ACCURATE OPTIMUM DISTANCE DETERMINATION OF REMOTE ELECTRODE PLACEMENT IN POLE-DIPOLE ARRAY FOR 2-D ELECTRICAL RESISTIVITY TOMOGRAPHY

FARID NAJMI BIN ROSLI

UNIVERSITI SAINS MALAYSIA

2025

ACCURATE OPTIMUM DISTANCE DETERMINATION OF REMOTE ELECTRODE PLACEMENT IN POLE-DIPOLE ARRAY FOR 2-D ELECTRICAL RESISTIVITY TOMOGRAPHY

by

FARID NAJMI BIN ROSLI

Thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

August 2025

ACKNOWLEDGEMENT

Alhamdulillah, all thanks and prasies are to Allah SWT for bestowing upon me a journey to become closer to Him. This research work has been fruitful with the contributions of intellectuals, families, and friends who were by my side during my journey. I express my sincere graditude towards my diligent, main supervisor, Assoc. Prof. P.Geol. Dr. Nordiana Mohd Muztaza, for her overflowing support, motivation, patience and funding throughout the entire PhD candidature. I am grateful for every single chances she has given to me in order to grow better as a geophysicist. I want to offer a token of gratitude to my co-supervisor, Dr. Nur Azwin Ismail, for her constant support and motivation. I bid the utmost appreciation to my family members; Prof. Dr. Rosli Sa'ad, Hartini Abd Hamid, Dr. Aishah, Dr. Nehlah, Dr. Najmiah, Athirah and Ahmad Za'im. Even though they are occupied with their personal work and studies, they still make time to metticulously clarify the quality of my work, yet asking nothing in return. A special appreciation to Dr. Najmiah and her husband, Dr. Muhammad Nazrin A Rahman, for their perpetual counsel and inspiration while overseeing my research. My heartfelt appreciation goes to my pillar of emotional support, Nur Hanis Alisa Md Hasri for lending me her ears to listen to my everyday grumble of this journey. Not to overlook the geophysics team from Universiti Sains Malysia (USM); Dr. Taqiuddin Zakaria, Alyaa Nadhira Salleh, Nazirah Mahmud, and Shahil Ahmad Khosaini for sacrificing their time and energy to aid me in my research, especially during data acquisition. Thank you Ministry of Higher Education for Fundamental Research Grant Scheme with Project Code: FRGS/1/2022/STG08/USM/03/1 entitled 'Performance-based Multimodal Geophysical Design for Soil Dynamic Properties to Improve Visualisation of Subsurface Conditions'.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

LIST OF SYMBOLS

1D	1–dimensional
2D	2–dimensional
3D	3–dimensional
α	Alpha
ρ_A	Apparent resistivity
β	Beta
ρ_c	Calculated apparent resistivity values
A	Cross-sectional area
I	Current
°	Degree
a	Dipole length
n	Dipole separation factor
=	Equals
γ	Gamma
k	Geometric factor
L	Length
ρ_m	Measured apparent resistivity values
m	Meter
−	Minus
Dx	Multiplier index
*	Multiply
±	Plus, and minus
V	Potential difference
Rx	Receiver index
R	Resistance
ρ	Resistivity
N	Sum of data
Tx	Transmitter index

LIST OF ABBREVIATIONS

ERT	2-D electrical resistivity tomography
CI	Confidence Interval
C1	Current electrode 1
C2	Current electrode 2
DD	Dipole-dipole
DC	Direct current
ES 10–64C	Electrode selector 10–64 channels
HW	Half wenner
MAPE	Mean absolute percentage error
MPR	Midpoint-potential-referred measurement
GD	Multiple gradient
N	North
PP	Pole-pole
PD	Pole-dipole
P1	Potential electrode 1
P2	Potential electrode 2
Res2DInv	Resistivity 2–Dimensional Inversion
RMSe	Root mean square error
SC	Schlumberger
SAS4000	Signal Averaging System 4000
SD	Standard deviation
SE	Standard error
VES	Vertical electrical sounding
WA	Wenner- α
WG	Wenner- γ
WB	Wenner-β

LIST OF APPENDICES

PENENTUAN JARAK OPTIMUM TEPAT BAGI PENEMPATAN ELEKTROD JAUH MENGGUNAKAN SUSUNATUR POLE-DIPOLE UNTUK TOMOGRAFI KEBERINTANGAN ELEKTRIK 2-D

ABSTRAK

Tomografi keberintangan elektrik (ERT) telah digunakan secara meluas oleh para penyelidik dan pengamal untuk penyiasatan subpermukaan bumi. ERT mempunyai pelbagai susunatur yang berbeza, dan setiap satu daripadanya mempunyai kelebihan dan kekurangan. Oleh itu, pemilihan susunatur yang betul diperlukan bagi memenuhi objektif kajian. *Pole-dipole* merupakan salah satu susunatur yang digemari oleh para penyelidik kerana susunatur ini boleh menembusi subpermukaan dengan lebih dalam berbanding dengan kebanyakan susunatur yang lain sambil mengekalkan resolusi data yang diperlukan untuk sesuatu kajian. Susunatur ini adalah salah satu daripada dua susunatur yang memerlukan sebatang elektrod jauh, yang secara teorinya harus diletakkan pada jarak infiniti atau sekurang-kurangnya lima kali ganda jarak pemisahan elektrod C1-P1 mengikut panduan am lapangan. Namun, syarat jarak elektrod jauh ini sukar untuk dicapai di lapangan, terutamanya di kawasan yang mempunyai akses terhad atau apabila garisan tinjauan yang panjang. Oleh itu, kajian ini memanupulasi jarak elektrod jauh pada dua arah yang berbeza, iaitu secara serenjang dan selari untuk mendapatkan jarak minimum yang diperlukan pada kedua-dua arah bagi menghasilkan data resistiviti yang tepat. Kajian ini dihadkan pada kawasan topografi yang rata dan subpermukaan yang homogen bagi mengelakkan kesan dari pembolehubah lain seperti kesan dan struktur geologi yang kompleks. Hasil kajian menunjukkan bahawa jarak minimum elektrod jauh yang diperlukan untuk mendapatkan tinjauan ERT yang tepat adalah lebih pendek daripada jarak yang

dilaporkan dalam sorotan kajian, iaitu 1.5 kali ganda jarak panjang garisan tinjauan untuk konfigurasi serenjang manakala 2.5 kali ganda jarak panjang garisan tinjauan untuk konfigurasi selari. Oleh itu, perolehan data di kawasan yang mempunyai akses terhad boleh dijalankan secara tepat pada masa hadapan dengan menggunakan jarak elektrod jauh yang lebih pendek.

ACCURATE OPTIMUM DISTANCE DETERMINATION OF REMOTE ELECTRODE PLACEMENT IN POLE-DIPOLE ARRAY FOR 2-D ELECTRICAL RESISTIVITY TOMOGRAPHY

ABSTRACT

2-D electrical resistivity tomography (ERT) has been widely used by researchers and practitioners for subsurface investigation. ERT has numerous distinct arrays, and each one of them has its own advantages and disadvantages. Therefore, the correct array selection is needed to fit the objectives of a study. Pole-dipole is one of the arrays that are often favored by researchers as it penetrates deeper into the subsurface as compared to most arrays, while retaining the data resolution needed for a study. This array is one of the two arrays that requires an offset remote electrode that theoretically must be placed at infinity or at five times the largest C1-P1 electrode separation according to the field rule of thumb. However, the remote electrode distance requirement is difficult to achieve on the site especially with limited accessibility or when lengthy survey line is deployed. Hence, this study manipulates the remote electrode distance in both perpendicular and parallel directions to obtain the minimum distance required in both directions to produce accurate resistivity data. This study was restricted to only flat topographic and homogeneous subsurface areas to neglect effects from other variables such as topography effect and complex geological structures. Results indicate that the minimum remote electrode distance needed to obtain an accurate ERT survey is much shorter than mentioned in previous literatures, which are 1.5 times the survey line and 2.5 times the survey line for perpendicular and parallel configurations respectively. Therefore, future data collections in tight accessibility areas can be conducted accurately using shorter remote electrode distance.

CHAPTER 1

INTRODUCTION

1.1 Background

2-D electrical resistivity tomography (ERT) is an active geophysical method that utilizes electrical current injection into the ground through a multielectrode system arranged in a linear configuration (Singh, 2013). An automated computer is connected to the multielectrode system to select groups of four electrodes at a time to conduct a resistivity measurement at a designated datum point according to the position of the selected electrodes at a time (Rahman, 2023). ERT is an effective method to map shallow subsurface by measuring the resistivity contrasts between different Earth's mediums (Li *et al.*, 2018). Thus, ERT method has been widely applied in various studies, namely environmental investigations such as hydrogeology, waste inspection, civil engineering, archaeology (Junaid *et al.*, 2021; Pazzi *et al.*, 2020; Lech *et al.*, 2020; Riwayat *et al.*, 2018; Mol & Preston, 2010), and mineral prospecting (Junaid *et al.*, 2021; Song *et al.*, 2017; Mostafaie & Ramazi, 2015; Longo *et al.*, 2014; Saad *et al.*, 2012).

Several arrays are available to be utilized in an ERT data collection. These arrays reflect the electrode configurations being used during the survey. Each array has its own advantages and disadvantages, where the optimization of the array revolves around the objectives of the survey. The variables taken into consideration are depth of penetration, sensitivity to vertical and horizonal resistivity changes, horizontal data coverage and signal strength (Loke, 2012). In many study cases, a pole-dipole is often utilized as the prime choice of array in single-channel and multichannel acquisition settings (Wang *et* *al.*, 2024; Yue *et al.*, 2019; Dahlin & Zhou, 2004). Pole-dipole array is favorable due to its capability to penetrate deeper into the subsurface and produces strong, reliable resolution for precise data imaging analysis (Xiao *et al.*, 2015; Niu *et al.*, 2013).

However, the pole- dipole array has its own complication during the layout of electrodes, in which the electrode configuration consists of an offset electrode called remote electrode. Theoretically, the remote electrode placement has to be at infinity, away from the center of the survey line (Wang *et al.*, 2024; Razafindratsima & Lataste, 2013; Robain *et al.*, 1999). Practically, the placement of this electrode has to be as far away from the survey line as possible, but till today, no uniform standard on the minimum distance of its placement from the center of the survey line that can be regarded as infinity, which is critical in most study areas with limited accessibility (Wang *et al.*, 2024; Abd Malik *et al.*, 2019).

Researchers proposed numerous achievable distances of the perpendicular remote electrode placement which are: at least five (5) times the largest current electrode 1 (C1) and potential electrode 1 (P1) separation (Geotomo, 2017), five (5) to ten (10) times the penetration depth of the survey (Smith, 1986), at least the length of the survey line (Patrizi *et al.*, 2022), or twice the length of the survey line (Wang *et al.*, 2024). Although each researchers recommended a distance with different variables as a reference, all of them concluded that the position of the remote electrode is often mentioned to be perpendicular to the survey line, as affirmed by Abd. Malik *et al.* in their literature from 2019. Additionally, only Wang *et al.* (2024), mentioned that the position of remote electrode could vary, in which it can be placed not only at perpendicular, but also at parallel and at an angle away from the center of the survey line.

Due to the absence of uniform standard for the minimum distance of remote electrode placement and the restriction on site accessibility in most study cases, the correct placement of remote electrode for a pole-dipole array in ERT is often neglected.

1.2 Problem statement

Most ERT surveys are conducted in areas with spatial restrictions such as infrastructures and utilities in urban areas, and extreme natural phenomena in rural areas such as topography, rivers and vegetations. These restrictions limit the placement of remote electrode during the employment of pole-dipole array of ERT survey, and to achieve the distance required as mentioned in previous literatures is difficult. Furthermore, as the positioning of remote electrode is narrowed to only perpendicular in reference to the survey line, ERT surveys often neglect the remote electrode distance requirement to retain the direction of the survey line intended for the study.

Pole-dipole array is also prone to measuring negative apparent resistivity data due to its asymmetrical electrode configurations (Lee & Cho, 2020; Lee *et al.*, 2016; Doetsch *et al.*, 2010; Wilkinson *et al.*, 2008; Kim *et al.*, 2006). Naturally, negative apparent resistivity is seen to be measured in areas with rapid topographic changes (Xiao *et al.*, 2015; Jung *et al.*, 2009; SEGJ, 2004) or in areas with complex geological structures or formations (Jung *et al.*, 2009). However, the conventional approaches to solving negative apparent resistivity occurrences are either to disregard the measurements as they are considered to be measurement errors (Lee & Cho, 2020) or to use the absolute values of the negative apparent resistivity measured (Jung *et al.*, 2009). However, the prior approach could lead to misinterpretation of subsurface conditions because negative apparent resistivity values could also be a reflection of complex geological formations, rather than just measurement errors.

1.3 Research objectives

This study applies to pole-dipole array in ERT method with the objectives:

i. To identify and resolve the effects of remote electrode placement towards the accuracy of apparent resistivity measurements.
ii. To verify the accuracy of apparent resistivity data obtained at different remote electrode positions with the reference model by optimizing mathematical and statistical analyses.
iii. To establish the optimum distance for placement of remote electrode that measures accurate apparent resistivity data.

1.4 Scope of study

Homogeneous study areas were chosen to eliminate disruptions of current flow due to topography and complex geological formations that could lead to measurements of negative apparent resistivity values (Xiao *et al.*, 2015; Jung *et al.*, 2009; SEGJ, 2004). Therefore, the causes of emergence of negative apparent resistivity data can be narrowed down to the inaccurate placement of remote electrode. This study pivots on the pole-dipole array of the ERT method. The survey was conducted in homogeneous areas located in four locations, two of which are in Kedah and another two in Penang. A total of four pole-dipole ERT survey lines were employed.

Referring to previous literature published by Xiao *et al.*, in 2015, there are two (2) factors influenced by the positioning of remote electrode in a pole-dipole array ERT survey. The first factor is the angle joining the remote electrode to the in-line electrodes at the center of the survey line. Thorough investigation regarding this factor was imposed by segregating the survey into two (2) different remote electrode configurations. Data collection of each survey line was done twice, whereby initially the remote electrode positioned perpendicularly from the center of the survey line, then repeated by placing the remote electrode parallelly from the center of the survey line.

The second factor mentioned in the literature is the ratio of remote electrode distance to half the survey line length. The ratio was manipulated by employing various remote electrode distances from the center of the survey line while maintaining the survey line length. Concisely, the data collection process was taken multiple times on a single survey line to study the effects of remote electrode distance to the apparent resistivity data measured.

The data were extracted using the SAS4000 Utilities software to acquire the apparent resistivity data to be analyzed. The quality of the data was assessed using numerical comparison and a series of statistical analyses. Inversions were made and the true resistivity models were plotted to obtain the penetration depth of each dataset. Further assessment of the dataset quality was done by evaluating the occurrences of negative apparent resistivity data as the study areas chosen in this research eliminates the possibility of these occurrences as a reflection of complex subsurface geological structures. Therefore, negative values obtained in this research are considered to arise from measurement errors. Thereafter, the computation of mean absolute percentage error to numerate the percentage differences in resistivity values of each dataset to the reference model. Data outliers were identified by utilizing box and whiskers method, and the range of acceptable remote electrode distances to produce accurate apparent resistivity data were developed by employing the 95% Confidence Interval (CI) approach.

1.5 Novelty

Previous studies with the implementation of conventional pole-dipole array placed the remote electrode distance perpendicular to the survey line at the furthest possible accessible distance. This research proposed an approach to validate the accuracy of raw data obtained from different remote electrode positions – perpendicular and parallel (extension to the survey line on the negative distance) – as well as from different distances. Moreover, the conventional approaches to resolve the occurrences of negative apparent resistivity measurements are reevaluated to produce the best procedure in resolving this issue. If this research is proven successful, practitioners and researchers are given more options with the deployment of remote electrode in pole dipole array in terms of position and distance, especially in study areas with limited accessibility. Moreover, the ERT data quality of future studies can be optimized with a proper data quality assessment produced in this research.

1.6 Thesis layout

This dissertation consists of five chapters, with each emphasizing different components of this research were presented. Chapter 2 discussed previous literatures regarding the principles of an ERT surveys. Array differences that highlighted each of the advantages and disadvantages is presented here. The conventional approach for pole-dipole ERT data collection and inversion are also demonstrated in this chapter, which summarizes the placement of remote electrode in the array, occurrences of noise in the dataset, and the root mean square error (RMSe) as the standard data quality assessment of inversed tomography. An exhibition of suitable statistical approaches to validate apparent resistivity data was included in this chapter as well.

Chapter 3 delivers the methodology implemented in the whole study. This chapter includes details on regional geology of study areas, extensive ERT survey and statistical analyses methods employed throughout this study. In the ERT survey method section, the instruments, configurations and data collection details of this study are demonstrated. Besides, the procedures of an alternate data quality assessments utilizing numerical and statistical analyses are explained thoroughly in this section as well.

Chapter 4 marks as the main component of this dissertation which materializes the results from utilizing numerical and statistical analyses onto the datasets obtained. The variables subjected to the numerical analysis includes the depth of penetration and the occurrences of negative apparent resistivity values. The execution of statistical analyses includes mean absolute percentage error (MAPE), box and whiskers analysis, and 95% Confidence Interval (CI). Pole-dipole ERT data quality obtained from different remote electrode distances and positions are evaluated in this particular chapter.

Finally, Chapter 5 concludes the major findings of this study and suggests recommendations that can be implemented onto the future studies.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter discusses the concept of 2-D electrical resistivity tomography (ERT), which utilizes the implication of electrical current to measure shallow subsurface potential difference that will then be employed in mathematical calculation to convert it into resistivity. Differences of array configurations and their respective advantages and disadvantages are thoroughly evaluated in this chapter. Related literature is presented to assess the contributions made by earlier researchers, and to establish a research gap that will be overcome in this research for a better understanding of ERT.

2.2 Principles of 2-D electrical resistivity tomography (ERT)

2-D electrical resistivity tomography (ERT) is the extension of vertical electrical sounding (VES) method whereby both implement the use of direct current (DC) to map shallow subsurface by measuring the resistivity contrasts between different Earth's mediums (Li *et al.* 2018). These electrical methods utilize four electrodes where electrical current is induced into the ground via a pair of electrodes and the electrical potential drop is measured using the other pair of electrodes (Singh, 2013). The former method is a 1–dimensional (1D) survey that only covers data vertically below a station, while the latter method measures in both vertical and horizontal direction, thus producing a 2–dimensional (2D) profile (Mohammed *et al.*, 2019). ERT utilizes a multielectrode system arranged in a linear configuration, where an automated computer system selects groups of four electrodes system at a time to conduct the resistivity measurements (Rahman *et al.*, 2023).

VES is primarily implemented to delineate horizontal geological structures, identify groundwater level, and determine depth of bedrock or aquifers. On the other hand, ERT is an effective method to map subsurface structures (Abreau & Fernandes, 2014), identify and map aquifers (Karaoulis *et al.*, 2022; Boucher & Ménard, 2012) assess contamination plumes in soil and groundwater (Lesage & Pidou, 2016), and explore mineral resources (Martinez *et al.*, 2019). To differentiate these two methods, VES acquires data with lower spatial resolution in 1–dimension, while ERT measures data with higher spatial resolution that covers a whole section beneath the survey line, thus produces a 2–dimensional data (Loke, 2012). Both methods can be utilized for similar objectives, but VES is more suitable for simpler investigations as the product of this method covers mainly only vertical variations while ERT is more fitting for detailed and spatially complex subsurface analysis.

ERT surveys are used to map subsurface structures by computing the true resistivity distributions from apparent resistivity data measured in the ground surface (Nordiana, 2013). The basis of this method is to employ a four electrodes system to measure the potential difference between two potential electrodes (P1 and P2) by imbuing electrical current through two electrical currents (from C1 to C2) as shown in Figure 2.1. This figure also portrays the pattern of electrical current flow in homogeneous subsurface region.

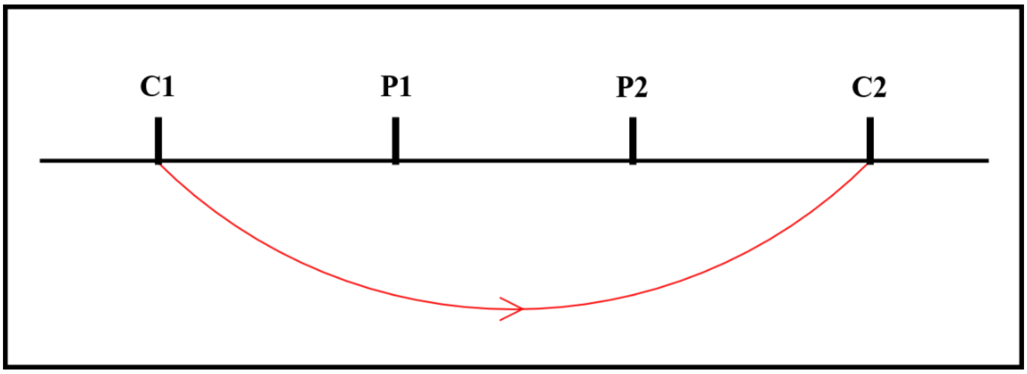

Figure 2.1: Current flow of a conventional four electrodes system for an ERT survey

The fundamental principle of ERT revolves around Ohm's Law (Kirsch, 2006), whereby the resistance (R) is calculated from known injected current (I) and measured potential difference (V) using equation 2.1 as follow:

$$V = I * R \tag{2.1}$$

Resistance (R) is defined as the restrain of electrical current flow in an object depending its physical properties such as material and dimension. On the other hand, resistivity (ρ) quantifies the strength of a specific material to refrain the flow of electrical current, regardless of its shape or size (Tipler & Mosca, 2008). Resistance is related to resistivity as illustrated in the following equation 2.2:

$$R = \rho * \frac{L}{A} \tag{2.2}$$

Where R : Resistance of the object in ohm (Ω)

ρ : resistivity of the material in ohm meter (Ωm)

L : Length of current path in meter (m)

A : Cross-sectional area of the object in meter squared (m^2)

However, in subsurface resistivity investigation, the properties of subsurface objects remained unseen from ground level. Therefore, the measurement of resistivity is labeled as apparent resistivity (ρ_A), which is defined as the average resistivity over a volume of subsurface material sampled in the electrode array (Abdul-Nafiu *et al.*, 2013). Apparent resistivity does not directly correspond to the specific layer or material in the subsurface, but it reflects the subsurface resistivity distribution of the region of interest (Abdul-Nafiu *et al.*, 2024). Equation 2.3 below is the mathematical definition of apparent resistivity that is implied in ERT:

$$\rho_A = k * \frac{V}{I} \tag{2.3}$$

Where ρ_A : Apparent resistivity

k : Geometric factor

V : Potential difference

I : Current

This calculation only computes the apparent resistivity values, which does not portray the exact subsurface conditions. The exact representation of subsurface conditions can be obtained by implementing correction factor on apparent resistivity pseudosections, thus obtaining true resistivity tomography. Correction factor is the influence of the geometry of the survey, electrode spacing and subsurface stratigraphy that contradicts with the hypothetical homogeneous half-space that refers the subsurface as a homogeneous body (Loke, 2012).

2.3 Array configurations

Geophysicist have demonstrated that reconstructing a precise subsurface resistivity image is feasible providing adequate measured data that covers good spatial samples and coverage areas, with the employment of 2–dimensional (2D) or 3–dimensional (3D) inversion techniques (Dahlin and Zhou, 2004). ERT compromises numerous series of electrode arrangements known as arrays, and each array has its own advantages and disadvantages that are exploited by practitioners by utilizing the benefits depending on the suitability of the study mainly on four factors: penetration depth, array sensitivity to vertical and horizonal subsurface resistivity changes, horizontal data coverage and signal strength (Loke, 2012). Figure 2.2 illustrates the commonly practiced arrays in explorations which are Wenner-α, Wenner-β, Wenner-γ, pole-pole, dipole-dipole, pole-dipole, Wenner-Schlumberger, and equatorial dipole-dipole.

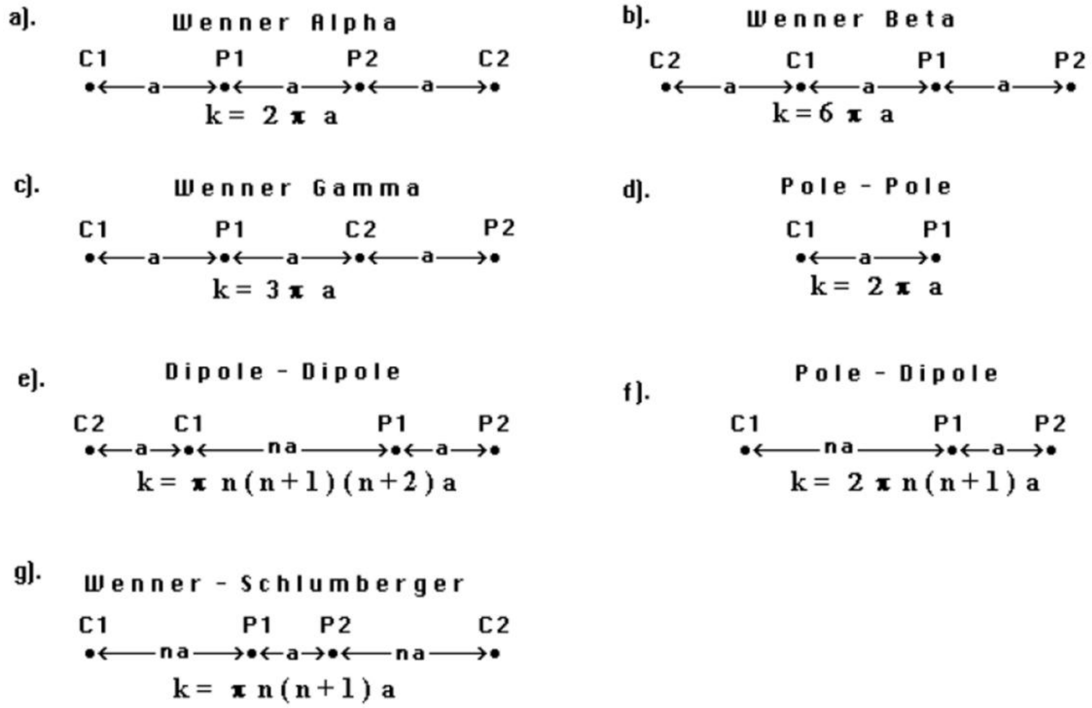

Figure 2.2: Common arrays used in ERT surveys and their respective geometric factors, k (modified from Loke MH, 2012)

Common arrays are configured by parameter dipole length, denoted by “a”. However, some arrays such as dipole-dipole, pole-dipole and wenner-Schlumberger are manipulated by the dipole separation factor “n”, a factor that can be both an integer and a fraction but is typically an integer (Loke, 2012). Longer dipole length and larger dipole separation factor produce deeper penetration into the subsurface, offering more general information of the Earth’s structures. Conversely, shorter dipole length and smaller dipole separation factor produce better horizontal resolution on the shallower subsurface part of the whole tomography (Dahlin and Zhou, 2004; Bernard, 2003). While both parameters are equally important, it is best to adjust the values accordingly to comply with the specific objective of the study. Therefore, when subjected to a constant consistent electrode separation to ERT data collection in a constant study area, the penetration depth is sustained as long as no changes are being made to the array type employed in the study.

Figure 2.4 also illustrates the geometric factor of each array, denoted by “k”. Geometric factor is an influence of electrode configuration and geometry of the measurement of apparent resistivity data. This factor is implemented into the calculation to correct the apparent resistivity data obtained in the field, thus produces true resistivity data of the subsurface (Loke, 2012). Each array corresponds to distinct current and potential electrodes configurations; thus, the distinct geometric factors of each array are utilized to adjust the apparent resistivity values to account for the spatial configuration of these electrodes (Loke, 2012).

In a numerical comparison of 2D resistivity tomography study conducted by Dahlin and Zhou in 2004, four synthetic models as shown in Figure 2.3 were used to compare the output of each array. This study diverged the dike synthetic model (c) into conductive dike model and resistive dike model. For each model, a series of data collections were conducted by utilizing different array types with similar parameters, such as number of electrodes, electrode spacing and current input. The arrays being employed in this study were pole-pole (PP), pole-dipole (PD), half-Wenner (HW), Wenner-α (WA), Schlumberger (SC), dipole-dipole (DD), Wenner-γ (WG), Wenner-β (WB), multiple gradient (GD), and midpoint-potential-referred measurement (MPR) array. A comparison of signal-to-noise ratio between these arrays are demonstrated in Figure 2.4.

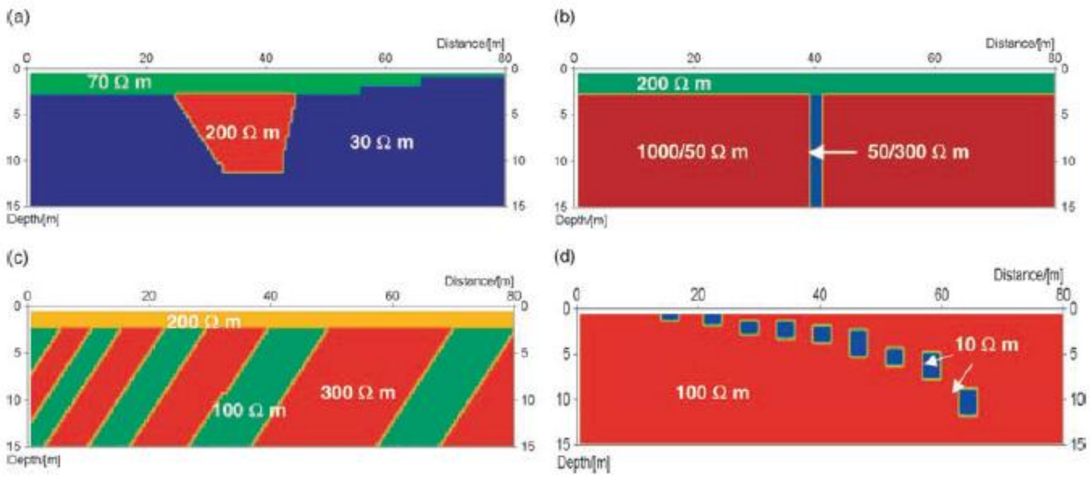

Figure 2.3: Synthetic models for numerical imaging study. a) river channel in clay environment topped with silty sediment, b) dike in coarse-grained sediment, c) dipping blocks under a till layer, and d) a waste pond simulating an actual formation in southern Sweden (Dahlin and Zhou, 2004)

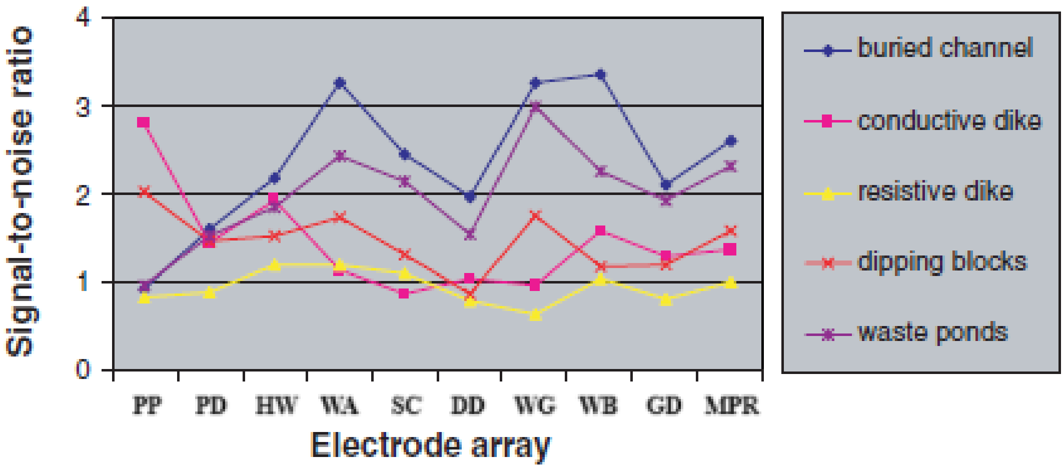

Figure 2.4: Synthetic signal-to-noise ratios achieved from different electrode arrays in four geological models (Dahlin and Zhou, 2004)

Referring to the result in Figure 2.4, the signal-to-noise ratio of PD array is well distributed for all five synthetic models, resulting to the efficiency usage of PD array in most case studies. Additionally, PD array yields better spatial resolution image than PP, SC and WA (Razafindratsima & Lataste, 2013; Dahlin & Zhou, 2004). Even so, the presence of a remote electrode limits the arrangement of the PD array especially in study areas with restricted accessibility (Dahlin and Zhou, 2004). DD array produces a tomography equivalent to PD array, but with slightly lower penetration depth. Both arrays are better than any available arrays, especially in mapping vertical and dipping structures. Nonetheless, DD array is more exposed to noise contamination, thus produces a lower signal-to-noise ratio when compared to WA and WB.

Considering factors to achieve a high-quality survey such as anomaly effect, signal-to-noise ratio, and noise contamination, WA, WB, and WG arrays are not the best, as they do not always produce the best-resolved tomography due to their limited resolution capabilities (Dahlin and Zhou, 2004). Since pole-dipole array penetrates the subsurface deeper than other arrays, more sensitive to non-uniformity subsurface, has good horizontal coverage (Prakash *et al.*, 2022), it is often favored by countless researchers in ERT (Wang *et al.*, 2024; Yue *et al.*, 2019; Dahlin & Zhou, 2004).

2.4 Pole-dipole array

Among these well-known arrays, pole-pole and pole-dipole are the two arrays that require a remote electrode, in which the current electrode 2 (C2) and potential electrode 2 (P2) for pole-pole array and only current electrode 2 (C2) for pole-dipole array. In both arrays, the placement of remote electrode has to be at a distance of infinity (Wang *et al.*, 2024; Razafindratsima and Lataste, 2013; Robain *et al.*, 1999). However, in field study cases, the arbitrary distance can be measured from the center of the survey line to the position of remote electrode, thus a specific numerical value is possible to be assigned to it. In contrast to pole-dipole array, the complexity in employment pole-pole array is bigger, due to the deployment of two remote electrodes that theoretically need to be placed perpendicularly away from the center of the survey line.

The manual book for Res2DInv software version 3.59 (Geotomo, 2017), mentioned that the finite distance of the remote electrode in pole-dipole array has to be more than five (5) times the largest current electrode 1 (C1) and potential electrode 1 (P1) spacing, and in another literature by Abd Malik *et al.* (2019), they specified that the remote electrode has to be placed perpendicularly from the center of the survey line. However, previous study done by Smith (1986) on the application of the pole-dipole resistivity array technique, it is stated that the transmitting remote electrode should be placed at a distance of five (5) to ten (10) times of the penetration depth of the survey line to allow an equipotential flow of current. On the other hand, Patrizi *et al.* (2022) concluded that the placement of transmitting remote electrode perpendicularly to the center of the ERT survey line at a distance of at least the length of the survey line itself will minimize the effect of finite transmitting remote electrode. Furthermore, it states that the distance of the transmitting remote electrode does not have to stretch further than the mentioned distance as it will not improve the data any further since the geometric factor remains quite similar (Patrizi *et al.*, 2022).

In the research conducted by Wang et al. (2024), the authors investigated the effect of remote electrode placement on root-mean-square error (RMSe) in resistivity imaging. They concluded that the minimum required distance between the remote electrode and the survey line, to maintain acceptable RMSe values, should be at least twice the length of the survey line. The study employed four different remote electrode configurations: parallel (positive and negative extensions), perpendicular, and at a 60° angle, as illustrated in Figure 2.5. Among these, the parallel negative extension configuration (Figure 2.5a) was used as the reference setup for validating data accuracy obtained from the other configurations.

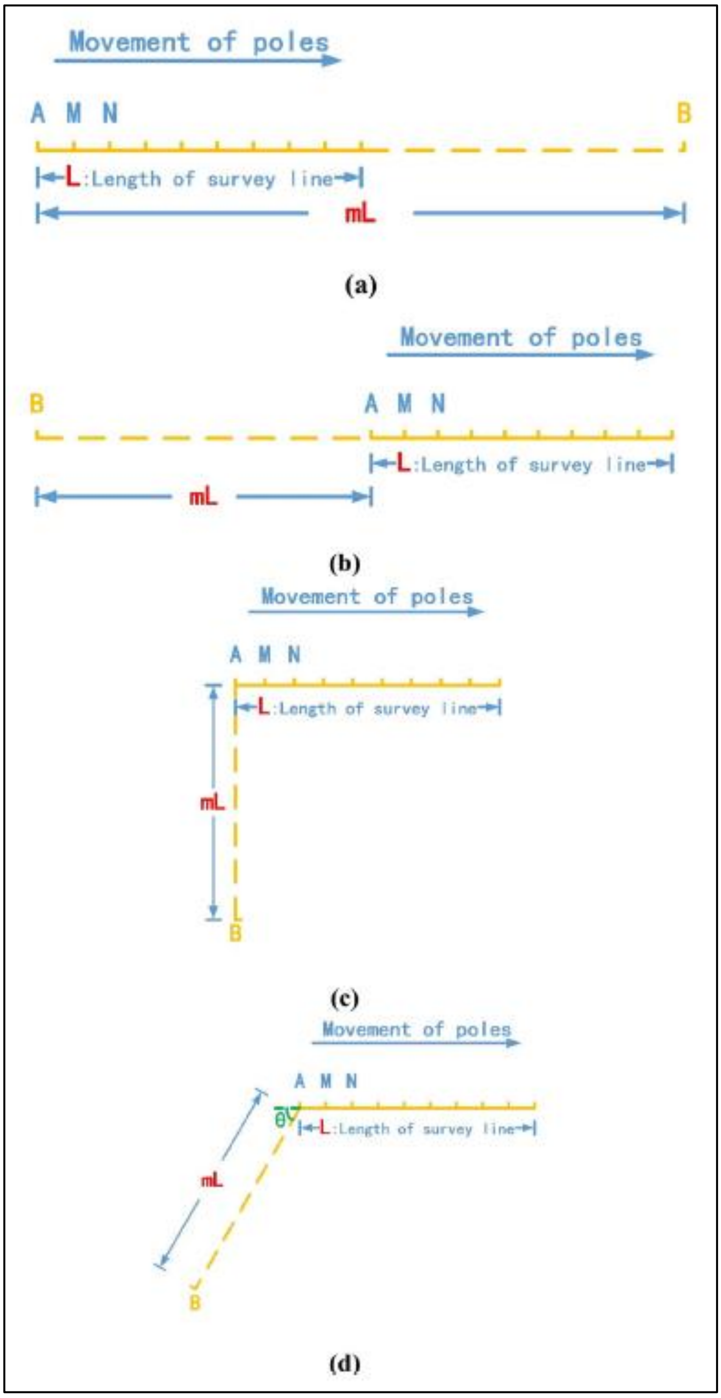

Figure 2.5: Four locations of remote electrode in pole-dipole array: (a) parallel, positive extension of survey line, (b) parallel, negative extension of survey line, (c) perpendicular to the survey line and (d) 60° to the survey line (Wang *et al.*, 2024)

The research was conducted in two (2) different environments, which includes both laboratory and field test, with electrode spacing of 0.1m and 0.2m respectively. Various remote electrode distances were tested to assess their impact on RMSe, particularly in scenarios with insufficient spacing. The experimental design included the use of twenty (20) electrodes connected via a single resistivity cable, producing a half-resistivity tomography layout. A comparative analysis was conducted between theoretical RMSe values—derived from standard computational equations—and measured RMSe values, which reflect specific conditions of the survey environments.

The findings are summarized in Table 2.1 and Table 2.2. Results from the laboratory experiments indicated that a remote electrode distance equal to the survey line length was sufficient to ensure data reliability. However, the field experiments revealed that a distance of at least twice the survey line length was necessary to minimize errors effectively. Even though the study employed three remote electrode orientations (perpendicular, parallel, and angled), the reference RMSe values used for accuracy assessment were based on a reference with inadequate confidence as the negative extension configuration is not commonly mentioned and utilized in the deployment of a pole-dipole array.

Table 2.1: Example of occurrences of negative apparent resistivity values for each remote electrode distance

Remote electrode distance multiplier to survey line length	**Theoretical RMSe (%)**	**Actual RMSe (%)**
1	9.54	9.88
2	3.94	4.13
3	2.15	2.47
4	1.35	1.56

Table 2.2: Example of occurrences of negative apparent resistivity values for each remote electrode distance

Configuration	Remote electrode distance multiplier to survey line length			
	1	2	3	4
B ~ AMN	RMSe = 8.98%	RMSe = 3.47%	RMSe = 2.19%	RMSe = 1.42%
B⊥AMN	RMSe = 11.52%	RMSe = 4.77%	RMSe = 3.33%	RMSe = 3.00%
B∠AM (θ = 60°)	RMSe = 10.68%	RMSe = 4.04%	RMSe = 2.31%	RMSe = 2.12%

Despite its complexity, a pole-dipole array is often being the array of choice in most study cases for multiple reasons. The pole configuration is efficient in drawing current flow into a more concentrated region, which enhance the sensitivity of this array on the deeper anomalies (Loke & Barker, 1996). This allows a higher resolution in terms of depth profiling, making pole-dipole array effective in exploring deeper geological structures in studies such as hydrogeological and mineral explorations (Loke & Dahlin, 2002). The resolution of a pole-dipole array is reflected laterally as well, especially in areas with varying lateral properties (Okpoli, 2013).

Furthermore, the constant need of high resolution and high coverage data invoke the application of a pole-dipole array. The large separation distance between the current electrode and the potential electrode pair causes this array to generate superior signal penetration (Gómez-Ortiz *et al.*, 2011; Acworth & Hill, 1990). The influence of surface resistivity effect is significantly reduced with larger separation distance between the current electrode and potential electrodes, which allows the electrical current generated to be more focused on the deeper region of the resistivity measurements (Gómez-Ortiz *et al.*, 2011). The surface resistivity effect refers to the influence of near-surface layers and conditions on the measurements such as topography, electrode positioning, shallow current leakage and surface materials. These factors arise due to the nature of electrical current that tends to propagate through shallow, more conductive layers, which skews the readings of deeper region of the study (Loke & Van Schoor, 2013; Zhou *et al.*, 2011; Sánchez *et al.*, 2006). This effect also causes the distortion of deeper subsurface imaging, whereby the significant underestimation of near-surface resistivity masks the true resistivity characteristics of deeper layers (Loke & Van Schoor., 2013).

2.5 Apparent resistivity data

2-D electrical resistivity tomography (ERT) data collection measures subsurface apparent resistivity data. Apparent resistivity is defined as the resistivity of hypothetical homogeneous half-space that will generate similar potential difference when measure over real Earth without manipulating the acquisition parameters (Lee & Cho, 2020). However, in actual geological settings, inhomogeneous subsurface areas are widely found, and these features are reflected in the negative apparent resistivity values recorded (Loke, 2012). Therefore, the collected data do not portray the exact subsurface conditions unless the subsurface layers are homogeneous. In addition to this drawback, the depth obtained from apparent resistivity pseudosections data is the apparent depth (Loke, 2012). Similarly, the apparent depth is not a representation of the exact subsurface depth except for homogeneous subsurface cases.

Apparent resistivity data can also be measured in negative values, and this phenomenon favors the asymmetrical electrode configuration arrays such as pole dipole and dipole-dipole array (Lee & Cho, 2020; Lee *et al.*, 2016; Doetsch *et al.*, 2010; Wilkinson *et al.*, 2008; Kim *et al.*, 2006). Negative apparent resistivity values are considered as measurement errors or noises (Lee & Cho, 2020; Cho & Kim, 2010; ABEM, 200), as negative apparent resistivity is theoretically impossible to be measured over flat topographic areas (SEGJ, 2004; Jung *et al.*, 2009). However, according to Jung *et al.* in 2009, rapid changes in topography or severe anisotropic mediums can also cause the measurement to be negative in values, thus insisted that complex geological structures would also contribute to the negative measurements. This was also confirmed by Binley and Kemna in 2005, and Loke in 2004, that in cases of highly conductive materials or other complex features in the subsurface can break the linear relationship between electrical potential and current flow, which lead to negative measurements.

2.6 True Resistivity Data

A pseudosection of apparent resistivity data is not reliable to precisely describe the subsurface conditions (De Donno & Cardarelli, 2017). However, it can serve as an initial guide for in depth quantitative interpretation (Loke, 2013). To acquire a tomography that accurately represents the subsurface conditions of an area, true resistivity data has to be computed. A true resistivity tomography is computed by inversing the initial apparent resistivity pseudosection using apparent resistivity models (Muhammad & Saad, 2018) that calculate the apparent resistivity differences of various subsurface formations between the on-field measured data to the calculated model data (Oldenburg & Li, 2005). A true resistivity tomography displays the fundamental properties of the materials by eliminating influences from external factors such as geometrical effects, electrode configuration, and boundary conditions (Loke, 2012).

Even though resistivity inversion portrays the true subsurface conditions of the Earth, it does not have its own uniqueness (Sharma & Verma, 2015). This suggests that multiple resistivity models can generate similar responses with the measured data within the limits of the data's accuracy (Hoffmann & Dietrich, 2004). To achieve uniqueness of an inversion while preserving the resolution, regularization is implied in the form of smoothing (Sharma & Verma, 2015), but on the inverted areas with lower model resolution will strongly depend on the type of constraint used (Oldenburg & Li, 1999; Oldenburger *et al.*, 2007). Therefore, accurate inversions that reflect the actual subsurface conditions are only produced when the constraints are realistic (Sharma & Verma, 2015). Inman *et al.* (1973) conducted resistivity inversion research by inversing a set of noise-free apparent resistivity data using two different models, one with increasing resistivity with depth, while the other possesses an intermediate resistive layer. Both models resolve the data with a high degree of accuracy. However, when artificial noise values were added to the data, the error produced in response rises up to 15% depending on the location of the noise values placement. That being the case, the quality of the apparent resistivity data itself needs to be free from as much noise as possible, because noisy data will contribute to inversion error that could lead to misinterpretation of subsurface conditions.

Inversion constraints were elaborated by Loke *et al.*, in 2003 whereby the author assessed the benefits and drawbacks of smooth and blocky constraints in ERT inversion techniques. The smooth (standard) data constraint exploits a cell-based model that minimizes the squared sum of spatial changes in the inversion, which is suitable to be employed when the subsurface structures have random resistivity distributions or "Gaussian" noise, where smooth changes in resistivity values is applied. However, if the data contains outlier data points (noises originate from non-random sources such as mistakes or equipment problems), then this approach is unsatisfactory (Geotomo, 2017; Loke, 2003). The blocky (robust) data constraint is more suitable for resolving the effects of outlier data points, which minimizes the absolute difference between the on-field measured and calculated model apparent resistivity (Geotomo, 2017; Loke *et al.*, 2003; Claerbout & Mur 1973).

Figure 2.6 illustrate the contrast between smooth and blocky inversion constraint used to investigate the Magusi River in Canada. Three (3) different profile are illustrated in Figure 2.6, where (a) displays apparent resistivity pseudosection, (b) illustrates the use of smooth constraint during the inversion process, and (c) illustrates the use of blocky constraint during the inversion process. The smooth constraint inversion produces a smooth spatial variation in resistivity values, making it suitable to be utilized in areas with gradual changes in subsurface geology (Loke *et al.*, 2003). On the other hand, a distinct sharpness separating true resistivity boundaries is produced when the blocky constraint is implemented during the inversion, making it better suited to be implemented in areas with sharp subsurface geology boundaries (Loke *et al.*, 2003).

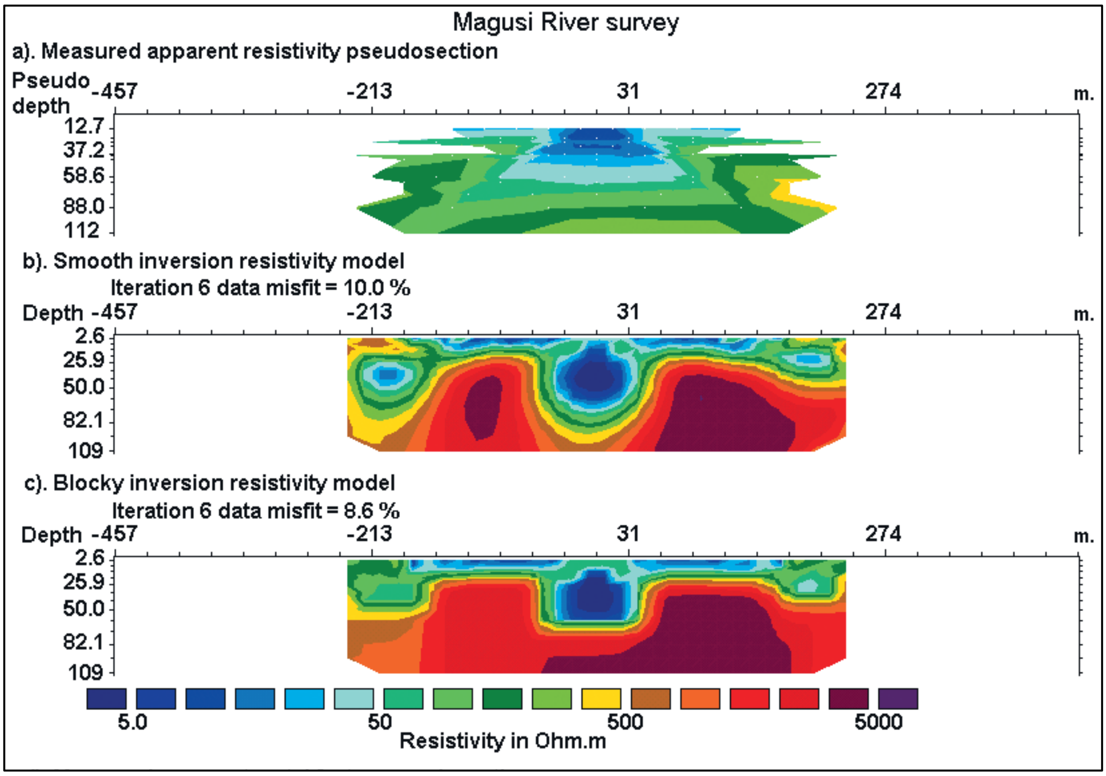

Figure 2.6: The ERT survey of Magusi River in Canada: (a) the apparent resistivity pseudosection, (b) inversion optimizing smooth constraint, and (C) inversion optimizing blocky constraint (modified from Loke *et al.*, 2003)

2.7 Statistical approach in data quality assessment

Apparent resistivity pseudosections are processed using inversion software to produce true resistivity tomography, and this software optimizes model block that mathematically creates possible subsurface geological formations to compare it with the pseudosections (Alel *et al.*, 2015). This software, such as Res2DInv, then calculates the differences between the pseudosections and the model block using root-mean-square error (RMSe), which is expressed as follows (equation 2.4):

$$RMSe = \sqrt{\frac{\sum_{i=1}^{n} |\rho_m(i) - \rho_c(i)|^2}{N}} \tag{2.4}$$

where ρ_m corresponds to the measured apparent resistivity values, ρ_C corresponds to the calculated apparent resistivity model values, and N corresponds to the sum of data in the apparent resistivity dataset. Alternately, researchers compute numerical differences between the measured resistivity pseudosections and the calculated resistivity model by employing other approaches such as mean absolute percentage error (MAPE) (Kim & Kim, 2016; Bowerman *et al.*, 2004), which is expressed as follows (equation 2.5):

$$MAPE = 100 \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\rho_{m_i} - \rho_{c_i}}{\rho_{m_i}} \right| \tag{2.5}$$

Although both metrics can be utilized to access the performance of measured apparent resistivity to the calculated apparent resistivity model (Wang & Lu, 2018), they each reflect the effectiveness of the two data comparison depending on the data distribution, where the former approach is more sensitive to outliers in datasets with a normal distribution (Chicco *et al.*, 2021; Chai & Draxler, 2014), and the latter approach