12:40:00	2.616125	2.454087	14.30453
12:45:00	2.680841	2.454087	14.43963
12:50:00	3.867875	1.012771	14.2504
12:55:00	2.389172	1.736889	14.16912
13:00:00	2.3242	1.736889	14.54748
13:05:00	2.356693	1.736889	14.54748
13:10:00	2.389172	1.769639	14.30453
13:15:00	2.454087	1.867802	14.06055
13:20:00	2.486523	1.933173	13.76094
13:25:00	2.518945	1.998487	13.32236
13:30:00	2.551353	2.096351	12.79724
13:35:00	2.583746	2.161522	12.29543
13:40:00	2.583746	2.259172	11.76115
13:45:00	2.583746	2.291693	11.13658
13:50:00	2.616125	2.356693	10.50562
13:55:00	2.583746	2.356693	9.897343
14:00:00	2.583746	2.486523	9.341917
14:05:00	2.616125	2.454087	8.899999
14:10:00	2.616125	2.486523	8.455047
14:15:00	3.388976	2.356693	8.216495
14:20:00	8.066959	1.933173	14.54748
14:25:00	2.9069	1.27689	16.11459
14:30:00	3.931489	0.880367	15.5354
14:35:00	2.842383	0.614868	15.42943
14:40:00	2.551353	0.91349	15.5354
14:45:00	2.616125	1.045836	15.42943
14:50:00	2.680841	1.30984	15.34983
14:55:00	2.777809	1.54009	15.19027
15:00:00	2.777809	1.769639	14.86979
15:05:00	3.867875	1.54009	14.38563
15:10:00	3.324883	-0.18717	13.59686
15:15:00	2.551353	0.481773	11.81761
15:20:00	2.486523	0.979692	10.96514
15:25:00	2.486523	1.144946	10.53444
15:30:00	2.583746	1.243925	10.44794
15:35:00	3.772349	0.348447	10.15875
15:40:00	2.810103	0.214889	9.780813
15:45:00	2.421637	0.84723	9.57637

15:50:00	5.658937	0.880367	9.839105

15:55:00	3.132265	2.454087	8.544281
16:00:00	3.00357	1.867802	6.949811
16:05:00	3.100112	2.194086	6.122757
16:10:00	3.132265	2.486523	5.782927
16:15:00	3.164403	2.713178	5.658937
16:20:00	3.196527	2.874649	5.565799
16:25:00	3.196527	2.939138	5.503638
16:30:00	3.164403	3.067946	5.472536
16:35:00	3.228637	3.164403	5.503638
16:40:00	3.228637	3.196527	5.534725
16:45:00	3.228637	3.260733	5.534725
16:50:00	3.260733	3.292815	5.534725
16:55:00	3.228637	3.388976	5.565799
17:00:00	3.228637	3.356936	5.627905
17:05:00	3.228637	3.356936	5.627905
17:10:00	3.260733	3.388976	5.627905
17:15:00	3.292815	3.421001	5.596859
17:20:00	3.260733	3.485009	5.565799
17:25:00	3.260733	3.485009	5.565799
17:30:00	3.260733	3.485009	5.658937
17:35:00	3.228637	3.516992	5.627905
17:40:00	3.260733	3.516992	5.627905
17:45:00	3.292815	3.516992	5.627905
17:50:00	3.292815	3.580916	5.658937
17:55:00	3.260733	3.548961	5.627905
18:00:00	3.260733	3.548961	5.658937
18:05:00	3.260733	3.548961	5.627905
18:10:00	3.260733	3.548961	5.658937
18:15:00	3.260733	3.580916	5.627905
18:20:00	3.260733	3.612857	5.627905
18:25:00	3.292815	3.612857	5.658937
18:30:00	3.292815	3.580916	5.627905
18:35:00	3.292815	3.612857	5.658937
18:40:00	3.260733	3.580916	5.627905
18:45:00	3.292815	3.612857	5.689955
18:50:00	3.260733	3.580916	5.658937
18:55:00	3.260733	3.644783	5.689955
19:00:00	3.292815	3.612857	5.627905
19:05:00	3.260733	3.644783	5.627905
19:10:00	3.260733	3.644783	5.627905
19:15:00	3.292815	3.644783	5.689955
19:20:00	3.292815	3.644783	5.627905

19:25:00	3.260733	3.612857	5.627905
19:30:00	3.228637	3.644783	5.627905
19:35:00	3.292815	3.676696	5.627905
19:40:00	3.228637	3.644783	5.658937
19:45:00	3.260733	3.676696	5.658937
19:50:00	3.260733	3.708594	5.658937

APPENDIX C

Additional Results

Gravel-Filled Capillary Barrier System

Changes in Soil Moisture Content

The first storm event was on the 14th of December 2022 (as seen in figure 1), followed by a second storm 28 days later, on the 11th of January 2023. The starting conditions in the column were dry, with an average moisture content of 5.8% in the topsoil and 4.7% at the bottom in the underlying gravel. During Storm Event 1, the data shows that water did break through the capillary barrier and entered the gravel. Moisture content in the gravel increases from 4.7% to a maximum moisture content of 9.2%. After Storm Event 1, the moisture content in the underlying gravel returns to similar pre-storm conditions (4.9%) before Storm Event 2 is initiated. Moisture levels in the topsoil decreased gradually over the recorded 28 days. However, they did not return to starting values due to the capillary barrier in effect and the lower porosity of the topsoil compared to the gravel. After drying, the moisture content in the topsoil before Storm Event 2 was 16.1% and 13.8% in the top and middle regions of the soil, respectively.

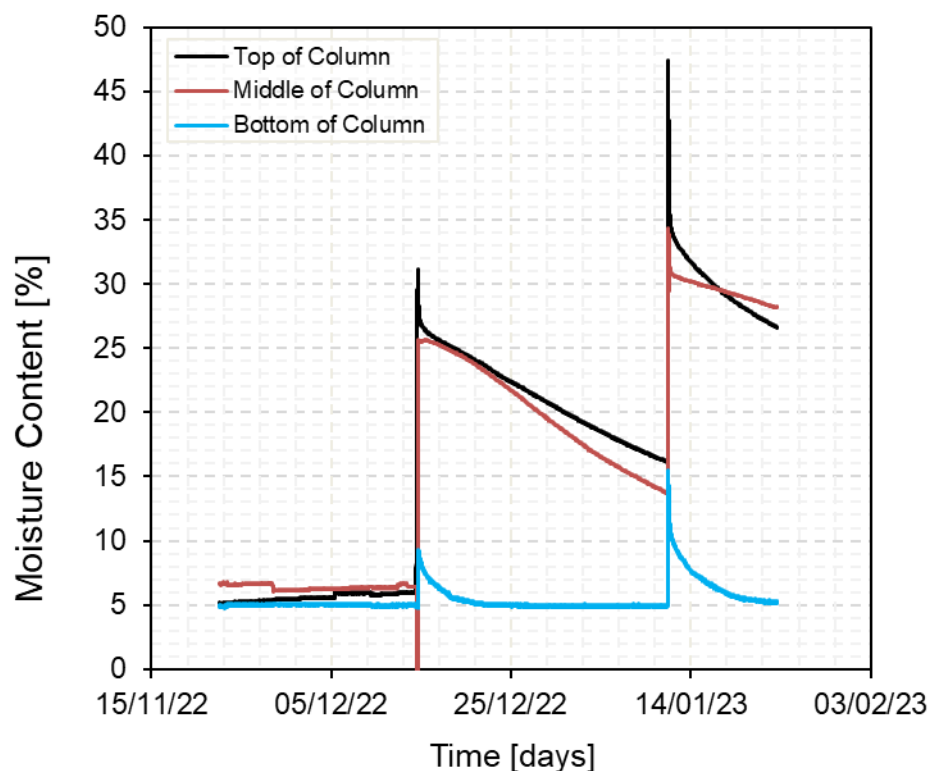


Figure 1 Moisture content data captured by TEROS 12 sensors in the gravel-filled capillary barrier system column experiment during two simulated storm events.

Storm Event 2 yielded similar results to Storm Event 1. Moisture content in the topsoil (top and middle of the column) increases to 47.4% and 34.3%, respectively. In the gravel, the moisture content increases to 15.1%, indicating that breakthroughs occurred. After Storm Event 2, moisture levels in the upper region of the topsoil fell significantly in 24 hours and began to fall steadily over ten days. As water percolates through the topsoil, moisture content in the lower section of the topsoil layer increases steadily, surpassing levels observed in the top section of the topsoil. Despite this percolation captured by the point sensors after storm event 2, moisture levels in the underlying coarse-grained material continue to decrease steadily, suggesting that water is being held in the overlying fine-grained topsoil, indicating that the capillary barrier is still in effect. Ideally, consecutive drying and watering events could have been conducted on the CBS to better gauge the effectiveness of CBSs after consecutive extreme wetting events. Doing so would have shown how quickly the system recovered as conditions in the column inevitably became more saturated. However, this was not possible due to difficulties experienced during geoelectrical modelling.

Sand-Filled Capillary Barrier System

Changes in Soil Moisture Content

Figure 2 indicates that the starting moisture content averaged 4.0% in the topsoil and 5.0% in the sand. Moisture content in the top and middle sections of the overlying topsoil increased during Storm Event 1 (43.8% and 26.1% in the top and middle regions, respectively). No water breakthrough into the sand was detected during or after Storm Event 1 despite the steady decrease in moisture content observed in the overlying topsoil, indicating that the capillary barrier was still in effect. There is a gap in the data on February 8th when the point sensor monitoring failed. This issue was rectified before commencing Storm Event 2. During Storm Event 2, a breakthrough occurs, and water enters the sand layer, leading to moisture content in the sand rising to 10.3%. Due to water draining into the sand, moisture levels in the topsoil do not rise to the same levels observed in the first storm event (between 35.1 and 38.7%). After storm Event 2, the moisture content in the topsoil steadily decreases whilst levels in the sand remain at approximately 10.0%.

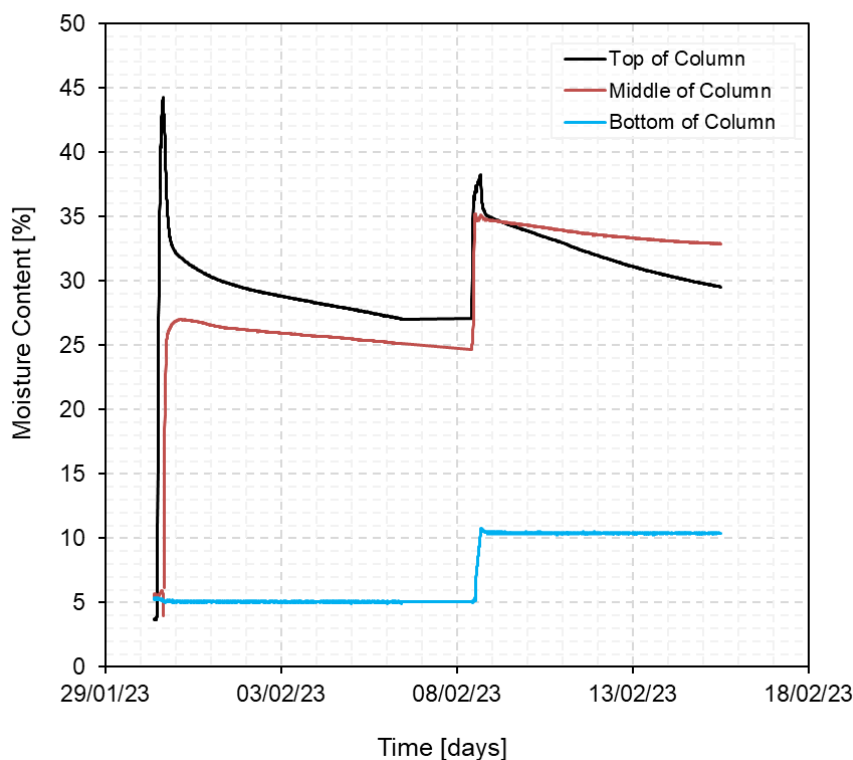


Figure 2 Moisture content data captured by TEROS 12 sensors in the sand-filled capillary barrier system column experiment during two simulated storm events.

Compacted Clay Topsoil Column Experiments

Analysis of surface water runoff during storm events

Figure 3 shows the runoff measured by the tipping gauges during the storm for each compacted CT during Exp. 2. Water infiltration was low for each compacted clay, and little drainage occurred throughout the experiments. At 1.57 Mg/m^3 and 1.69 Mg/m^3 , the number of surface runoff tips recorded is higher than soil compacted at 1.46 Mg/m^3 . This indicates that water was regularly removed at higher dry densities from the system. The range of values at 1.46 Mg/m^3 and 1.57 Mg/m^3 is also high. At 1.46 Mg/m^3 , the average volume of water removed throughout the storm event is between 4 ml and 12 ml. The volume of water removed is lower than that observed at a higher compaction as more water infiltration occurred at 1.46 Mg/m^3 . However, where gaps in the data appear, these are followed by two significant drainage events where 68 ml and 56 ml of water were removed from the soil surface at 13:15 and 14:45, respectively. This highlights the inconsistency in the drainage regime and suggests that, at times, water was allowed to pond on the surface despite efforts made to avoid this.

These sporadic increases in the volume of water removed as runoff can be attributed to two scenarios:

1. Some settlement occurred when water was added to the column, increasing the distance between the soil surface and the runoff tube aperture. No settlement occurred at maximum dry density (1.69 Mg/m^3), resulting in consistent water runoff and no ponding.
2. Blockages occurred at the aperture of the runoff tube or in the tube itself due to fine material washing into it. As more ponding happened, pressure at the aperture increased to a point where blocking material was washed through the tube.

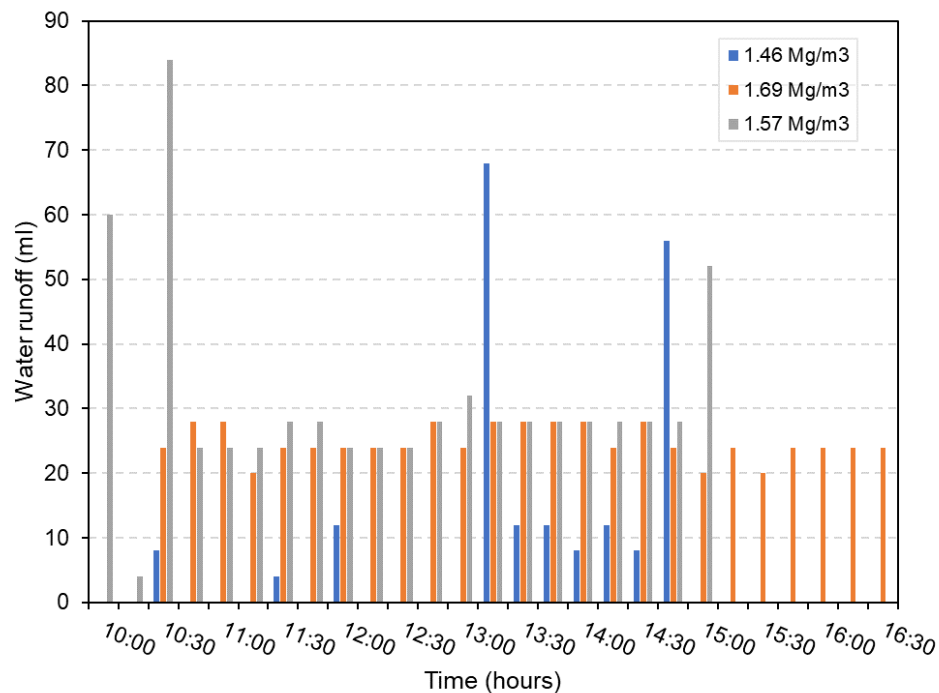


Figure 3 Tipping gauge data comparing surface runoff during simulated storm events in clay-topsoil compacted at different dry densities.

Clay Topsoil Compacted to 1.46 Mg/m³ Dry Density

Changes in Soil Moisture Content

The moisture content at the top of the column increases from 10.3% to 19.8% when water is added. Moisture levels in the middle of the clay topsoil fell from 11.7% to 10.0% during the storm. This is likely caused by the positive head increase from the stormwater on the surface, leading to increased pore air pressure below, which drives drainage through the column. This is supported by the reduced water content in the middle and a slight uptick in moisture content recorded near the bottom of the column during the storm event (starting at 8.4% and increasing to 9.2%). One day later, moisture levels in the top region of the soil declined steadily, reaching 18.2% seven days later. Moisture content in the middle of the soil column rises significantly from 10.0% to 29.6%. The data suggests that water is held in the middle of the column and cannot percolate to the lower regions of the soil.

Clay Topsoil Compacted to 1.69 Mg/m³ Dry Density

Soil Transfer Resistances

Figure 4 measures the change in transfer resistances during the storm on day 1. The top four lines of electrodes are analysed to plot the transfer resistances, given that the percentage difference in resistivity shown in the time-lapse survey is most pronounced at the soil surface to a depth of approximately -250mm. Figure 5 shows the change in transfer resistances on day 2, one day after the storm. Transfer resistances were extracted from the bottom four lines of electrodes, as most of the artefacts are observed at the base of the soil. Both Figures 4 and 4.20 show slight changes in moisture content ($\leq 1\%$) that correspond with the lack of changes in the transfer resistance measurements. Similar to the ERT images depicted in Figure 4.14 (CT at 1.46 Mg/m³), the modelled artefacts at 1.69 Mg/m³ are likely a product of the ponded water and not actual measurements. The appearance and prevalence of artefacts at maximum dry density are greater than those observed at 1.46 Mg/m³ because little water infiltration occurred at the higher compacted state.

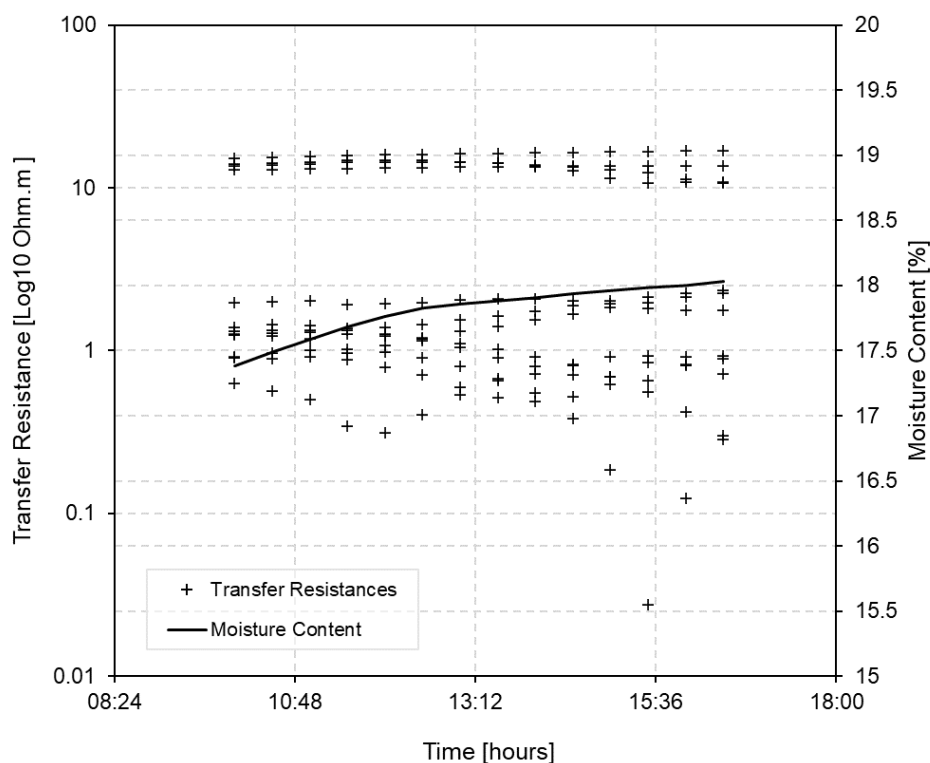


Figure 4 Transfer resistances of the clay topsoil compacted to a dry density of 1.69 Mg/m³. Data shows the changes in moisture content and transfer resistances during the storm event from the soil surface to -250mm depth.

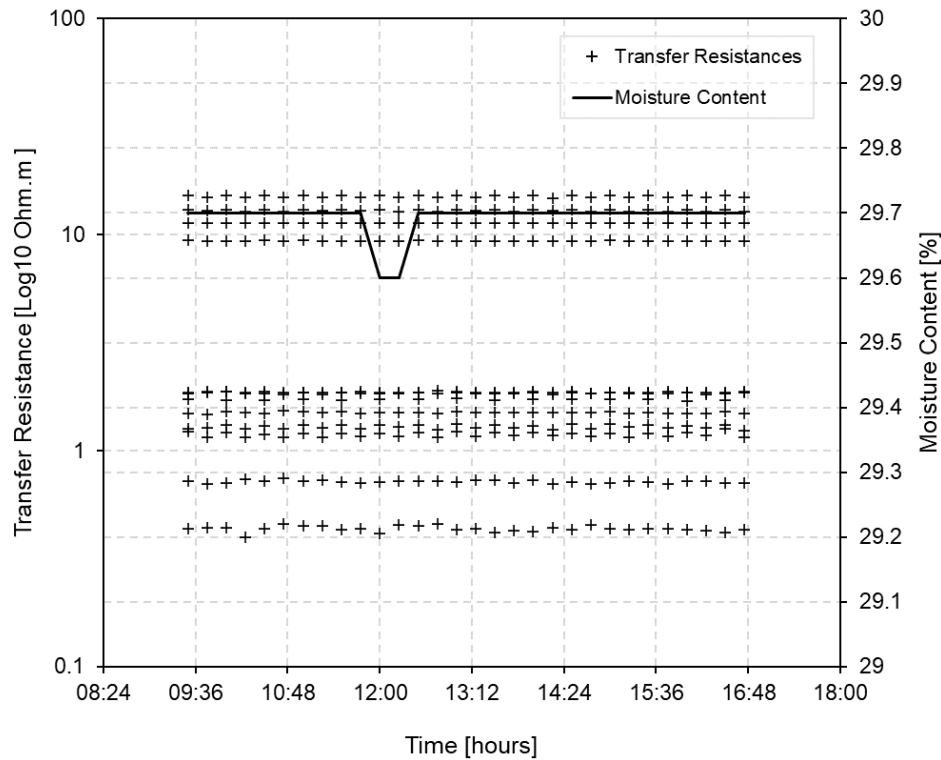


Figure 5 Transfer resistances of the clay topsoil compacted to a dry density of 1.69 Mg/m^3 . Data shows the changes in moisture content and transfer resistances one day after the storm event from -250mm to the base of the soil (-500mm).

Differences in Resistivity - Compacted Clay Topsoil in Experiment 1

In CT compacted to 1.46 Mg/m^3 , a wetting front is observed in the ERT imaging despite ponding. However, due to low infiltration at 1.69 Mg/m^3 and 1.57 Mg/m^3 , no wetting front is observed, and artefacts dominate the ERT images. In Sections 4.2 - 4.4, soil transfer resistances are analysed to establish whether suspected modelling artefacts resulted from inversion errors or are real measurements. Transfer resistances demonstrate that when soil moisture content increases, transfer resistances decrease. However, the reduction in electrical resistivity and progression of a wetting front during a simulated storm is only partially observed in the ERT images. At the time of carrying out the CT soil column experiments, the source of the artefacts in the ERT imaging was unknown. In the gravel and sand-filled CBS experiments, artefacts are attributed to high contact resistances and reciprocal errors. However, these were reduced significantly in the CT, resulting in the inversion converging before 20 iterations with a low RMS (root mean square). As previously stated, the exact cause of modelling artefacts was not realised during soil column tests, and despite establishing the artefacts were a product of

modelling errors and not actual measurements, it was challenging to determine if the modelling errors were attributed to a physical aspect of the experiment (e.g. electrode geometries or injected current input, etc.) or an oversight in the code or formulae of the inversion.

Series 2 Compacted Clay Topsoil Column Experiments

Clay Topsoil Compacted to 1.46 Mg/m^3 Dry Density (Experiment 2)

Figure 6 provides a side-by-side comparison of moisture content at the top, middle and bottom of the soil in Exp. 1 (left) and Exp. 2 (right). Data in Exp. 2 highlights the influence of the runoff tube on soil moisture content. Including the runoff channel reduced the amount of water that could percolate through the soil over time. As a result, moisture content in the middle and bottom of the soil increased by less than 2.0%, whereas moisture content at the top increased by 26%.

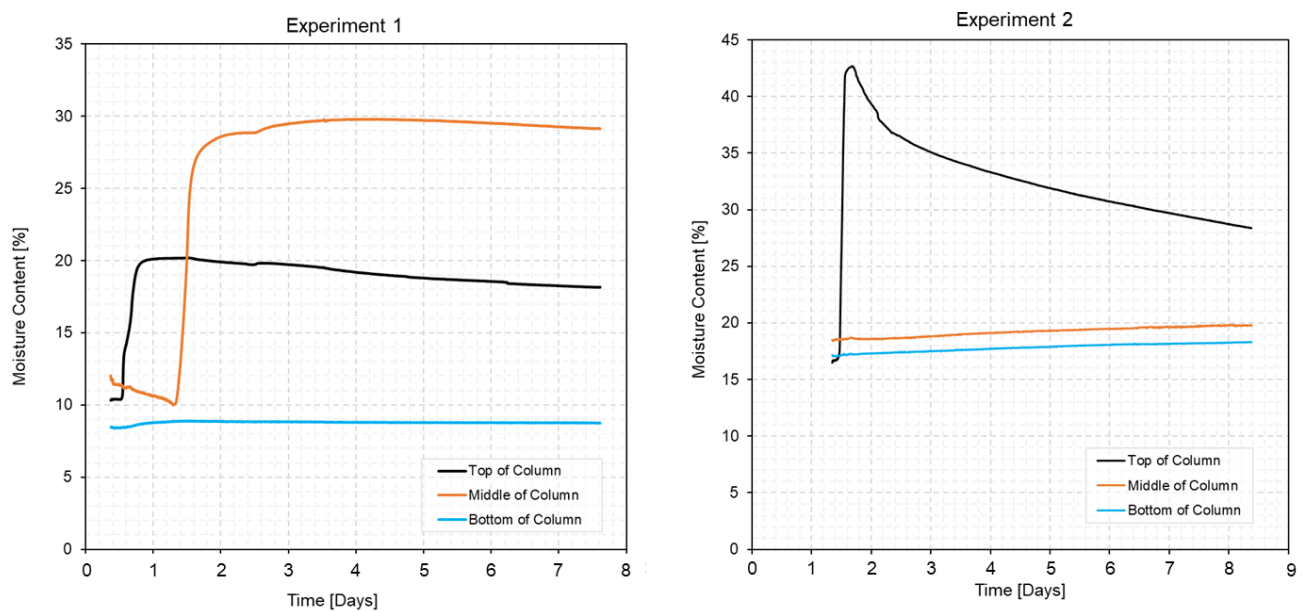


Figure 6 Point sensor data collected from clay topsoil compacted to 1.46 Mg/m^3 . Changes in moisture content over time with no drainage tube (Exp. 1) versus including a drainage tube (Exp. 2).

In Exp. 1, of the three CT column experiments, soil compacted to 1.46 Mg/m^3 shows a visible wetting front over time in the ERT imaging. However, in Exp. 2, artefacts in the inversion (Figure 7) conceal any imaging of a wetting front despite moisture content increasing at the top of the soil by approximately 26%. Data across the entire experiment timeframe was inverted and analysed. However, the distribution and extent of artefacts remains the same. The outflow tube did reduce the extent of ponding. However, ponding still occurred due to soil settlement during the storm. As settlement occurred over time, the distance between the aperture and soil surface increased, and surface water drainage was intermittent.

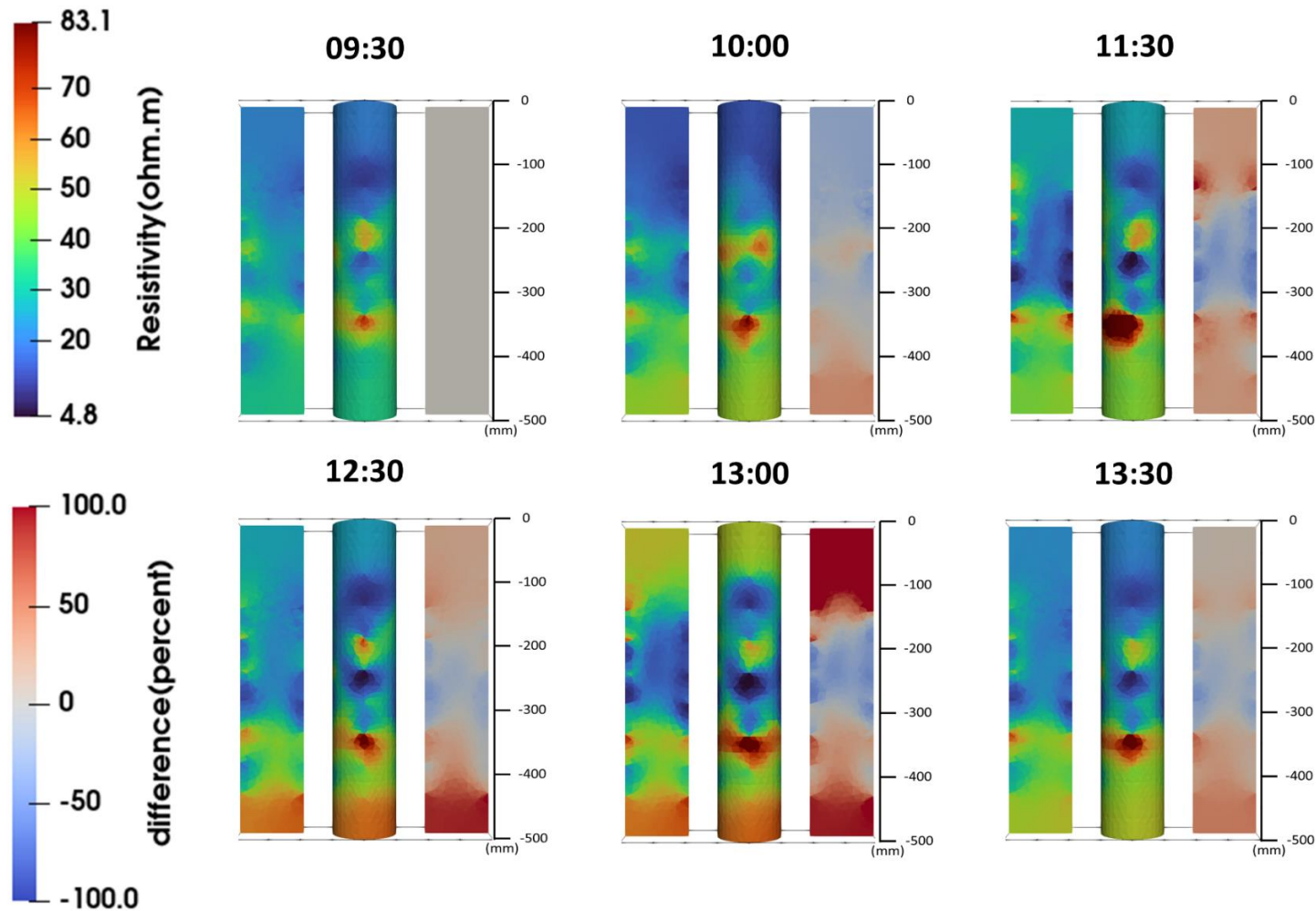


Figure 7 A timelapse survey of clay topsoil compacted to a dry density of 1.46 Mg/m^3 . Data was collected during a simulated storm in Experiment 2 after deploying a surface water outflow tube. Images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

Clay Topsoil Compacted to 1.69 Mg/m³ Dry Density (Experiment 2)

Figure 8 shows the changes in moisture content during a storm event in Exp. 1 and Exp. 2 in CT compacted at maximum dry density (1.69 Mg/m³). In Experiment 2, where runoff occurs, moisture content decreases throughout the experiment as little infiltration occurs at maximum dry density. After the storm, water in the top region of the soil evaporates, drying out the soil by 1%. The moisture content in the middle of the column did not change. Moisture content in the lower column increased from 17.0% to 17.3%. Ultimately, because changes in soil moisture content were minimal, it was anticipated that the ERT soil column would not capture a change in electrical resistivity over time or would measure an increase in resistivity, given that water was continuously removed from the soil surface.

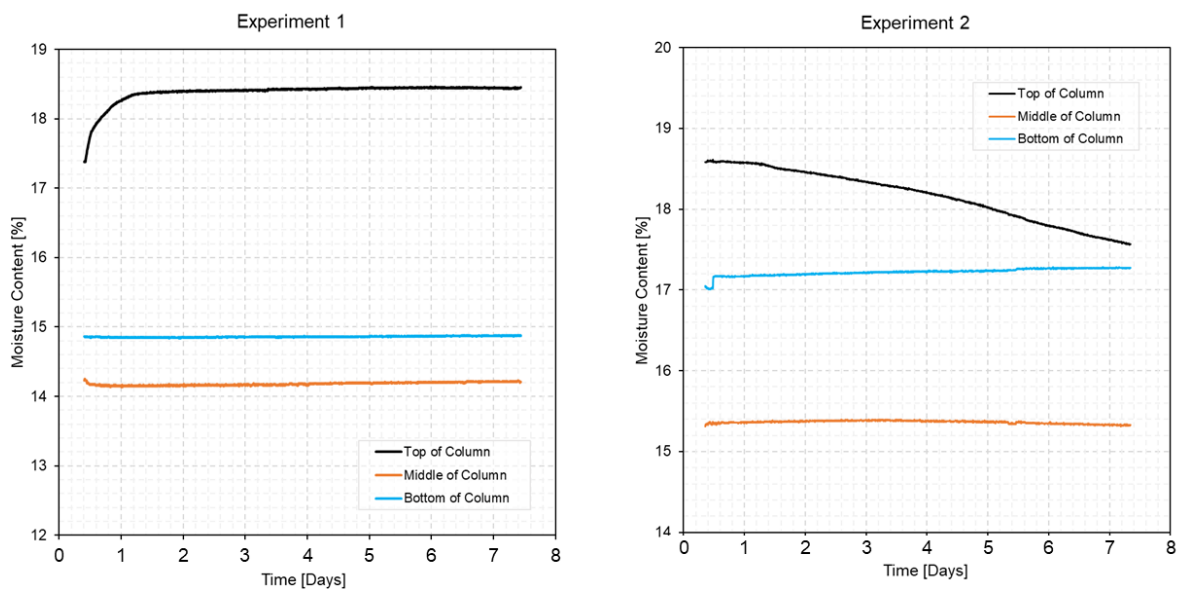


Figure 8 Point sensor data collected from clay topsoil compacted to 1.69 Mg/m³. Changes in moisture content over time with no drainage tube (Exp. 1) versus including a drainage tube (Exp. 2).

A sample of the timelapse ERT results produced on CT compacted to 1.69 Mg/m³ dry density during Exp. 2 is shown in Figure 9. The percentage difference in resistivity is given as a percentage change of $\leq 15\%$, as changes in resistance were minimal throughout the experiment. A storm event was initiated on day 1. No changes in resistivity were detected during the storm as water was continually drained from the soil surface via the tube. Unlike the previous experiment at a dry density of 1.46 Mg/m³, this soil was compacted at maximum dry density. As a result, little to no settlement occurred that could induce ponding. Two days after the storm

(day 3), there was an increase in resistivity ($\leq 3\%$) indicative of the soil drying. Changes in electrical resistivity throughout the experiment are consistent with point sensor measurements depicted in Figure 8. On day 5, at 10:00 and 14:00, artefacts appear in the modelled data. The exact cause of these artefacts is unknown, as no changes to the environment or soil conditions were detected after the storm simulation. These two timesteps are the only ones in the series to present artefacts suggesting an error during the inversion process that was rectified in the subsequent timesteps. At the end of the experiment (day 7), resistivity throughout the soil increased between 5.0% and 10.0%, with resistivity higher at the top of the soil profile, where water evaporated from the soil surface.

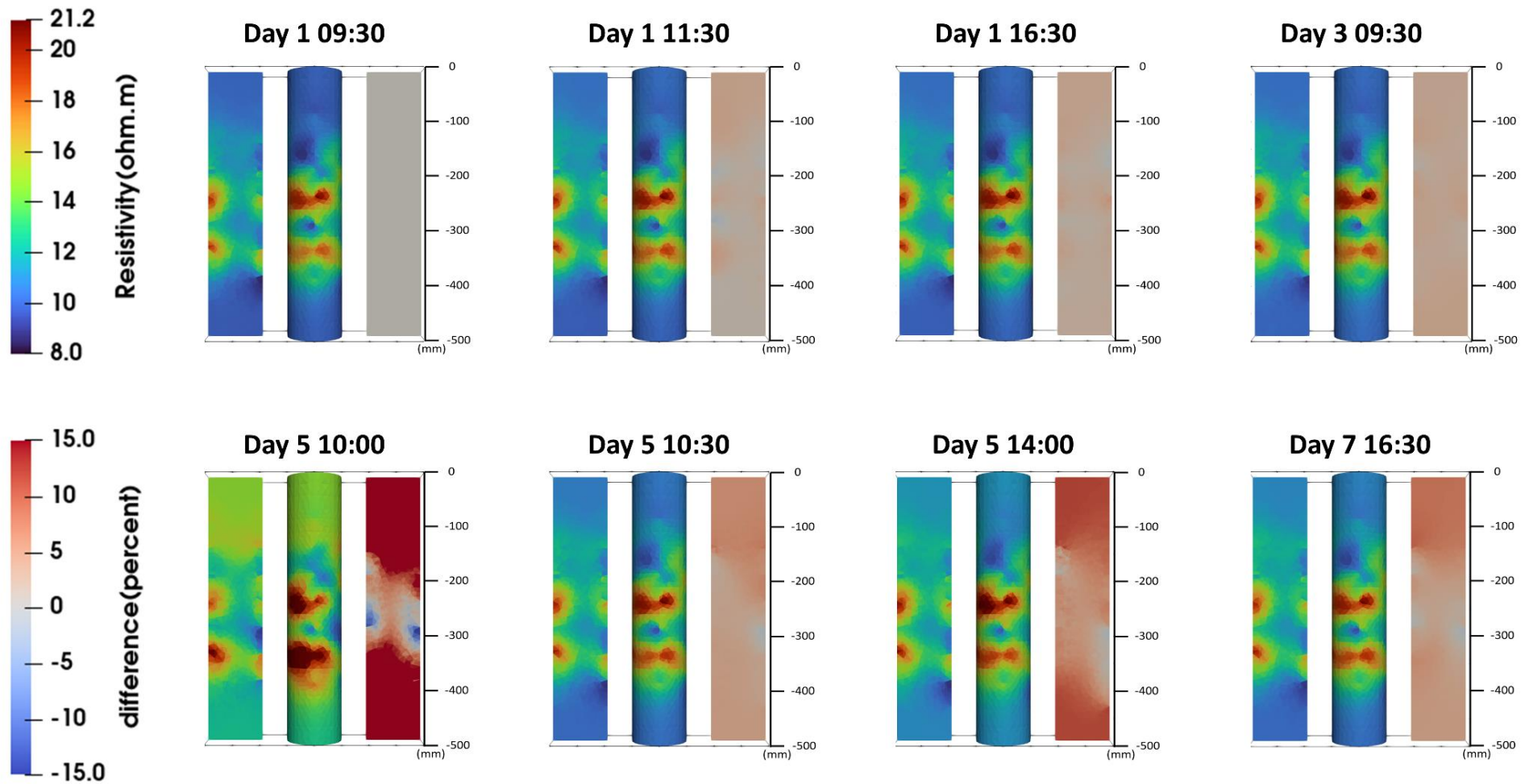


Figure 9 A timelapse survey of clay topsoil compacted to a dry density of 1.69 Mg/m^3 (maximum dry density). Data was collected during Experiment 2 after deploying a surface water outflow tube. Images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

Clay Topsoil Compacted to 1.57 Mg/m³ Dry Density (Experiment 2)

In CT compacted at 1.57 Mg/m³, point sensor data in Figure 10 compares moisture content in Exp. 1 and 2 during and after a simulated storm. In Exp. 2, the data shows that on day 1, the moisture content at the base was approximately 4.0% higher than at the top and middle levels. During the storm, there is a rapid increase in moisture content at the top of the soil from 21.6% to 29.4%. 2 days later, however, moisture content decreases to 18.9%, falling below the moisture content in the middle and bottom of the soil column. During the storm, the moisture content in the middle and bottom of the column did not change. Three days later, moisture content increases by <1% in the middle and bottom of the soil. The slight uptick in moisture content in the lower regions of soils indicates a small amount of water transport. However, it does not account for the rapid decrease in moisture from the top of the soil, suggesting that water loss was predominately through evaporation as the tipping buckets capture no basal drainage from the column.

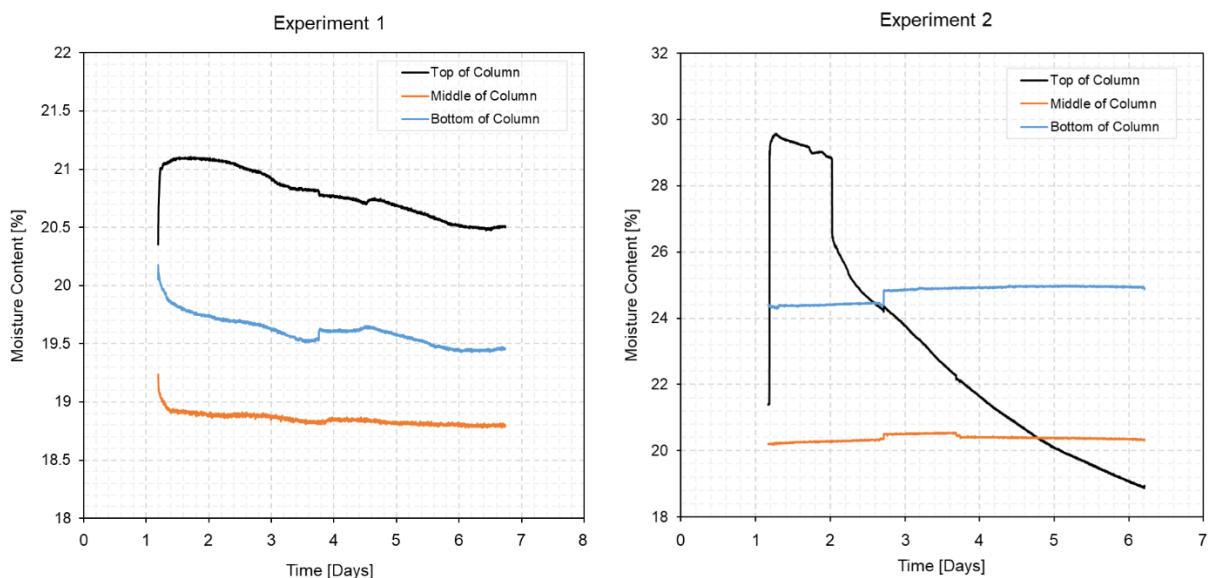


Figure 10 Point sensor data was collected from a soil column experiment on clay topsoil compacted at 1.57 Mg/m³ during Experiment 1 (left), where ponding occurred, and Experiment 2 (right), where a runoff channel was included to reduce surface water ponding.

Like ERT imaging in CT at 1.46 Mg/m³ (Exp.2), artefacts appear in the inversion shown in Figure 11 (CT = 1.57 Mg/m³). Surface water drainage was intermittent, leading to some ponding. Images shown in the survey were taken during the simulated storm. Artefacts were most prevalent at 11:00 and 16:30. In the other timesteps, artefacts in the data appear to a lesser extent, although they are still visible in the images.

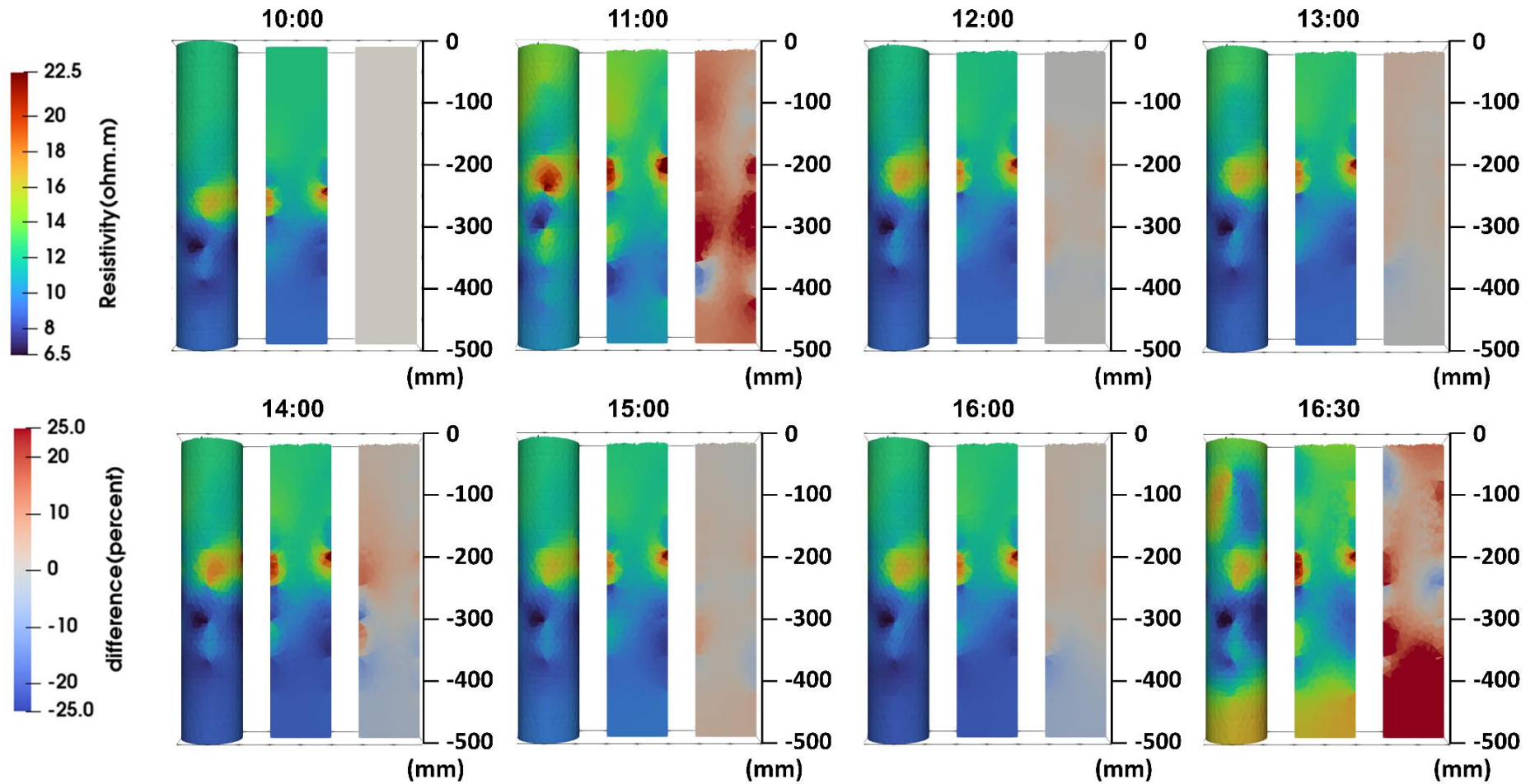


Figure 11 A time-lapse survey of clay topsoil compacted at 1.57 Mg/m^3 . Data was collected during Experiment 2, which included a runoff channel. Images show the spatial distribution of resistivity (left and centre of each timestep) and the percentage difference in resistivity (right).

Bourne Amenity Topsoil Column Experiment

Soil Moisture Content Changes

Topsoil was added to the column at 10% moisture content, as reflected in the point sensor data in Figure 12. The soil was loosely added to the column and not compacted to a specific dry density to avoid ponding and reduce the time water percolated through the material. Water was first added to the column on day 1. The moisture content at the top of the soil profile increased to 43.5%. Moisture content in the middle and bottom of the column rose to 33.8% and 35.3%, respectively. At the end of the storm (16:00), moisture levels in the soil declined. As water percolated through the soil, the moisture content in the top and middle sections of the soil decreased steadily during the drying phase. Towards the end of the experiment (day 7), the moisture content at the top of the column was lower than at the bottom. Moisture content near the bottom remained unchanged after an initial decrease, which was directly after the end of the simulated storm. Precisely 20 ml of water was drained from the base three days after the storm.

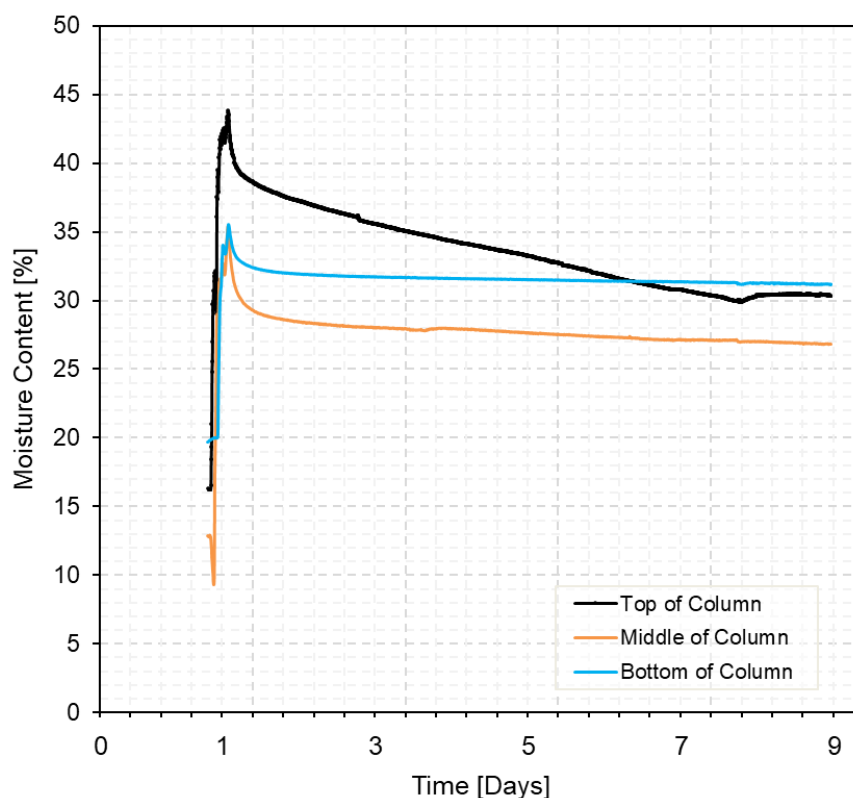
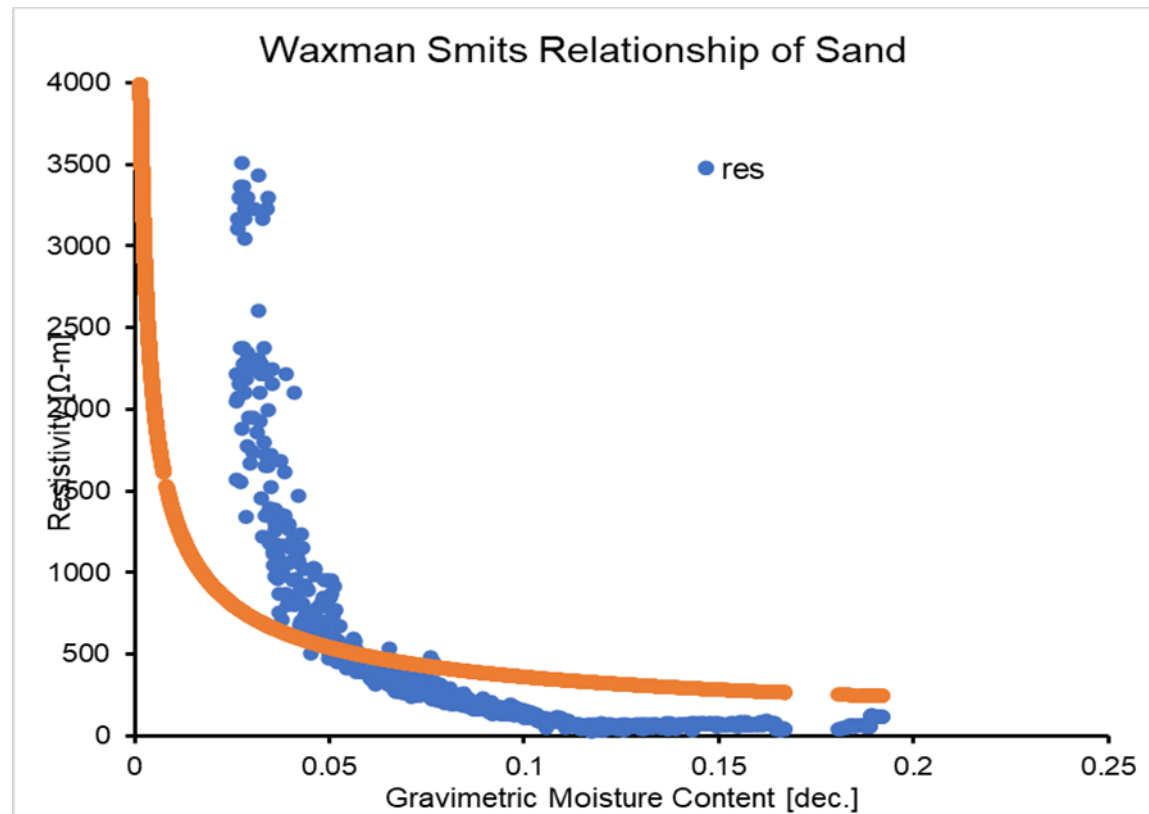


Figure 12 Point sensor data collected from soil column experiments on topsoil during and after a simulated storm.

APPENDIX D

Petrophysical Data – Waxman Smits and Power Law Fit

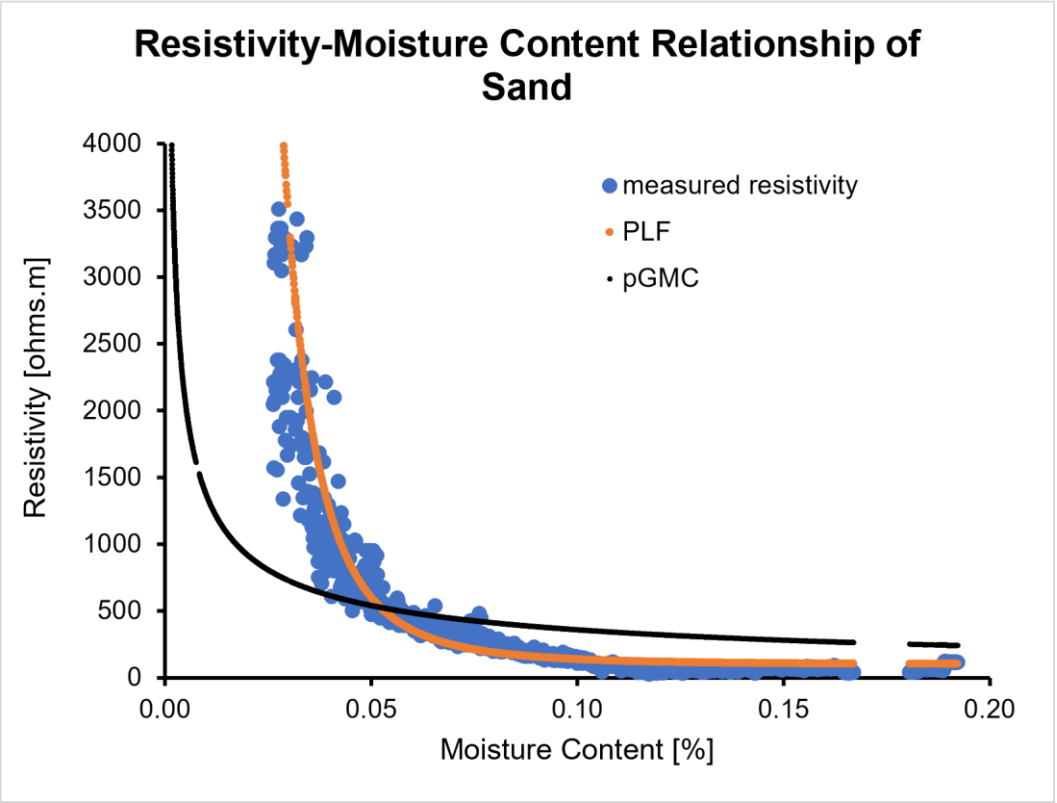


Records: 4024 Timestamp	ES-2 mS/cm EC	calibrated ES2 mS/cm EC	ES-2 °C Water Temperature	ES-2 mS/cm Weighted EC	Barometer kPa Reference Pressure	Date / Time
19/04/2023 11:20	1.355	0.0854035	21.3	1.355	102.48	19*04*2023 12:21:58
19/04/2023 11:30	1.361	0.0857737	21.3	1.361	102.48	19*04*2023 12:23:04
19/04/2023 11:40	1.361	0.0857737	21.2	1.361	102.48	19*04*2023 12:24:08
19/04/2023 11:50	1.365	0.0860205	21.4	1.365	102.47	19*04*2023 12:25:12
19/04/2023 12:00	1.355	0.0854035	21.5	1.355	102.47	19*04*2023 12:26:16

19/04/2023 12:10	1.355	0.0854035	21.6	1.355	102.46	19*04*2023 12:27:20
19/04/2023 12:20	1.355	0.0854035	21.7	1.355	102.45	19*04*2023 12:28:24
19/04/2023 12:30	1.349	0.0850333	21.7	1.349	102.45	19*04*2023 12:29:28
19/04/2023 12:40	1.352	0.0852184	21.8	1.352	102.44	19*04*2023 12:30:32
19/04/2023 12:50	1.355	0.0854035	21.9	1.355	102.45	19*04*2023 12:31:37
19/04/2023 13:00	1.349	0.0850333	21.9	1.349	102.44	19*04*2023 12:32:41
19/04/2023 13:10	1.355	0.0854035	21.9	1.355	102.44	19*04*2023 12:33:45
19/04/2023 13:20	1.355	0.0854035	22	1.355	102.43	19*04*2023 12:34:49
19/04/2023 13:30	1.346	0.0848482	22	1.346	102.43	19*04*2023 12:35:53
19/04/2023 13:40	1.349	0.0850333	22	1.349	102.42	19*04*2023 12:36:57
19/04/2023 13:50	1.346	0.0848482	22.1	1.346	102.42	19*04*2023 12:38:01
19/04/2023 14:00	1.349	0.0850333	22.1	1.349	102.41	19*04*2023 12:39:05
19/04/2023 14:10	1.343	0.0846631	22.2	1.343	102.4	19*04*2023 12:40:09
19/04/2023 14:20	1.346	0.0848482	22.2	1.346	102.39	19*04*2023 12:41:12
19/04/2023 14:30	1.346	0.0848482	22.3	1.346	102.39	19*04*2023 12:42:16
19/04/2023 14:40	1.343	0.0846631	22.3	1.343	102.38	19*04*2023 12:43:20
19/04/2023 14:50	1.337	0.0842929	22.3	1.337	102.36	19*04*2023 12:44:23
19/04/2023 15:00	1.334	0.0841078	22.4	1.334	102.35	19*04*2023 12:45:27
19/04/2023 15:10	1.33	0.083861	22.4	1.33	102.35	19*04*2023 12:46:30
19/04/2023 15:20	1.324	0.0834908	22.5	1.324	102.35	19*04*2023 12:47:33
19/04/2023 15:30	1.318	0.0831206	22.5	1.318	102.35	19*04*2023 12:48:36
19/04/2023 15:40	1.315	0.0829355	22.5	1.315	102.34	19*04*2023 12:49:39
19/04/2023 15:50	1.321	0.0833057	22.5	1.321	102.34	19*04*2023 12:50:42
19/04/2023 16:00	1.318	0.0831206	22.6	1.318	102.34	19*04*2023 12:51:46
19/04/2023 16:10	1.318	0.0831206	22.6	1.318	102.34	19*04*2023 12:52:49
19/04/2023 16:20	1.315	0.0829355	22.6	1.315	102.34	19*04*2023 12:53:52
19/04/2023 16:30	1.928	0.1207576	22.6	1.928	102.34	19*04*2023 12:54:55
19/04/2023 16:40	2.624	0.1637008	22.6	2.624	102.34	19*04*2023 12:55:59
19/04/2023 16:50	2.754	0.1717218	22.7	2.754	102.34	19*04*2023 12:57:02
19/04/2023 17:00	2.844	0.1772748	22.7	2.844	102.33	19*04*2023 12:58:05

19/04/2023 17:10	2.938	0.1830746	22.7	2.938	102.33	19*04*2023 12:59:08
19/04/2023 17:20	2.818	0.1756706	22.7	2.818	102.33	19*04*2023 13:00:11
19/04/2023 17:30	2.754	0.1717218	22.7	2.754	102.32	19*04*2023 13:01:15
19/04/2023 17:40	2.748	0.1713516	22.7	2.748	102.32	19*04*2023 13:02:20
19/04/2023 17:50	2.761	0.1721537	22.7	2.761	102.31	19*04*2023 13:03:24
19/04/2023 18:00	2.716	0.1693772	22.7	2.716	102.31	19*04*2023 13:04:27
19/04/2023 18:10	2.805	0.1748685	22.8	2.805	102.32	19*04*2023 13:05:30
19/04/2023 18:20	2.864	0.1785088	22.8	2.864	102.32	19*04*2023 13:06:34
19/04/2023 18:30	2.793	0.1741281	22.8	2.793	102.32	19*04*2023 13:07:37
19/04/2023 18:40	2.767	0.1725239	22.8	2.767	102.32	19*04*2023 13:08:40
19/04/2023 18:50	2.692	0.1678964	22.8	2.692	102.33	19*04*2023 13:09:43
19/04/2023 19:00	2.679	0.1670943	22.8	2.679	102.33	19*04*2023 13:10:47
19/04/2023 19:10	2.667	0.1663539	22.9	2.667	102.34	19*04*2023 13:11:50
19/04/2023 19:20	2.71	0.169007	22.9	2.71	102.34	19*04*2023 13:12:53
19/04/2023 19:30	2.685	0.1674645	22.9	2.685	102.35	19*04*2023 13:13:57
19/04/2023 19:40	2.624	0.1637008	22.9	2.624	102.35	19*04*2023 13:15:00
19/04/2023 19:50	2.636	0.1644412	22.9	2.636	102.35	19*04*2023 13:16:03
19/04/2023 20:00	2.692	0.1678964	22.8	2.692	102.35	19*04*2023 13:17:07
19/04/2023 20:10	2.506	0.1564202	22.8	2.506	102.34	19*04*2023 13:18:10
19/04/2023 20:20	2.553	0.1593201	22.8	2.553	102.34	19*04*2023 13:19:13
19/04/2023 20:30	2.6	0.16222	22.8	2.6	102.35	19*04*2023 13:20:16
19/04/2023 20:40	2.588	0.1614796	22.8	2.588	102.35	19*04*2023 13:21:20
19/04/2023 20:50	2.512	0.1567904	22.8	2.512	102.34	19*04*2023 13:22:23
19/04/2023 21:00	2.559	0.1596903	22.8	2.559	102.34	19*04*2023 13:23:26
19/04/2023 21:10	2.541	0.1585797	22.8	2.541	102.34	19*04*2023 13:24:29
19/04/2023 21:20	2.523	0.1574691	22.8	2.523	102.33	19*04*2023 13:34:30
19/04/2023 21:30	2.594	0.1618498	22.8	2.594	102.32	19*04*2023 13:44:31
19/04/2023 21:40	2.624	0.1637008	22.8	2.624	102.32	19*04*2023 13:54:32
19/04/2023 21:50	2.506	0.1564202	22.7	2.506	102.31	19*04*2023 14:04:35
19/04/2023 22:00	2.704	0.1686368	22.7	2.704	102.31	19*04*2023 14:14:35

19/04/2023 22:10	2.449	0.1529033	22.7	2.449	102.3	19*04*2023 14:24:35
19/04/2023 22:20	2.564	0.1599988	22.7	2.564	102.3	19*04*2023 14:34:36
19/04/2023 22:30	2.559	0.1596903	22.7	2.559	102.29	19*04*2023 14:44:37
19/04/2023 22:40	2.541	0.1585797	22.7	2.541	102.29	19*04*2023 14:54:38
19/04/2023 22:50	2.754	0.1717218	22.7	2.754	102.29	19*04*2023 15:04:40
19/04/2023 23:00	3.451	0.2147267	22.7	3.451	102.29	19*04*2023 15:15:12
19/04/2023 23:10	3.622	0.2252774	22.7	3.622	102.28	19*04*2023 15:25:12
19/04/2023 23:20	3.42	0.212814	22.7	3.42	102.27	19*04*2023 15:35:13
19/04/2023 23:30	3.758	0.2336686	22.7	3.758	102.26	19*04*2023 15:45:14
19/04/2023 23:40	3.648	0.2268816	22.7	3.648	102.25	19*04*2023 15:55:15
19/04/2023 23:50	3.793	0.2358281	22.7	3.793	102.25	19*04*2023 16:05:18
20/04/2023 00:00	3.908	0.2429236	22.7	3.908	102.24	20*04*2023 00:07:12



resistivity ohms-m	gravimetric mc dec	Simulated res.	ABSOLUTE DIFFERENCE ^2	RMS	Pgmc	a	b	c constant
117.091	0.192	103.460	185.806	75159275.115	243.0021	130	3.7	100
116.586	0.192	103.445		172.68190	242.8243			
116.586	0.192	103.460		172.28374	243.0021			
116.251	0.192	103.474		163.26833	243.1603			

117.091	0.192	103.479	185.29782	243.2197
117.091	0.191	103.486	185.11244	243.299
117.091	0.191	103.496	184.83369	243.4181
117.601	0.191	103.506	198.66441	243.5372
117.346	0.191	103.515	191.29097	243.6367
117.091	0.191	103.518	184.22688	243.6765
117.601	0.191	103.523	198.17902	243.7362
117.091	0.191	103.534	183.80448	243.8558
117.091	0.191	103.541	183.61614	243.9356
117.858	0.191	103.549	204.72209	244.0354
117.601	0.190	103.556	197.25007	244.1154
117.858	0.190	103.563	204.32191	244.1954
117.601	0.190	103.570	196.85628	244.2755
118.115	0.190	103.581	211.24318	244.3957
117.858	0.190	103.588	203.61771	244.4759
117.858	0.190	103.597	203.36501	244.5763
118.115	0.190	103.600	210.67748	244.6165
118.634	0.190	103.608	225.79150	244.6969
118.895	0.190	103.617	233.43332	244.7976
119.245	0.190	103.615	244.30362	244.7774
119.774	0.189	103.624	260.82277	244.8781
120.307	0.189	103.629	278.15817	244.9386
120.576	0.189	103.636	286.94314	245.0193
120.040	0.189	103.643	268.84090	245.1001
120.307	0.189	103.651	277.43768	245.1809
120.307	0.189	103.656	277.25685	245.2415
120.576	0.189	103.663	286.02537	245.3225
82.811	0.189	103.667	434.99170	245.363

59.040	0.188	103.718	1996.16991	245.9316
57.186	0.188	103.722	2165.61943	245.9724
56.020	0.188	103.720	2275.34198	245.952
57.429	0.188	103.729	2143.73456	246.0539
57.963	0.188	103.735	2095.08154	246.1151
59.561	0.188	103.741	1951.88078	246.1764
59.846	0.188	103.744	1927.02732	246.2172
60.113	0.188	103.750	1904.20211	246.2785
59.169	0.188	103.756	1987.95086	246.3399
59.714	0.188	103.759	1939.97893	246.3808
61.087	0.188	103.765	1821.40478	246.4422
60.812	0.187	103.769	1845.28045	246.4832
59.561	0.187	103.773	1954.69806	246.5241
63.930	0.187	103.774	1587.54669	246.5446
62.767	0.187	103.782	1682.24880	246.6266
61.645	0.187	103.788	1776.02773	246.6882
61.927	0.187	103.791	1752.60191	246.7293
63.779	0.187	103.795	1601.26401	246.7703
62.621	0.187	103.767	1692.96411	246.4627
63.060	0.187	103.778	1657.98749	246.5856
63.505	0.187	103.824	1625.64732	247.079
61.786	0.186	103.864	1770.61699	247.5127
61.087	0.186	103.907	1833.58518	247.9691
63.930	0.185	103.953	1601.82028	248.4486
59.299	0.185	103.977	1996.13869	248.6996
65.401	0.184	104.010	1490.64052	249.0354
62.500	0.184	104.036	1725.21824	249.309
62.621	0.184	104.044	1715.88402	249.3934
63.060	0.183	104.088	1683.31377	249.8373
58.234	0.183	104.119	2105.49935	250.1557

46.571	0.183	104.155	3315.99199	250.5177
44.390	0.182	104.190	3576.04481	250.8597
46.989	0.182	104.224	3275.84599	251.2028
42.796	0.181	104.262	3778.06287	251.5687
44.076	0.181	104.301	3627.12230	251.9575
42.404	0.180	104.340	3836.03703	252.3261
41.165	0.167	105.811	4179.06072	264.8143
41.260	0.167	105.840	4170.67994	265.0354
44.281	0.166	105.870	3793.25514	265.2569
42.304	0.167	105.795	4031.03340	264.6917
40.416	0.167	105.817	4277.36208	264.8634
43.778	0.166	105.847	3852.52077	265.0846
40.978	0.166	105.873	4211.41530	265.2816
38.523	0.166	105.903	4540.03241	265.5036
42.694	0.166	105.933	3999.17270	265.7262
38.341	0.166	105.960	4572.32477	265.9244
35.156	0.166	105.943	5010.85865	265.8004
39.684	0.165	105.980	4395.26369	266.0733
37.053	0.165	106.014	4755.71626	266.3219
42.796	0.165	106.042	4000.05805	266.5212
38.875	0.165	106.076	4516.05073	266.7709
42.304	0.165	106.104	4070.39217	266.9711
78.253	0.164	106.139	777.63529	267.2219
71.456	0.164	106.167	1204.83479	267.4229
75.307	0.164	106.195	954.04121	267.6243
76.697	0.164	106.227	872.00138	267.8514
80.990	0.163	106.255	638.35696	268.0536
76.516	0.163	106.284	886.13682	268.2562
69.704	0.163	106.317	1340.47493	268.4847
78.442	0.163	106.346	778.63322	268.6881

86.065	0.163	106.375	412.51966	268.892
79.520	0.162	106.408	723.00797	269.1218
92.977	0.162	106.438	181.20502	269.3264
76.697	0.162	106.472	886.50857	269.5572
82.264	0.162	106.502	587.45350	269.7627
79.170	0.162	106.539	749.08402	270.0202
66.913	0.161	106.570	1572.66785	270.2266
67.979	0.161	106.600	1491.58080	270.4334
72.771	0.161	106.631	1146.47966	270.6406
83.795	0.161	106.662	522.89172	270.8483
71.804	0.161	106.693	1217.24353	271.0563
71.804	0.160	106.728	1219.70527	271.2908
74.786	0.160	106.780	1023.59629	271.6305
65.692	0.160	106.828	1692.11123	271.9449
71.456	0.159	106.868	1254.00282	272.2077
68.122	0.159	106.921	1505.31419	272.5503
72.608	0.159	106.966	1180.41613	272.841
73.100	0.159	107.007	1149.69785	273.106
60.517	0.158	107.057	2165.96113	273.4249
64.955	0.158	107.107	1776.77666	273.7447
68.122	0.158	107.154	1523.44954	274.0386
65.243	0.157	107.201	1760.44764	274.3334
71.142	0.157	107.248	1303.61013	274.629
83.193	0.157	107.300	581.14094	274.9524
64.799	0.156	107.361	1811.51588	275.3309
74.786	0.156	107.410	1064.31492	275.6292
71.804	0.156	107.464	1271.58899	275.9556
85.701	0.156	107.509	475.59095	276.2284
68.758	0.155	107.568	1506.18505	276.584
66.311	0.156	107.518	1698.02000	276.283

64.082	0.155	107.586	1892.58665	276.6936
54.512	0.155	107.646	2823.15769	277.0507
64.362	0.155	107.706	1878.71686	277.409
70.187	0.154	107.777	1412.95705	277.8239
75.659	0.154	107.848	1036.12724	278.2404
60.113	0.153	107.925	2285.98804	278.6864
74.959	0.153	107.998	1091.55827	279.1061
67.667	0.153	108.057	1631.32870	279.4431
74.102	0.152	108.126	1157.64197	279.8376
62.913	0.152	108.192	2050.17006	280.2051
65.243	0.152	108.263	1850.71270	280.6023
65.243	0.151	108.340	1857.34351	281.0295
71.804	0.151	108.418	1340.54547	281.4583
73.765	0.151	108.486	1205.54208	281.8313
70.005	0.150	108.560	1486.47982	282.2344
76.516	0.150	108.635	1031.64367	282.6389
57.839	0.149	108.711	2588.01183	283.045
74.614	0.149	108.788	1167.87656	283.4525
67.837	0.149	108.871	1683.82266	283.8909
68.439	0.148	108.961	1642.09694	284.3603
78.442	0.148	109.041	936.31012	284.7727
74.102	0.148	109.104	1225.14019	285.0978
76.157	0.147	109.174	1090.13836	285.4536
68.439	0.147	109.256	1666.05322	285.87
68.294	0.147	109.339	1684.65096	286.288
72.285	0.146	109.417	1378.80611	286.6776
77.727	0.146	109.496	1009.23505	287.0685
81.725	0.146	109.581	775.98331	287.491
71.964	0.145	109.656	1420.68528	287.8544
70.987	0.145	109.743	1502.07777	288.2799

68.904	0.145	109.825	1674.54736	288.6764
78.632	0.144	109.876	976.20403	288.9211
66.913	0.144	109.967	1853.62210	289.3507
54.257	0.144	110.064	3114.47456	289.8127
77.025	0.143	110.157	1097.68568	290.2456
34.120	0.143	110.250	5795.82355	290.6802
75.800	0.143	110.345	1193.29052	291.1164
61.927	0.142	110.440	2353.48994	291.5543
67.667	0.142	110.537	1837.80984	291.9939
54.004	0.142	110.621	3205.47540	292.3721
69.228	0.141	110.705	1720.37423	292.7515
70.005	0.141	110.812	1665.20998	293.2276
72.446	0.141	110.921	1480.29629	293.7056
59.979	0.140	111.008	2603.97243	294.0895
72.446	0.140	111.097	1493.89582	294.4746
71.804	0.140	111.194	1551.56347	294.8933
63.505	0.139	111.307	2285.11442	295.3784
44.076	0.139	111.422	4535.52320	295.8654
57.695	0.139	111.531	2898.29745	296.3219
64.670	0.138	111.632	2205.46022	296.7474
54.623	0.138	111.735	3261.88650	297.1744
78.442	0.138	111.848	1115.94845	297.6361
41.824	0.137	111.953	4918.12332	298.0664
40.782	0.137	112.060	5080.53034	298.4984
76.516	0.137	112.176	1271.62155	298.9654
50.098	0.136	112.285	3867.28822	299.4007
64.082	0.136	112.396	2334.20018	299.8376
56.136	0.136	112.481	3174.79503	300.1748
59.299	0.135	112.568	2837.57576	300.513
47.751	0.135	112.664	4213.72528	300.8861

54.752	0.135	112.752	3364.05674	301.2264
51.712	0.135	112.841	3736.76568	301.5676
64.799	0.134	112.922	2315.77204	301.8756
65.401	0.134	113.012	2266.85688	302.2187
69.228	0.134	113.104	1925.07530	302.5628
68.439	0.134	113.196	2003.19243	302.908
61.927	0.133	113.279	2637.01947	303.2195
68.904	0.133	113.354	1975.79614	303.497
50.441	0.133	113.448	3969.97890	303.8449
58.360	0.133	113.544	3045.27938	304.1938
66.610	0.132	113.630	2210.84396	304.5087
71.964	0.132	113.727	1744.16116	304.8596
53.878	0.132	113.815	3592.39446	305.1763
62.621	0.132	113.913	2630.86044	305.5292
47.319	0.132	113.993	4445.40987	305.8122
67.979	0.131	114.083	2125.50895	306.1315
49.974	0.131	114.173	4121.55080	306.4516
50.788	0.131	114.255	4027.97093	306.7368
42.989	0.131	114.337	5090.53366	307.0227
68.122	0.130	114.429	2144.36145	307.3452
56.785	0.130	114.523	3333.67452	307.6686
41.354	0.130	114.607	5365.95794	307.9568
65.112	0.130	114.691	2458.14312	308.2457
72.285	0.130	114.787	1806.47808	308.5715
55.124	0.129	114.873	3569.93483	308.8618
57.695	0.129	114.960	3279.25560	309.1529
59.714	0.129	115.058	3062.89311	309.4812
51.844	0.129	115.145	4007.01517	309.7738
68.122	0.129	115.234	2219.50652	310.0671
64.955	0.128	115.334	2538.03763	310.3979

66.748	0.128	115.413	2368.30668	310.6558
63.779	0.128	115.503	2675.35336	310.9512
57.963	0.128	115.606	3322.69547	311.2844
61.645	0.128	115.686	2920.48473	311.5443
65.112	0.127	115.790	2568.31150	311.8792
53.154	0.127	115.884	3935.05201	312.1776
56.785	0.127	115.989	3505.14592	312.5142
63.629	0.127	116.084	2751.52600	312.8143
52.313	0.126	116.180	4078.95948	313.115
71.142	0.126	116.276	2037.03889	313.4165
43.380	0.126	116.373	5327.98043	313.7188
45.512	0.126	116.471	5035.17523	314.0218
65.401	0.126	116.569	2618.17876	314.3256
33.814	0.125	116.668	6864.86935	314.6301
69.080	0.125	116.768	2274.11464	314.9354
41.165	0.125	116.869	5731.02686	315.2414
38.781	0.125	116.957	6111.48741	315.5099
55.884	0.125	117.060	3742.40434	315.8174
63.207	0.124	117.175	2912.56058	316.1642
61.504	0.124	117.279	3110.84668	316.4734
62.213	0.124	117.384	3043.87455	316.7833
49.759	0.124	117.489	4587.35971	317.094
41.727	0.124	117.596	5756.04985	317.4055
51.368	0.123	117.716	4402.07850	317.7569
52.670	0.123	117.810	4243.28893	318.0309
64.516	0.123	117.919	2851.93621	318.3448
49.866	0.123	118.029	4646.10211	318.6595
61.365	0.123	118.139	3223.35139	318.975
58.486	0.122	118.236	3570.13315	319.2517
70.493	0.122	118.349	2290.19548	319.5687

48.845	0.122	118.461	4846.51517	319.8865
61.927	0.122	118.575	3208.98379	320.2052
68.612	0.122	118.690	2507.74949	320.5246
60.675	0.121	118.791	3377.42060	320.8048
53.276	0.121	118.907	4307.48944	321.1258
62.070	0.121	119.025	3243.87773	321.4477
40.416	0.121	119.128	6195.61419	321.73
36.379	0.121	119.247	6867.13157	322.0534
50.900	0.120	119.367	4687.73803	322.3776
43.778	0.120	119.488	5731.97638	322.7027
60.517	0.120	119.610	3491.99525	323.0287
74.614	0.120	119.733	2035.70585	323.3555
60.949	0.120	119.857	3470.08465	323.6831
57.045	0.119	119.981	3961.00916	324.0117
34.199	0.119	120.107	7380.25516	324.341
63.930	0.119	120.218	3168.32654	324.63
44.894	0.119	120.346	5693.02600	324.961
61.645	0.119	120.475	3460.97668	325.2929
40.875	0.118	120.605	6356.87692	325.6256
34.674	0.118	120.735	7406.47913	325.9593
44.076	0.118	120.867	5896.92484	326.2938

