DEVELOPMENT OF NEW SELF-POTENTIAL ACQUISITION TECHNIQUE FOR GROUND SUBSURFACE INVESTIGATION

MARK BIN JINMIN

UNIVERSITI SAINS MALAYSIA

2024

DEVELOPMENT OF NEW SELF-POTENTIAL ACQUISITION TECHNIQUE FOR GROUND SUBSURFACE INVESTIGATION

by

MARK BIN JINMIN

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

August 2024

DEDICATION

This thesis work is dedicated to my late Father, Jinmin Bin Albat for his advice and unconditional moral support.

ACKNOWLEDGEMENT

I would like to express my gratitude to God for giving me an opportunity and to help me endlessly in finishing this Thesis.

First and foremost, I would like to thank my thesis supervisor Associate Professor Dr. Nordiana Mohd Muztaza, for her guidance, encouragement, and invaluable feedback. Her expertise and mentorship were essential to the completion of this thesis. Not to forget, I am indebted to my co-supervisor Professor Dr. Rosli Saad who has been passionate about my work. His guidance assisted me throughout my research and completion of this thesis. He has been supportive and nurtured me to be a good person all the time like my own father.

I am also grateful to the members who were involved in my thesis journey and my sincere thanks to Professor Dato' Dr. Mokhtar Saidin, Dr. Nur Azwin Ismail, Dr. Andy Anderson Bery, Dr. Muhammad Sabiu Bala, Dr. Yakubu Samuel Minyi, and to the late Dr. Hazreek Zainal Abidin for their insightful feedback and constructive criticism, which help me improve the quality of my research. I would like to extend my thankfulness for the help and assistance from Dr. Kiu Yap Chong, Dr. Rais Yusoh, Dr. Muhammad Nazrin A Rahman, Dr. Mohammed Mustapha Adejo, Dr. Sabiu Bala, Dr. Muhammad Taqiuddin Bin Zakaria, Dr. Najmiah Binti Rosli, Mr. Shyeh Sahibul Karamah Bin Masnan, Mr. Fauzi Andika, Mr. Tarmizi, Mr. Amsir, Mr. Zul Fadhli, Mr. Sabrian Tri Anda, Ms. Nurina Auni Binti Ismail, Ms. Nur Farhah Binti Ali, Mr. Muhammad Danial Fikri Bin Mohd Rani, Mr. Mohamad Fadzli Bin Bakri, Mr. Ahmad Ritauddin, Mr. Engku Imran, Ms. Aqillah Binti Abdul Rahman, Ms. Umi Maslinda, Mr. Muhammad Afiq, Mr. Hazrul Hisham, Ms. Nur Amalina, Ms. Nabila Sulaiman, and Mr. Helmi. In addition, special thanks to lab assistants; Mr. Low Weng Leng, Mr.

Yaakub Othman, Mr. Shahil Ahmad Khosaini, and Mr. Zulkeflee Ismail for providing their expertise in handling and operating the geophysical equipment.

I would like to thank my family, especially my parents late Jinmin Albat and Mary Lahat, my sister Marilyn Jinmin and Diana Joos for their unwavering support and encouragement throughout my academic journey. Their love and belief in me have been a constant source of motivation.

I would like to thank Kementerian Pengajian Malaysia (KPM) for offering the sponsorship scheme of MyPhD program and financial support from the Centre for Archaeological Research (CGAR) for the research assistant position through my studies. I wanted to take a moment to express my gratitude and appreciation to Universitas Syiah Kuala, Aceh for allowing me to conduct the research in Banda Aceh. I am incredibly grateful for Researching University Grant (RUI) entitle Integrated Geophysical Characterization of Geothermal Exploration and Strategy for A Sustainable Use of Geothermal Resources with grant no. 1001/PFIZIK/8011110 and Fundamental Research Grant Scheme (FRGS) entitle Development Approach for Soil or Rock Characteristics with grant no. 203/PFIZIK/6711663

Thank you to all those who supported me during this challenging yet rewarding journey. I am forever grateful for your contribution and encouragement.

TABLE OF CONTENTS

ACKNOWLEDGEMENT ..... **ii**

TABLE OF CONTENTS ..... **iv**

LIST OF TABLES ..... **vii**

LIST OF FIGURES ..... **viii**

LIST OF SYMBOLS ..... **xii**

LIST OF ABBREVIATIONS ..... **xiv**

ABSTRAK ..... **xv**

ABSTRACT ..... **xvii**

CHAPTER 1 INTRODUCTION **1**

1.1 Overview 1

1.2 Problem statement 3

1.3 Research objectives 4

1.4 Scope of study 5

1.5 Novelty and significance of the research 7

1.6 Thesis structure 8

CHAPTER 2 LITERATURE REVIEW **10**

2.1 Introduction 10

2.2 Self-potential anomalies 11

2.3 Self-potential principle 16

  2.3.1 Redox potential 21

  2.3.2 Nerst potential 22

  2.3.3 Streaming potential 23

  2.3.4 Diffusion potential 24

  2.3.5 Thermoelectric potential 24

2.4 Previous work 26

2.5 Chapter Summary 34

CHAPTER 3 MATERIALS AND METHODOLOGY 37

3.1 Introduction 37

3.2 Research methodology 37

- 3.2.1 Stage one 38
- 3.2.2 Stage two 41

3.3 Location and geology of the study area 48

- 3.3.1 Green field site, USM 48
- 3.3.2 Bukit Selambau and Kuala Ketil, Kedah 49
- 3.3.3 Alue Naga, Banda Aceh (Indonesia) 51

3.4 Test site 53

- 3.4.1 Green field site, USM 54
- 3.4.2 Performance validation 55

3.5 SP Equipment 59

3.6 Research methodology overview 61

3.7 SP Data processing 62

3.8 Numerical accuracy assessment 71

- 3.8.1 Standard deviation (σ) 72
- 3.8.2 Root-mean-square (*RMS*) 72

3.9 Chapter summary 74

CHAPTER 4 RESULTS AND DISCUSSION 75

4.1 Introduction 75

4.2 Stage one 76

- 4.2.1 Test and calibration site 76

4.3 Stage two 81

4.4 Performance validation 85

- 4.4.1 Optimum electrode time 87

4.2.2 Electrode calibration 88

4.4.3 Self-potential conventional technique and SPET in 1D results 90

4.4.4 Self-potential conventional technique and SPET in 2D results 94

4.4.5 Data acquisitions time duration... 95

4.4.6 Data analysis for self-potential convetional technique and SPET.. 96

4.5 Chapter summary 98

CHAPTER 5 CONCLUSION AND FUTURE RECOMMENDATIONS 100

5.1 Conclusion.. 100

5.2 Recommendation for future research 101

REFERENCES 102

LIST OF PUBLICATION

LIST OF TABLES

Page

Table 2.1 Self-potential sources and anomalies (Reynolds, 1997) 13

Table 3.1 SP equipment and quantity 61

Table 4.1 The electrode calibration at Bukit Selambau 89

Table 4.2 The electrode calibration at Kuala Ketil 90

Table 4.3 The electrode calibration at Alue Naga.. 90

Table 4.4 Data acquisition time duration 96

Table 4.5 Data analysis at Bukit Selambau.. 97

Table 4.6 Data analysis at Kuala Ketil... 97

Table 4.7 Data analysis at Alue Naga 97

LIST OF FIGURES

Page

Figure 2.1 The primary illustrator for self-potential equipment on site (modified from Revil and Jardani, 2013) 17

Figure 2.2 Illustrator of the silica surface with pH 5-9. The electrical double layer (EDL) is the electrical diffuse region (Kim and Lawler, 2005) 19

Figure 2.3 Illustrator of self-potential an ore body (modified after Sato and Mooney, 1960) 22

Figure 2.4 Common sources of electrical potential in self-potential method: a) Redox potential developed as geobattery (Sato and Mooney, 1969); b) Diffusion potential generated by the migration of ions during chemical diffusion; c) Streaming potential generated by the reaction of ions in the stern layer of the electrical double layer (EDL); d) Thermoelectric potential created by the differential migration of ions in thermal diffusion 26

Figure 2.5 Self-potential map at Pasanggrahan region, South Sumedang, Indonesia (Santoso et al., 2019) 27

Figure 2.6 Self-potential map over the cave Vers-Chez-Le-Brandt (Gurk and Bosch, 2001) 29

Figure 3.1 Illustration of the common electrode for the self-potential method (Cabusson et al., 2021) 37

Figure 3.2 Illustration of leapfrog electrode configuration 39

Figure 3.3 Illustration of moving base electrode configuration 40

Figure 3.4 Illustration of fixed base electrode configuration 40

Figure 3.5 Flow chart of the SP conventional technique 41

Figure 3.6 Procedure of OET technique 43

Figure 3.7 Measuring the OET at Green field site, USM 43

Figure 3.8 Procedure on electrode calibration technique 44

Figure 3.9 Multiple electrodes gathered at the base station 45

Figure 3.10 Preparation of closed loop...46

Figure 3.11 Illustration on closed loop 46

Figure 3.12 Flow chart of the research methodology in developing SPET...........47

Figure 3.13 Green field site, USM (Google earth, 2019) 49

Figure 3.14 Regional geological map of Penang Island (Mineral and Geoscience Department, 2008) 49

Figure 3.15 Study area in Bukit Selambau (A) and Kuala Ketil (B) in Kedah (Google earth, 2019) 50

Figure 3.16 The geology setting at the study area Bukit Selambau (A) and Kuala Ketil (B) in Kedah (Mineral and Geoscience Department, 2008) 51

Figure 3.17 Study area in Alue Naga, Banda Aceh, Indonesia (Google earth, 2019) 52

Figure 3.18 Banda Aceh's geology map (Rusdi et al., 2015)................................53

Figure 3.19 SP stations at Green field site, USM (Google earth, 2019) 55

Figure 3.20 SP survey area at Green field site, USM...55

Figure 3.21 SP stations at Bukit Selambau, Kedah (Google earth, 2019).............56

Figure 3.22 Survey area at Bukit Selambau, Kedah...57

Figure 3.23 SP stations at Kuala Ketil, Kedah (Google earth, 2019)....................57

Figure 3.24 Survey area at Kuala Ketil, Kedah 58

Figure 3.25 SP stations at Alue Naga, Indonesia (Google earth, 2019)................59

Figure 3.26 Survey area at Alue Naga, Aceh 59

Figure 3.27 Example of SP datasheet...59

Figure 3.28 SP technique equipment..61

Figure 3.29 SP conventional technique processing flowchart...............................63

Figure 3.30 SPET processing flow chart 64
Figure 3.31 SAS4000 utilities user interface (UI) in data conversion 65
Figure 3.32 SP data sorting template in Microsoft Excel 66
Figure 3.33 SP results on graph in Microsoft Excel 66
Figure 3.34 OET results in Microsoft Excel 67
Figure 3.35 OET template in Microsoft Excel 68
Figure 3.36 EC data correction template in Microsoft Excel 69
Figure 3.37 Illustration on the reference correction (Cabusson and Finizola, 2013) 70
Figure 3.38 Illustration on the closure correction (Cabusson and Finizola, 2013) 71
Figure 3.39 SPET pre-processing configuration 73
Figure 4.1 Fixed base at Green field site (Stage one) 77
Figure 4.2 Leapfrog at Green field site (Stage one) 78
Figure 4.3 Moving base at Green field site (Stage one) 80
Figure 4.4 All electrode configuration at Green field site (Stage one) 81
Figure 4.5 Results of optimum time at station one (Stage two) 82
Figure 4.6 Results of optimum time at station two (Stage two) 83
Figure 4.7 Results of optimum time at station three (Stage two) 83
Figure 4.8 Results of optimum time at station four (Stage two) 84
Figure 4.9 The SP conventional technique and SPET results (Stage two) 85
Figure 4.10 The optimum electrode time at Bukit Selambau 87
Figure 4.11 The optimum electrode time at Kuala Ketil 88
Figure 4.12 The optimum electrode time at Alue Naga 88
Figure 4.13 The SP conventional technique and SPET results at Bukit Selambau 91
Figure 4.14 The SP conventional technique and SPET results at Kuala Ketil 92

Figure 4.15 The SP conventional technique and SPET results at Alue Naga 93

Figure 4.16 The 2D SP surface mapping at Bukit Selambau 94

Figure 4.17 The 2D SP surface mapping at Kuala Ketil 95

Figure 4.18 The 2D SP surface mapping at Alue Naga...95

LIST OF SYMBOLS

T	Absolute temperature
°C	Degree Celcius
°E	Degree Easting
°N	Degree Northing
E_k	Electrokinetic potential
F	Faraday constant
RT	Gas constant
Q_H	Heat source ($Wm\text{-}^3$)
N	Ionic valence
°K	Kelvin
<	Less than
m	meter
mM	millimoles
mV	millivolts
I_a, I_c	Mobilities of the ion
M	Moles
ψ^0	Monopole term of voltage
>	More than
-	Negative value
E_n	Nerst potential
n	Number of electrons exchanged
1D	One-dimensional space
/	Or
pH	Power of hydrogen

RMS	Root mean square
C1,C2	Solution concentrations
σ	Standard deviation
κ	Thermal conductivity (Wm^{-1}K^{-1})
C_{TE}	Thermoelectric coupling coefficient (V/°C)
2D	Two-dimensional space
R_g	Universal gas constant
ξ	Zeta potential

LIST OF ABBREVIATIONS

ABEM	ABEM Instrument AB
*.AMP	ABEM Multi-Purpose Format
EDL	Electrical double layer
EC	Electrode Calibration
GPS	Global Positioning System
LSQR	Least Square Subspace Preconditioned
OET	Optimum Electrode Time
RMS	Root Mean Square
*.S4K	SAS4000 Raw Data
SP	Self-Potential
SPET	Self-Potential Enhancement Technique
SPS	Self-Potential-Surface
SAS	Signal Acquisition System
USA	United States of America
USM	Universiti Sains Malaysia
UI	User Interface
WOA	Whale Optimization Algorithm

PEMBANGUNAN TEKNIK BAHARU SWA-KEUPAYAAN UNTUK KAJIAN SUBPERMUKAAN TANAH

ABSTRAK

Teknik Swa-Keupayaan (SP) adalah satu teknik geoelektrik pasif. Teknik ini mengukur perbezaan swa-keupayaan semula jadi yang wujud antara mana-mana dua titik pada permukaan tanah. Titik-titik tersebut diukur dengan menggunakan elektrod yang dikenali sebagai elektrod bergerak dan elektrod induk. Dalam teknik SP, elektrod-elektrod ini sering dipanggil ‘periuk berliang’ yang direka untuk tidak mencipta mana-mana swa-keupayaan kimia apabila bersentuhan dengan permukaan tanah. Elektrod rujukan digunakan sebagai elektrod induk manakala elektrod kedua digunakan untuk mengukur swa-keupayaan pada tanah. Kajian utama adalah untuk memperkenalkan SPET iaitu gabungan teknik yang praktikal dalam pengumpulan data swa-keupayaan sendiri. Antara teknik-teknik yang diperkenalkan dalam kajian ini adalah teknik kalibrasi electrode (EC), teknik masa optimum electrod (OET) dan teknik gegelung tertutup. Dengan menggunakan sepasang elektrod akan memerlukan masa dan tenaga yang banyak semasa pengumpulan data. Oleh itu, ECT diperkenalkan untuk membuat kalibrasi dan membetulkan ralat elektrod semasa pengukuran data dan membolehkan penggunaan beberapa elektrod. Tempoh masa yang tidak konsisten untuk menyeimbangkan elektrod di atas permukaan tanah boleh menyebabkan bacaan data SP yang tidak tepat. Oleh itu, OET adalah untuk mengenal pasti jangka masa optimum bagi elektrod untuk mencapai kesimbangan di permukaan tanah. SP mempunyai beberapa konfigurasi elektrod dalam pengumpulan data seperti kaedah kecerunan dan kaedah pangkalan tetap. Kaedah kecerunan mempunyai beberapa kelemahan dalam kualiti data, seperti kesalahan data kumulatif, polarisasi elektrod, kesan rayapan, keupayaan perubahan data mengikut masa, kesan sentuhan tanah dan kesalahan bacaan. Pelaksanaan teknik gegelung tertutup bertujuan untuk mengurangkan kesalahan kualiti data dalam SP. Dalam penyelidikan ini, konfigurasi elektrod pangkalan tetap telah dipilih untuk mendapatkan taburan swa-keupayaan dalam subpermukaan. Kajian dijalankan di Green field site, Universiti Sains Malaysia, Pulau Pinang. Kemudian, data SP dieksport daripada sistem ABEM SAS4000 dan diproses menggunakan Microsfot Excel. Satu tutorial yang dibuat oleh S. Barde Cabusson dan Anthony Finizola mengenai pengurangkan kesalahan data untuk pemetaan swa-keupayaan telah digunakan. Hasil dalam kajian ini menunjukkan bawah ECT dalam dilaksanakan dengan menggunakan beberapa elektrod dan dapat dijadikan elektrod yang bergerak dengan cepat. Tempoh pengumpulan data hanya memerlukan masa selasa 36 minit berbanding dengan teknik SP yang umum yang memakan masa selama 53 minit. Manakala dalam OET, menunjukkan hasil yang menjanjikan dimana nilai swa-keupayaan sendiri bermula dengan nilai 0.8550 mV pada 0 saat dan meningkat dengan cepat ke 2.1290 mV pada 200 saat, nilai swa-keupayaan sendiri adalah pada bacaan terbaik dan seterusnya berkurang pada jangka masa 400 saat dengan nilai 2.0160 mV. Oleh itu, dapat diperhatikan OET di kawasan sekitar tersebut adalah selama 200 saat. Pengenalan teknik gegelung tertutup dalam pengumpulan data SP amat penting. Dalam satu data di Kuala Ketil menunjukan sisihan piawai bagi SPET adalah 26.157 mV manakala teknik SP umum adalah 28.802 mV. Dengan SPET, ia dapat menjimatkan masa, tenaga, kos dan juga mampu membetulkan kualiti data SP. SPET adalah gabungan teknik yang praktikal dalam pengumpulan data SP.

DEVELOPMENT OF NEW SELF-POTENTIAL ACQUISITION TECHNIQUE FOR GROUND SUBSURFACE INVESTIGATION

ABSTRACT

Self-potential (SP) method is a passive geoelectrical method. It measured the natural potential differences which exist between any two points on the ground. The points are measured using an electrode known as the roving electrode and the base electrode. In the SP method, these electrodes are often called ‘porous pots’ which are designed not to create any chemical potential once they are contacted on the ground. A reference electrode is used as a base electrode, and the second electrode is used to measure the potential on the ground. The primary research is to introduce the practical techniques in SP data acquisition which is Self-Potential Enhancement Technique (SPET). SPET is a combination of techniques which are the electrode calibration technique (EC), the optimum electrode time technique (OET), and the closed loop. Using a pair of electrodes consumes more time and energy during data acquisition. Hence, the EC is to calibrate and correct the electrode error during data measurement, which is able to use multiple electrodes. An inconsistent time period for mitigating an electrode on the ground can lead to inaccurate self-potential data readings. Thus, the OET purpose is to identify the time frame for an electrode to be in equilibrium on the ground. The SP has an electrode configuration for acquiring the electrical potential data such as gradient and fixed base. The gradient technique has some disadvantages in the data quality, such as cumulative error, electrode polarization, drift effect, time-varying potential, soil contact effect, and reading errors. The implementation of a close loop aims to reduce noise in SP data. In this research, the fixed based electrode configuration is chosen to obtain the distribution of electrical potential in the subsurface. The study was conducted at Green field site, Universiti Sains Malaysia, Penang. The SP data were exported from the ABEM SAS4000 system and processed using Microsoft Excel. A tutorial made by S. Barde Cabusson and Anthony Finizola on data reduction for self-potential mapping provides comprehensive insights and practical steps for efficiently processing and interpreting SP data. The results in this study show that ECT was able to be executed using multiple electrodes and proven to be a fast-moving electrode. The acquisition time duration took only 36 minutes compared to the common SP survey, which took 53 minutes. Whereas OET shows promising results where the initial electrical potential value is 0.8550 mV at 0 seconds and increased rapidly towards 2.1290 mV at 200 seconds, the electrical potential value is at steady reading and decreased at the duration of 400 seconds with a value of 2.0160 mV. Hence, it is observed that the OET in the vicinity area is 200 seconds. The implementation of the close loop is also vital, one of the study areas which is at Kuala Ketil shows the SPET standard deviation of 26.157 mV while the SP conventional technique is 28.802 mV respectively. The SPET shows a minimal value of SD compared with the SP conventional technique. With SPET, it can save time and money, and it can correct the SP data and manage SP data quality control. SPET is a combination of the techniques which are the new practical way of SP data acquisition.

CHAPTER 1

INTRODUCTION

1.1 Overview

Self-potential (SP) technique is one of the geophysics methods that measure the naturally occurring electrical potential in the subsurface. The SP is a passive technique, a non-intrusive, non-destructive, fast, inexpensive method, and user-friendly (Nyquist and Corry, 2002). The SP conventional technique is widely used for environmental investigations, engineering geology investigations, and archaeological prospection. To date, these cases focused on SP conventional technique as the primary tool such as to map seepage flow (Moore et al., 2011), leaky containment (Nyquist and Corry, 2002), geothermal (Rahayudin et al., 2020), landslides investigation (Sujitapan et al., 2019), land movement mitigation (Santoso et al., 2019), including buried archaeological detection (Yousef et al., 2020). The anomalies identified in environmental investigation, engineering geology investigation, as well as archaeological prospection, are caused by background potentials. The background potentials included those caused by human activity, telluric currents, and cultural activity. The background potential helps to distinguish electrical potential behaviour related to solving these problems.

The SP conventional technique is generally being accepted and practised, and this technique has the possibility to contribute flexible data acquisition and improved data processing. Now and then, geophysicists neglected the background potential sources such as electrode drift, drift due to soil moisture and temperature, telluric currents, topographic effect, and instrumental drift. Besides that, human-made environmental structures such as electric power lines, buried utilities, and metal fences are also an example of background potential sources. Other undesired voltages are considered noise, which will affect the SP data. (Nyquist and Corry, 2002).

The SP conventional technique often used a pair of the porous pot, a cable, and a high-input impedance multimeter to conduct the survey. The porous pot is an electrode in SP conventional technique, which is non-polarizing material designed to reduce instrumental drift. These electrodes are designated as moving electrodes and base electrodes (Barde-Cabusson et al., 2021). The joint solution used in this method was Copper (II) Sulphate as a salt bridge in the porous pots. The SP conventional technique measured the natural occurrence of potential differences that exist between the two points. Thus, a pair of electrodes were used to measure these potential differences; the value of the potential differences at each point will be relative to the base point (Nyquist and Corry, 2002). In view of this conventional technique, the limitation of using two electrodes will take more time and energy when considering more stations and covering a large study area. Therefore, this research provides valuable insight by improvising the SP conventional technique and developing new techniques to solve these limitations.

In the course of SP data processing and interpretation, it was a long time ago that a qualitative approach is used to interpret the SP results. Revolution-era took place when the analysis of signals started 40 years ago with the works by Fitterman (1978) and Sill (1983). Recent works on revised SP data processing were carried out by Barde-Cabusson et al., (2021) and applied in structural control volcanism investigations. Barde-Cabusson et al., (2012; 2014) conducted a self-potential mapping to identify tectonic volcano events using their trusted data processing. This research developed a new data acquisition technique where it is correspondent with new data processing in minimizing the drift.

1.2 Problem statement

Mitigating the electrode on the ground is one controversial topic. Most practitioners conducting the SP conventional technique would have an inconsistent stance on planting the electrodes on the ground. Inconsistent time frames to allow the electrodes to settle down in order to have a stable reading during the data acquisition might lead to inaccurate SP data. This statement is one of the controversies in the SP conventional technique. From this problem, the time duration of the electrode on the ground is measured and the optimum time can be identified.

A pair of electrodes are tools in the SP conventional technique. The limitation of electrode usage is another critical issue. A long cable is insulated to minimize the connection leak, which will connect both electrodes to a high-impedance voltmeter. Depending on the station separation distance, if each station with a separation distance of 20 m, the moving electrode must travel every 20 m for each station. This conventional technique, which applies a pair of electrodes, will consume more time and energy to accomplish a longer separation distance in order to expand survey coverage. It is about time to consider a better technique in which multiple electrodes can be used in this survey.

The SP conventional technique has a disadvantage such as inaccurate procedures related to the possibility of introducing external noise or drift (Corwin, 1990). This technique commonly uses a pair of electrodes, which are designated as a moving electrode and a base electrode. The frequent activity of moving the base electrode would contribute to noise or drift in the SP data. This drift leads to results with an error that practitioners think to be negligible or insignificant. During data acquisition, when the SP value at the base station was not carefully measured in every cycle or profile, this would generate a huge drift and it will be affected the whole SP data. Therefore, a closed loop is introduced to reduce the drift.

The SP conventional technique has inapproachable revised data processing, which leaves a big gap in correcting the data. Thus, most of the processing software and steps for SP data correction are still doubtful. The practice will always be presenting SP results qualitatively instead of quantitatively, and the interpretation is rather complicated and subjective to interpret. Therefore, to validate that certain SP results align with previous studies, it is essential to consider the key features of electrical potential magnitude values and the types of electrical potential anomalies. These are the identifier or correlation attributes that will be considered in the SP data interpretation. Therefore, a proper pre-processing configuration will be introduced for the purpose of approachable SP data processing.

This study focuses on enhancing the current SP conventional technique by developing new SP techniques that are practical on-site and efficient workflow.

1.3 Research objectives

This research has the following objectives;

i. To develop the new Self-Potential Enhancement Technique (SPET) for shallow subsurface study.

ii. To establish a pre-processing configuration

iii. To validate SPET using SP data with statistical analysis by comparison to the SP conventional technique.

1.4 Scope of study

In this study, self-potential enhancement techniques (SPET) are incorporated with three new techniques, which are electrode calibration (EC), optimum electrode time (OET), and the closed loop. In this whole idea, the study focuses on developing the SPET by comparing it with the SP conventional technique. Both SPET and SP conventional technique is acquired using ABEM SAS 4000 (advanced multimeter), porous pot (electrode), electric cable, and Copper (II) Sulphate solution.

There will be two stages in this study, the first stage is the selection of reliable electrode configurations from the SP conventional technique. Understanding each electrode configuration's performances are important to observe the consistency of data results and efficiency of data acquisition. The factors of performance include the consistency of electrical potential data and the practicality of data acquisition. The SP stations were decided in a straight line and gridded with constant spacing between stations in order to have a better observation of SP data between the stations and the data is more organized and manageable. The SP data from the SP conventional technique will be processed using Microsoft Office Excel and commonly the reference correction is applied in this stage.

The second stage is applying SPET to the selected electrode configuration. Hence, two additional pre-processing SP data were introduced which are EC and OET data processing. These steps were taken during the SP data acquisition. In SPET, the closed loop was implemented, and the SP results were processed with reference correction and closure correction which is processed using a complete pre-processing configuration in Microsoft Office Excel. The SP reference and closure correction was referred to a researcher named Stephanie Barde-Cabusson, who established a proven SP data processing.

Four sites were considered in this study; green field site (USM), Bukit Selambau and Kuala Ketil (Kedah), and Alue Naga (Banda Aceh). For Green field site as a test and calibration site, the selection of the electrode configuration from the SP conventional technique was conducted. Hence, the electrode calibration (EC), optimum electrode time (OET), and closed loop which were altogether in SPET and SP conventional technique were applied for comparison to validate the practice of the data acquisition technique. In order to practice these techniques, the procedures were observed and identified.

The SPET together with SP conventional technique was also tested at Bukit Selambau, Kuala Ketil, and Alue Naga to demonstrate its practicality and efficiency of data acquisition. The time duration during both data acquisitions was recorded for time-saving purposes. Both SP value data were evaluated with relevant statistical data analysis to validate the SPET. The key parameter of the results in this study is to observe the SPET SP value data with SP conventional technique. Hence, SPET will be validated with the SP conventional technique in the study areas. Common practice, the SP interpretation consists of the magnitude of the electrical potential value, the vector of electrical potential flow movement, and the type of anomalies referred from the SP's previous study. Inadequate specific table or detail attributions on the classification of electrical potential was identified. Hence these parameters are the signature interpretation for both SP techniques.

1.5 Novelty and significance of the research

This research is focused on developing a new self-potential enhancement technique (SPET) that is practical in self-potential subsurface data acquisition. The main feature of this study is to find a solution where SP data acquisition is practical, efficient and can be followed by other practitioners. In this study, the fixed base electrode configuration is important to monitor the base station as a reference in SP data. The fixed base electrode configuration provides the best resolution qualitatively for shallow subsurface images that include a reliable revised data correction applied in the data processing.

The importance of multiple electrodes can be used with the aid of electrode calibration (EC) which is able to cover a larger area with better cost and energy efficiency, which the SP conventional technique is impossible to achieve.

The concept of measuring optimum electrode time (OET) provides a target and approximation time in SP data acquisition. By calculating the OET, the electrodes now have a reference time to be planted on the ground. The stable stage in OET refers to a period where the self-potential readings remain relatively constant over time. This provides an insight into time effectiveness in which the SP conventional technique is not applied.

The implementation of a closed loop in SPET aims to reduce the noise or drift effect in the SP data. External drift may exist in the data signal which will be interrupting the raw data during data acquisition.

The introduction of pre-processing configuration is for the SPET data processing, a complete template includes the OET, EC correction, reference correction, and closure correction as SP data processing. The complete processing template is a helpful guideline in the data processing. To recap, SPET contribution is applicable to be applied in different study cases with given a practical guideline and complete data processing configurations.

1.6 Thesis structure

This thesis consists of five chapters. The first chapter is a brief introduction to SP conventional technique including its application. This chapter also provides a general summary of developing the new SP techniques. It also includes the problem statements, research objectives, and scope of the study. This chapter covers the novelty and significance of this research. Finally, the structure of the thesis is also discussed here.

Chapter 2 contains an overview of the history and principle of the SP conventional technique. The section included a brief on SP anomaly sources. This chapter discussed the type of electrical potential sources, the type of electrical potential anomalies, and a literature review of previous works with various self-potential applications.

Chapter 3 is dedicated to the methodological framework of the new self-potential enhancement technique (SPET). The research involved the selection of electrode configuration from the SP conventional technique. Hence, the SP common electrode configurations have been illustrated in this chapter. The flow of developing SPET will also be explained in this chapter. This chapter includes the study area design for SPET and SP conventional technique. In this chapter, the flow of pre-processing SP data is also discussed here.

Chapter 4 is dedicated to presenting the results of the research findings. It starts with presenting the results and discussion of each electrode configuration in the SP conventional technique. This chapter also presented the results of each new technique in SPET. This chapter proceeds with the SPET qualitative results with the SP conventional technique. This chapter continues to discuss the SPET and SP conventional technique of SP data with relevant data analysis. The time duration from both data acquisitions was presented to show the efficiency of the practical technique.

Finally, Chapter 5 summarises the significance of this research, including important findings from the study. The recommendation and suggestions for future research are also included.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The self-potential (SP) method is a passive geophysical method. It measured the natural potential differences between any two points on the ground, such as the moving station relative to the base station. Self-potential signals are naturally occurring electrical fields measured at the subsurface using a non-polarized porous pot, which provides a better signal-to-noise ratio and the possibility to segregate between the feature sources. The pioneer of developing a non-polarizing porous pot was in 1865 by Matteucci, where he consistently improved the field measurement. Then, the non-polarizing porous pot was used widely in ore bodies exploration during the 1900s. The self-potential was earliest mentioned by Robert Fox when an underground copper sulfide ore deposit was detected in Cornwall, England (Fox, 1830). The method consists of two primary sources that contribute to the electrical potential signal: electrokinetic potential and electrochemical potential. In other applications, self-potential signals occur to the electric field associated with the groundwater in a porous medium (Revil and Leroy, 2004). Understanding the fundamental of the potential difference will lead to a better understanding of the self-potential method.

Electrokinetic potential occurs due to the electrolyte flowing through a porous medium defined as streaming potential. Birch, 1993; Fournier, 1989; Aubert and Yene, 1996; Revil and Leroy, 2004 conducted a study on the self-potential method's streaming potential. On the other hand, the electrochemical occurred due to the differing ion concentration throughout the groundwater solution and mobility. Hence, the electrochemical potential is generated when there is a potential difference between two electrodes in a medium that contains a different concentration of solutions (Reynolds, 1997). The electrochemical potential or membrane potential related to chemical gradient potential, which studies the ionic in pore water were investigated (Sen, 1991; Naudet et al., 2003, 2004; Revil and Leroy, 2004). Electrical signals related to groundwater flow were applied using the self-potential method to distribute the groundwater flow system (Goto et al., 2012).

2.2 Self-potential anomalies

The self-potential or spontaneous potential is naturally occurring electrical potential differences in the earth, which have signatures or features affected by various sources. These primary sources are arranged into two groups: mineralization potential and background potential (Neev and Yeatts, 1989).

The mineralization potential is defined as the potential that occurred as a result of different chemical concentration ions formed when conductive minerals are deposited. The water table intersects examples of dense conductive mineral deposits such as sulfide ore or graphite ore. Generally, the identification of mineralization potential has constant values and negative polarity values, and it can reach up to a hundred millivolts.

The background potential is defined as potential origin due to electrolytes' flowing through porous media or the capillary system. The background potential also can be known as electro-filtration or streaming potentials. The background potential can be either positive polarity or negative polarity potential with a few tens of millivolts. The mechanism of background potential exists when a different concentration of two electrolytes is contacted, the flowing of electrolyte via porous media, the electrolyte contact with solid material, and the induced telluric current from the electromagnetic phenomenon.

The self-potential anomalies' definition and source of origin can be classified in table 2.1. Characteristics of the self-potential results consist of two parameters; one is the polarity anomalies, which can be positive polarity anomalies or negative polarity anomalies. To clarify, polarity refers to the sign of the voltage potential difference between two points in the subsurface. It is determined by comparing the potential values measured by the positive and negative electrodes. If the potential difference is positive, it means that the positive electrode has a higher potential than the negative electrode, and the anomaly has a positive polarity. If the potential difference is negative, it means that the negative electrode has a higher potential than the positive electrode, and the anomaly has a negative polarity. The magnitude values of the self-potential can be a high magnitude or low magnitude value. In self-potential measurements, the magnitude refers to the size or strength of the SP signal, which is measured in millivolts (mV). A high magnitude SP signal means that the voltage potential difference between two points in the subsurface is relatively large, indicating a significant electrical contrast between the materials or fluids in the subsurface.

As fluid flow through porous media, it collected and transported positive ions (cations) from the surrounding channel. The cations accumulate at the endpoint of porous media, giving a net positive charge. Hence, the uncollected and untransported negative ions (anions) will be accumulated at the entry point of porous media, carrying a net negative charge. Thus, the streaming potential can be measured by its magnitude values and polarity anomaly when there are different concentration electrolytes of positive and negative self-potential anomalies at the porous media's entry point and endpoint. The self-potential polarity can be either positive or negative, with a value range of only a few tens of millivolts (Li et al., 1995; Revil et al., 1999; Del Rio and Whitaker, 2001). Thus, the magnitude values and polarity anomalies of the potential will be affected by seepage flow or streaming potential due to subsurface features. In this case, streaming potential anomalies stated that the seepage flow could be identified into two anomalies: positive polarity anomalies, which represented fluid discharge, whereas the negative polarity anomalies represented fluid charging.

Table 2.1: Self-potential sources and anomalies (Reynolds, 1997)

Source	Self-potential anomaly (mV)
Mineral potentials	
Sulfide or graphite ore bodies, magnetite, and other electronically conducting minerals, coals, and manganese	Negative: -100 to -1000
Quartz veins, pegmatites	Positive: 10 to 100
Background potentials	
Fluid streaming, geochemical reactions	Positive/negative: < 100
Bioelectric effects from plants, trees	Negative: < 300
Groundwater flow	Positive/negative: 100 to 1000
Topography	Negative: up to - 2000

Moreover, the negative polarity anomalies are represented as fluid recharging or infiltration zone (Hassim Al Jaubi et al., 2013). The geophysical method, such as the self-potential method, is very sensitive to the subsurface's physical changes, including the groundwater flow system (Revil et al., 2003). Hence, the self-potential method's negative polarity anomalies indicate the groundwater flow along the fractured zones (Gao et al., 2018).

On the other hand, the self-potential anomalies resulting from subsurface features such as geology, slope, and faults or fractures play significant attribution on the potential anomalies. Azunna et al., (2018) clarified using the self-potential method to study regional geology for mineral prospecting. They stated that in the study area in Ohiya in the South Eastern region of Nigeria, the self-potential anomaly is predominantly negative polarity anomalies due to minerals containing sulfides and graphite. Nordiana et al., (2018) conducted a self-potential method to determine the water flow in Selangor, Malaysia. The result shows the area indicated as a recharging or infiltration zone where groundwater flows into the soil due to negative polarity anomalies. The seepage area is enriched with sandy silt soil and peaty sand at the surface. Hence, the percentage of sandy silt in the soil increased towards the infiltration zone, which has a high magnitude value of negative polarity anomalies.

The self-potential magnitude value provides sufficient information on slope failure investigation. The high magnitude self-potential values concluded as high infiltration of rainwater into slopes. Santoso et al., (2019) conducted a self-potential method and electrical resistivity tomography method to identify infiltration zones. By the resistivity method, authors were able to detect slope planes based on rock resistivity. The study area at Pasanggrahan, South Sumedang, Indonesia, shows that self-potential with high magnitude indicated as the weak zone where water table zone with high rainfall seepage rate. Hence, the positive polarity anomalies can represent areas of a higher content of impermeable such as claystone. Once the layer is saturated, the water will rise to the surface and flow laterally down to the slope which has a high potential for landslide risk. The existence of subsurface features, faults, and fractures, contributed to the potential anomalies. Investigation of the study area in a weathered hard rock terrain for groundwater exploration requires evaluating subsurface geological features, including faults or fracture zones. The fracture zones within the subsurface develop hydrogeological identification by controlling fluid movement. Hasan et al., (2019) applied the self-potential and electrical resistivity methods to study the fractured rock aquifer in South China. They found that the self-potential measurements provide negative polarity anomalies indicating the groundwater flow channel along faults or fractures. Hence, negative polarity anomalies show an inhomogeneous rock formation and represent existing fracturing zones. This study concluded that the self-potential method is useful to detect saturated faults or fracture zones.

The self-potential method has widely been used for relics' findings in archaeological investigations. Understanding the background potential and segregating it from geological and lithological structures is crucial to identifying archaeological anomalies' true polarity. The limitation is that the unwanted polarity anomaly happened in many cases where the anomaly was wrongly interpreted as fluid flowing through the subsurface as archaeological anomalies. For instance, if the archaeological anomalies have negative polarity polarities and the surrounding area has high fluid flow activity, it eventually gives negative polarity polarities. Thus, identifying the fluid flows from recharging or infiltration zones will give a low possibility of getting negative polarity archaeological anomalies. Steps such as sufficient correlation, observation of the surroundings, correlation with the local outcrops around the area, and regional geological study might help the result interpretations. These steps will eventually add value to the self-potential results of archaeological investigations.

The streaming potential is the primary generator of potential anomalies in archaeological areas (Drahor et al., 1996). Variations in soil properties and clay content caused by digging and backfilling should give rise to differences in the magnitude of potential values measured by the self-potential survey (Wynn and Sherwood, 1984). Solid buried material in the ground subsurface relatively non-porous body should interrupt the fluid flow and develop a rise positive polarity anomaly above it. A loose solid material with cracks and more significant movement fluid gives rise to a negative polarity anomaly on the ground. These occurred, provided the streaming potential is going in the overlying soil. The contribution of electrochemical potential plays a significant part in archaeological prospection. An extreme change in the soil's chemical properties on the ground could raise self-potential anomalies. For instance, the over-burnt structures observed by in-situ burial structures constructed due to the high burnt clay brick and burnt soils produce significant changes in chemical properties. Thus, these archaeological features might have been exposed to extremely high temperatures. Drahor et al., (1996) mentioned the self-potential anomalies could be detected by burnt walls, burnt pits, furnaces, and in areas where chemical changes are significant. Besides, the physical properties and chemical properties of these materials vary due to the burning process. The self-potential anomalies with positive polarity would generally be obtained over burnt walls and zones within the soil, which only can be verified by excavations revealing the archaeological relics.

2.3 Self-potential principle

The self-potential method is susceptible to natural and human-made electrical interferences. Self-potential is generated by measuring naturally occurring electric potential between two electrodes placed on the earth's subsurface, and the potential is measured (Figure 2.1). The used of $CuSO_4$ for its ability to maintain electrode performance, provide stable reference potentials and enhance the electrical conductivity between the electrode and the ground. The earliest investigation indicated that the ore body must lie partially in a reduction and oxidation zone for self-potential anomalies to develop. Preliminary work in this field was conducted by Sato and Mooney, 1960 which required the ore body to partially submerge at the water table. Underneath the water table, the fluid in the capillary undergoes oxidation, releases an electron, and is transported upwards through the ore body. Whereas at the top of the ore body, transported or released electrons cause the fluids' reduction process. A complete circuit exists in which the current flows electronically in the surrounding porous media and the ore body, creating a negative terminal at the top of the ore body. It has now been suggested that the negative polarity anomalies are observed at the ore body, and there is no chemical reaction process that occurred within the causative body. By having a self-potential principle, the ground subsurface's magnitude values are caused by the electrochemical mechanism. The groundwater movement acts as a fluid or solvent, which is a common factor in generating self-potentials. Generally, the electrons are drawn traveling through rock materials by electrolytic, dielectrics, and electronics. Thus, the electrical conductivity (σ) of porous rock depends on the material's porosity (Thanh et al., 2019).

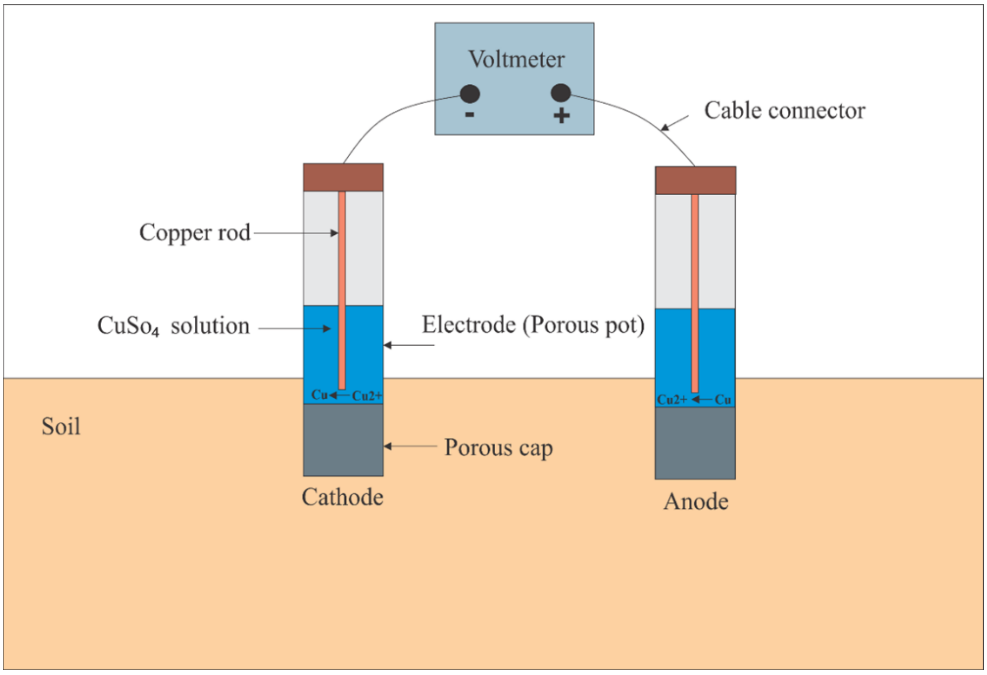

Figure 2.1: The primary illustrator for self-potential equipment on site (modified from Revil and Jardani, 2013).

In self-potential, the electrical double layer (EDL) is crucial in elaborating the self-potential mechanism. When surface particles or minerals are contacted with fluid or water, they become charged due to the chemical reactions between water and mineral particles. Hence, this mineral particle surface can act as either base or acid by gaining or releasing protons. This principle may produce the particle as negatively charged or positively charged. The diffuse region is generated in the vicinity of the surface with a high concentration of positive and negative ions. The electrochemical principle around the mineral particle surface is defined as EDL (Revil and Jardani, 2013).

Zeta potential (ξ) is a surface electrical charge principle when the mineral surface is contacted with water. This zeta potential is mostly dependent on the pH surface charge condition. Kim et al., (2005) stated that the particle surface charge at a pH of 5-9 is negative. Four mechanisms that can generate surface charge are absorption of the ion's particle surface, dissociation or ionization at the surface, lattice imperfection at the solid surface, and isomorphic replacement within the lattice (Kim and Lawler, 2005). A brief illustrator of silica minerals in contact with water is shown in Figure 2.2. The zeta potential is very sensitive to electrolyte resistivity, the valence of the ions, and the grain size of the sample (Lorne et al., 1999).

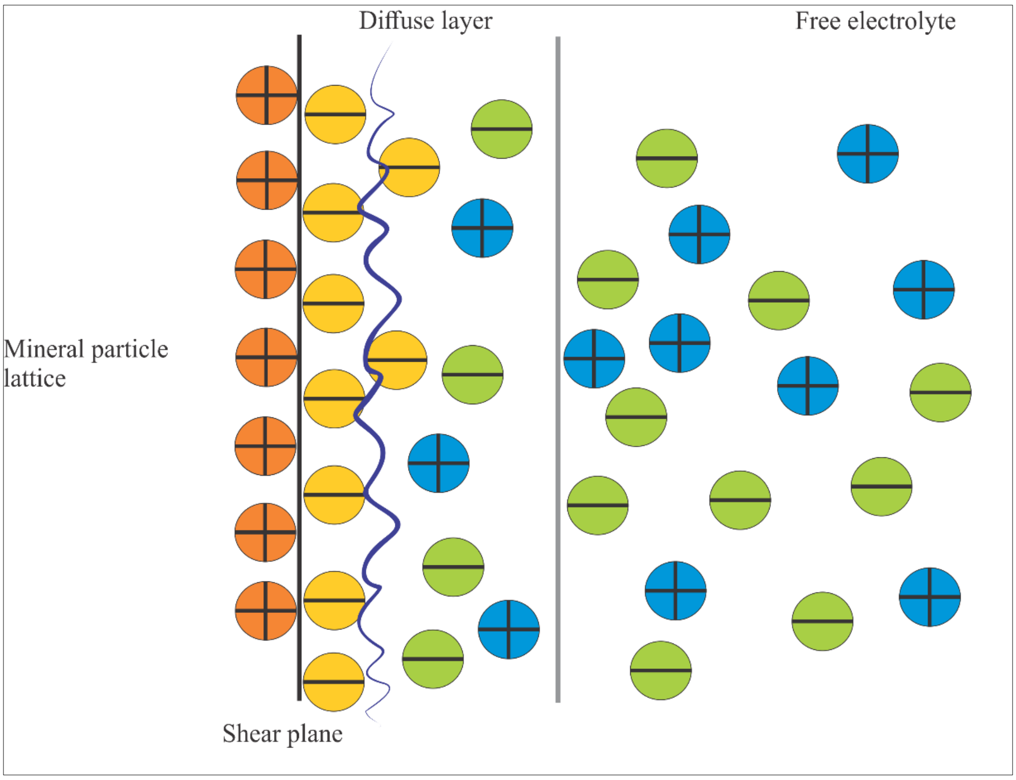

Figure 2.2: Illustrator of the silica surface with pH 5-9. The electrical double layer (EDL) is the electrical diffuse region (Kim and Lawler, 2005).

Regarding this zeta potential, Leroy and Revil (2004) studied the surface conductivity and zeta potential in clay water interface for a range of clay types and thermodynamic conditions using the electrochemical model. Wang and Revil (2010) mentioned in their work the electrochemical charge and zeta potential for silica sand in contact with high-ionic-strength solutions (1 mM to 1 M) and the effect of EDL through narrow porous media. EDL has been studied by Lorne et al., (1999) and Leroy and Revil (2004). Both Leroy and Revil (2004) successfully developed an electrical triple-layer model to predict the electrochemical properties of clay and water boundary. Revil and Jardani (2013) confidently claimed that surface conductivity is due to excess electrical conductivity in water and mineral particle boundary. The pore water in contact with a mineral particle is never uncharged, and the polarization of porous media is due to the electrical double layer.

An electrical potential is a valuable source to be measured in the self-potential method. Hence, sources can be resulting in the potential difference, and self-potential measurements are sensitive to external electrical noise such as telluric currents. These telluric currents are generated from current flow through power lines, electrical storms, and the ionosphere (Revil and Jardani, 2013). It is recommended to avoid data acquisition near a human-made electrical source during solar storms or even thunderstorms to overcome unwanted signals or drift. Another possible effect potential difference is from temperature difference during data acquisition using electrodes, which can generate drift. These potential differences are an effect of the equipment itself and not of the subsurface mechanism. Hence, the raw data with noise would provide an inaccurate interpretation. The common non-polarizing electrodes used for self-potential acquisition are Ag/AgCl or $Cu/CuSO_{4,}$ or $Pb/PbCl_2$, known as the Petiau-type electrode. It has been stated that the Petiau-type electrode is the most temperature stable with 0.2 mV/ °K dependence (Petiau, 2000). While it is advisable to use this particular type of electrode, it may not be feasible for all practitioners to do so. This limitation that most practitioners faced. Hence, the alternative way in a self-potential acquisition where temperature drift can be minimized through proper site data acquisition, such as controlling the electrodes' temperature exposure to heat sources from body heat (hands). It is advisable not to directly contact the electrode's bottom while handling the electrodes; body heat from hands could transfer the heat to the electrodes. To reduce the risk of sun exposure, it is advisable to place the electrodes in a shaded area during the process of data acquisition.

Another crucial part is the fitness of the electrodes. In the self-potential method, each electrode consists of a metal rod submerged in its salt's saturated solution. For example, the typical arrangement used a copper rod immersed in a copper sulfate solution. The copper rod and copper sulfate solution contained in the ceramic pot is working as complete self-potential electrodes. The pot has a porous wall at the bottom, which allows the electrolyte to leak slowly, creating electrical contact with the ground. The rate of electrolyte flows or porous pot to steady and stable is vital to avoid external polarization detected as a noise in the self-potential data. Hence, the electrodes are claimed to be planted on the ground, typically for several minutes for the electrodes to stabilize (Wynn and Sherwood, 1984). Theory related to the self-potential electrodes stated that if stainless steel or copper stakes are used as a complete electrode, the polarization effect may be introduced into the data. This effect is manifested as a low-level, slowly varying, extraneous voltage that can produce noisy data. Hence, it can take 10 to 20 minutes for the electrode to equilibrate and balance under certain conditions (Butler, 2005).

2.3.1 Redox potential

Redox potential or electrochemical potential occurred due to redox gradients. The redox potential is a measurement of a chemical or biological species' proneness to either lose or acquire electrons through the oxidation and reduction process. This potential only can be generated with a redox gradient and conductive connection present in a medium (Hubbard et al., 2011). Thus, for a vast scale of redox potential, a capable electronic conductor is recommended. A metallic body, biofilm, or iron precipitates have been suggested (Revil and Jardani, 2009). Electrochemical potential commonly related to the reduction and oxidation process could be used in mineral ore body exploration. Most practitioners' work was done based on the model that Sata and Mooney (1960) developed, which described the ore body and its surrounding medium as an electrochemical cell. Generally, stable negative polarity anomalies can occur over conductive deposits such as pyrite, chalcopyrite, pyrrhotite, magnetite, and graphite

(Sharma, 1997). The simplified description of Sato and Mooney (1960) work is the 'geobattery' model, which has been well accepted where the model is correlating all measured self-potential anomalies associated with the existence of the ore bodies performed. Hence, the ore body acts as an electronic conductor (Figure 2.3). The upper part of the ore acts as a cathode where the reduction process occurs, whereas the lower part acts as an anode where the oxidation process occurred. The key for electrochemical to happen is the water table exists and acts as a boundary in the mineral ore body.

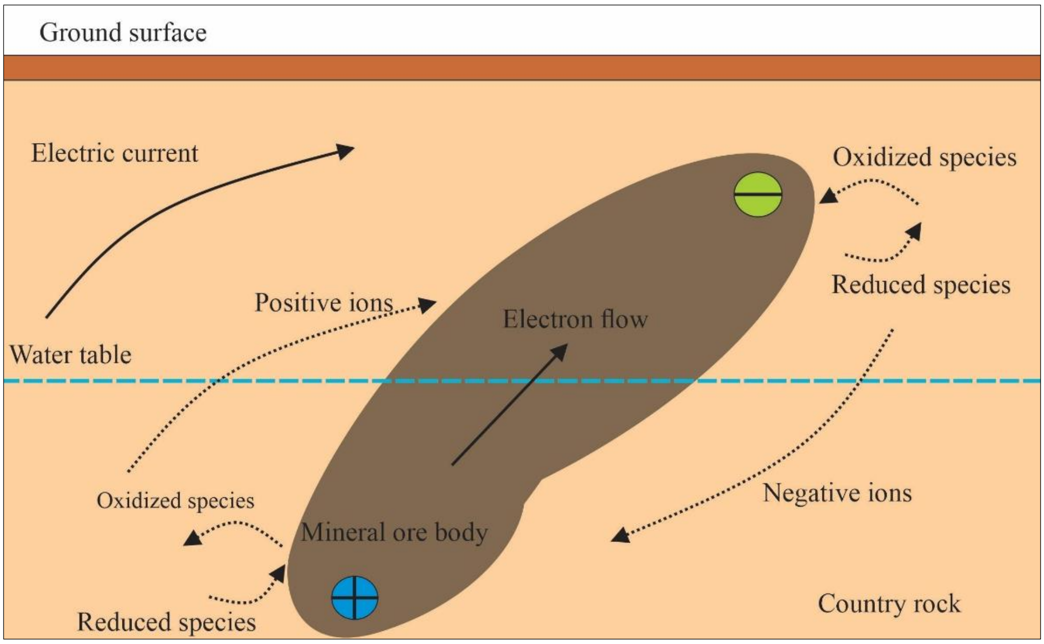

Figure 2.3: Illustrator of self-potential an ore body (modified after Sato and Mooney, 1960)

2.3.2 Nerst potential

Nerst potential occurs due to the differences in potential between the two potential electrodes planted into a medium that contains a different concentration of a solution. In a simple case, when two identical electrodes are immersed in a homogenous solution, it will be no potential difference to develop between both electrodes. Still, if there are different concentration solutions, then a potential difference will exist.

Equation 2.1 explained the calculation of Nerst potential due to different concentrations of a solution (Nyquist and Corry, 2002).

$$E_n = RT/nF \ In(C1/C2) \tag{2.1}$$

Where :

C1/C2 = Reaction quotient
n = Number of electrons exchanged
RT/F = Constant temperature value

2.3.3 Streaming potential

Streaming potential or electrokinetic potential, E_k is defined as voltage differences resulting from the flow of the water. This potential is generated by the small electrical currents produced by the movement of electrons transported by water through capillary or porous materials. The small electrical current does not mean the movement of water flow, which generated the current instead. The currents are generated by the excess charge in the mobile layer of the electrical double layer (EDL) of the mineral surface. Understanding the EDL would give better insight into zeta potential. The EDL occurred on a particle when the surface was contacted with the fluid resulting in the surfaces becoming charged. Hence, the charge's polarity depends on the mineral chemistry and pH of the medium fluid. Commonly, under a typical field (i.e., pH 5-9), the surface charge of silica grain is negative (Revil and Jardani, 2013). The minerals' negative surface charge attracts positive ions, resulting in an EDL becoming enriched in positive ions relative to the medium fluid. Moreover, other factors that affect this electric current flow are the hydraulic gradient, electrical properties of the electrolyte, and soil pores. The streaming potentials mechanism is considered fluid flow parallel to the geologic boundary and the water table. The result of the electrokinetics will differ when the properties change, as shown in Figure 2.2. Deformation of groundwater flow by preferential channel increased fluid flow velocity and magnitude of streaming potential caused by the seepage. These self-potential anomalies can be from tens to hundreds of millivolts depending on the pressure drop, geology, lithology, and chemical composition of the fluid. Vichabian and Morgan (2002) claimed that the electrokinetic potential is directly proportional to the potential difference between the immobile part of the electrochemical and free solutions.

2.3.4 Diffusion potential

Diffusion potential is defined as the voltage difference generated by chemical concentration gradients (Nyquist and Corry, 2002). Differing ion concentrations cause diffusion potential within the groundwater solution as their mobility medium. The diffusion potential value can rise by approximately 10 mV from the difference depending on the groundwater's electrolyte concentration. The mechanism needs to be maintained its imbalance in the electrolyte concentration before the diffusion of ions will eliminate the existing potential gradient. Equation 2.2 calculated the chemical concentration, which provides the diffusion potential (Nyquist and Corry, 2002).

$$Ek = - R_gT(I_a - I_c)/nF_c(I_a + I_c)\ \mathrm{In}(C_1/C_2) \qquad (2.2)$$

Where :

I_a, I_c = Mobilities of the positive ion (cations) and negative ions (anions)
R_g = Universal gas constant (8.314 $JK^{-1}\ mol^{-1}$)
T = Absolute temperature (K)
N = Ionic valence
F_c = Faraday’s constant (96487 $C\ mol^{-1}$)
C_1, C_2 = Solution concentrations

2.3.5 Thermoelectric potential

The thermoelectric potential is defined as a potential difference generated by the temperature gradient (Corwin and Hoover, 1979; Revil et al., 1999b). Thomas Seebeck well explained the work regarding temperature difference to electricity in 1821 (Seebeck effect). Jean Peltier pioneered a preliminary study on temperature gradient at