THE INFLUENCE OF CATION EXCHANGE CAPACITY TOWARDS ELECTRICAL RESISTIVITY VALUE FOR FINE GRAINED SOIL

MOHAMMAD IZZAT SHAFFIQ BIN AZMI

A project report submitted in fulfillment of the award of Master's Degree in Civil Engineering

Faculty of Civil Engineering and Built Environment
University Tun Hussein Onn Malaysia

December 2021

This study is wholeheartedly dedicated to my beloved parents who have been my source of inspiration and gave me strength when I thought of giving up, who continuously provided their moral, emotional, and financial support.

And lastly, I dedicated this thesis to Allah S.W.T, thank you for the guidance, strength, power of mind, protection, and giving me a healthy life.

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude to my supervisor Associate Prof Dr. Aziman Bin Madun for the continous support on my Masters Degree study and research, for his patience, motivation, enthusiasm, and immense knowledge. His guidance helped me in all the time in reasearch and writing of this thesis.

I would also like to thank my co-supervisor of my thesis Dr Mohd Khaidir Bin Abu Talib for the encouragement, insighful comment and hard question.

A heartful thank you to the technicians of Geotechnic Laboratory and Geology Laboratory, Faculty of Civil Engineering and Built Environment, Puan Siti Fadzilah Binti Kasno and Puan Nurul Farhani Binti Md Johani, who had helped in preparing the equipment and materials for this study.

Lastly, a hearfelt appreciation is also addressed to all who were directly or indirectly involved in helping the research and writing this thesis.

ABSTRACT

An electrical resistivity method (ERM) is a non-destructive test in subsurface exploration that would able to safe cost of project. However, an improvement is needed as there are some difficulties in the interpretation of earth material using resistivity chart due to overlapping values and not many researches were conducted to revise the earth minerals resistivity value based on the variable in Archies' Law. The objectives were to characterize physical properties and mineral compounds, identify the relationship of ERV with water content and CEC, and identify the effect of fine-grained artificial minerals' mixed proportion towards ERV and CEC value. The fine-grain artificial mineral used were kaolinite, montmorillonite, illite, quartz, mica, and feldspar, passing 0.063 mm sieve, tested its basic soil index properties via British Standard 1377 and tested mineral compound with X-Ray Diffraction (XRD). The samples were prepared in four (4) type of mixtures: individual minerals, major mineral, minor mineral, and major and minor mineral. The resistivity value of montmorillonite at degree of water saturation 10% and 100% were 347 Ωm and 5 Ωm respectively. The mineral's effects towards the ERV were clearly observed such as between kaolinite and montmorillonite at 10% water saturation were 5990 Ωm and 347 Ωm respectively. The study showed that minerals contained their own CEC. Hence, the CEC influenced the ERV of the fine-grain artificial mineral mixture. Hence the CEC value of kaolinite and montmorillonite were at 1 meq/100g and 70 meq/100g respectively. The CEC of a mineral mixture increased when a high percentage of minerals with high CEC were added and vice versa, for example the mixture of montmorillonite and illite were 29.82 meq/100g and the mixture of kaoline and quartz were 4.34 meq/100g. The correlation that was made showed that minerals contained their own CEC. Hence, the CEC influenced the ERV of the fine-grain artificial mineral mixture.

ABSTRAK

Kaedah kerintangan elektrik (ERM) ialah ujian tidak memusnahkan dalam penerokaan permukaan bawah tanah yang boleh menjimatkan kos projek. Walau bagaimanapun, penambahbaikan perlu dilakukan memandangkan terdapat sedikit kesukaran dalam tafsiran bahan bumi menggunakan carta kerintangan disebabkan nilai yang bertindih dan tidak banyak kajian yang dijalankan untuk menyemak semula nilai kerintangan mineral bumi berdasarkan Archies' Law Objektifnya adalah untuk mencirikan. sifat fizikal dan sebatian mineral, mengenal pasti hubungan ERV dengan kandungan air dan CEC, dan mengenal pasti kesan perkadaran campuran mineral buatan berbutir halus terhadap nilai ERV dan CEC. Mineral buatan bijirin halus yang digunakan ialah kaolinit, montmorilonit, illite, kuarza, mika, dan feldspar, melepasi ayak 0.063 mm, menguji sifat indeks tanah asasnya melalui British Standard 1377 dan diuji sebatian mineral dengan X-Ray Diffraction (XRD). Sampel telah disediakan dalam empat (4) jenis campuran: mineral individu, mineral utama, mineral kecil, dan mineral utama dan kecil. Nilai kerintangan montmorilonit pada tahap ketepuan air 10% dan 100% masing-masing ialah 347 Ωm dan 5 Ωm. Kesan mineral terhadap ERV diperhatikan dengan jelas seperti antara kaolinit dan montmorilonit pada ketepuan air 10% masing-masing ialah 5990 Ωm dan 347 Ωm. Kajian menunjukkan bahawa mineral mengandungi CEC mereka sendiri. Oleh itu, CEC mempengaruhi ERV bagi campuran mineral tiruan bijirin halus. Oleh itu nilai CEC kaolinit dan montmorilonit masing-masing pada 1 meq/100g dan 70 meq/100g. CEC campuran mineral meningkat apabila peratusan mineral yang tinggi dengan CEC tinggi ditambah dan begitu juga sebaliknya, contohnya campuran montmorilonit dan illite ialah 29.82 meq/100g dan campuran kaolin dan kuarza ialah 4.34 meq/100g. Korelasi yang dibuat menunjukkan bahawa mineral mengandungi CEC mereka sendiri. Oleh itu, CEC mempengaruhi ERV bagi campuran mineral tiruan bijirin halus..

TABLE OF CONTENT

LIST OF TABLE

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

Ω	-	ohm
Ωm	-	ohm.m
φ	-	Porosity
ρo	-	Sample resistivity
ρw	-	water resistivity
β	-	counter-ion conductance which is a CEC dependent parameter (temperature)
m	-	cementation exponent
n	-	saturation exponent
v	-	volume
Q_v	-	counter -ion conductance which is a CEC dependent parameter
S_w	-	water saturation
PSD	-	Particle size distribution
LL	-	Liquid Limit
PL	-	Plastic Limit
PI	-	Plastic Index
WC	-	Water Content
CEC	-	Cation exchange capcity
XRD	-	X-Ray Diffraction
ERT	-	Electrical Resistivity Tomography
ERM	-	Electrical Resistivity Method
ERV	-	Electrical Resistivity Value
°C	-	Degree Celcius

CHAPTER 1

INTRODUCTION

1.1 Project background

Electrical Resistivity Tomography (ERT) is a method used for subsurface profiling in soil. The subsurface profile characterization determines the layer, thickness, soil lithology, presence of groundwater, fracture zones, variations in soil saturation, areas of increased salinity, or groundwater contamination. The obtained geotechnical data is an important parameter used in design and construction, monitoring, and maintenance during pre and post-construction or forensic investigation. Previously, conventional geotechnical site investigation methods were used, such as boring, drilling, probing, and in situ testing. However, the effectiveness of the conventional method, on the other hand, was determined by several parameters, including site topography and accessibility, the total area of sites covered, time consumption, and cost.

ERT is a non-destructive method where the current is being injected into the ground. The value of the sub-surface resistivity is determined by adopting the geophysical electrical technique survey such as electrical resistivity method (ERM). The principle of electrical resistivity technique is about how the current is opposed to flow between electrodes. However, the interpretation tasks in deciding the layer of soil is unable to directly refer to the earth material-resistivity chart due to the overlapping values. Thus, it is essential to understand the influence of the mineralogy towards the resistivity values.

Due to the saturated condition, it is challenging to differentiate between silt and clay body in the Quaternary geological formation. The saturated ground resulting the resistivity value is lowered for all materials including silt and clay. Therefore, the resistivity parameter could be utilized to recognize the change of soil parameters such as the soil moisture, porosity, and mineralogy. Multiple site investigation studies have been conducted in relation to the resistivity value of the subsurface. However, for this particular study, the testing was performed in a lab scale environment where the important factor affecting the resistivity values was mineralogy. There were multiple factors which could influence the analysis results of ERM, especially the particle size distribution, porosity, mineralogy, density, Cation Exchange Capacity (CEC), and water content. These parameters were controlled and tested to define the major factors which might affect the resistivity value. It was hoped that this study could improve the understanding of resistivity value and improve the earth material-resistivity chart.

1.2 Problem statement

Electrical Resistivity Tomography (ERT) is a reliable method for subsurface exploration in determining the properties and profile of ground in non-destructive way. A non-destructive test in subsurface exploration would able to safe project cost and to avoid excavating or drilling hole which would disturb the condition of the subsurface. Usually, soil properties are determined based on the geotechnical method in a laboratory testing. However, an improvement is needed in assisting an engineer in terms of parameter in design. Other use of ERT is to identify the aquifer layer and types of earth materials. The interpretation of earth material was unable to directly refer to the resistivity chart due to the overlapping values. Resistivity values are overlapping due to several factor as stated in Archies' Law. Thus, it is important to understand the influence of the parameters in Archies' Law especially for fine grained soil such as the Cation Exchange Capacity (CEC) and porosity.

Not many researches were conducted to revise the earth minerals resistivity value based on the variable of water resistivity, porosity, degree of saturation, mineralogy and cation exchange capacity. By referencing the Archie's Law and the usage of fine-grained soil, this research was formulated to understand the issue of the electrical resistivity overlapping value. However, the study focused on the type of minerals and cation exchange capacity (CEC) as a variable parameter in order to understand the fine-grained earth material. This study in conducted in laboratory in a control environment and parameters, thus able to help in understanding the variable that influencing the electrical resistivity values and ease the interpretation concerning the fine-grained earth materials.

1.3 Aim and Objectives

This study aimed to evaluate the effects of cation exchange capacity (CEC) towards the electrical resistivity values (ERV). To achieve the aim of this study, the following objectives were established:

I. To characterize physical properties and mineral compounds of artificial fine-grain.
II. To identify the relationship of fine-grain artificial minerals' ERV with water content and CEC.
III. To establish correlation of the fine-grain artificial minerals' mixed proportion towards ERV and CEC value.

1.4 Scope of Project

In order to achieve the objectives, set, a few scopes of research were devised. Firstly, the research was focused only on fine-grained artificial soil. These fine-grained artificial soils were bought from a supplier which comprised kaolinite, illite, montmorillonite, quartz, mica, and feldspar. The soil test was focused on determining the basic physical properties of soil (grain size, water content, density, void ratio, and porosity) using hydrometer test, Atterberg limit test, specific gravity test, and density test according to BS 1377 (1990).

Secondly, in determining the microstructures and mineral compound of the samples, the X-Ray Diffraction (XRD) was used. Furthermore, the experiment on the effect of resistivity of minerals and their mixtures used a four-terminal resistance meter (soil box) and ABEM LS2 terrameter to obtain the value for resistivity. Cation Exchange Capacity (CEC) was determined by using ammonium acetate solution and

Atomic Absorption Spectrophotometer (AAS). The minerals had a mixed proportion in various ratios to simulate the probability of minerals mixture in a soil towards the resistivity value. Water content was mixed with the minerals, as mentioned earlier until it reached the liquid limit. Electrical Resistivity data analysis was performed using Microsoft EXCEL. The result may vary and were combined to understand the effect of water content and Cation Exchange Capacity (CEC) further towards the resistivity of minerals.

1.5 Significance of Study

The study was essential to improve the understanding of the effect of minerals in silt and clay size distribution for water content and CEC towards electrical resistivity value. The charts plotted based on this research could assist in understanding the effect on fined-grained artificial mineral in a soil sub-surface by using electrical methods. The contribution were as follows;

- This research filled the knowledge gap and added value to the resistivity of mineralogy.
- The availability of the improved electrical resistivity value data contributed a meaningful parameter input for engineering and environment purposes.
- Enhanced the quality of national study in the subsurface area, especially in the field of electrical resistivity.

1.6 Summary

Chapter 1 describes the background study of the related research involving ERT, which has been a common use for subsurface profiling. ERT is a non-destructive method where current is injected into the ground. The value of the sub-surface resistivity is determined by adopting the geophysical electrical technique survey such as resistivity method. The problem that contributed to this study was the difficulty in determining the precise identification or classification of soil beneath the surface. Any mistakes made during subsurface exploration would cost money, time, and effort. Therefore, in order to achieve the aim of this study, the geotechnical properties of artificial silt and clay mineral using geotechnical test were characterized. Hence, the electrical resistivity value of the fine-grained artificial soil due to the existence of water content was established. The effect of fine-grained artificial soil of mixed proportion towards the electrical resistivity value was identified. This showed that the fine-grained artificial, soil water content and cation exchange capacity with the electrical resistivity value was correlated. The scope that was devised for this study involved the use of fine-grain artificial soil. According to BS 1377 (1990), basic physical properties of soil were used. The types of equipment used such as XRD, ABEM LS2 terrameter and AAS were to determine the mineral compound, resistivity value, and CEC value of the mineral, respectively.

Chapter 2 discusses the pervious study literature related to the current study. Firstly, geophysics is a subsurface site characterization of the geology, geological structure, groundwater, and contamination beneath the Earth's surface. There are various types of geophysical methods but the main focus of this study is the electrical resistivity method. The electrical resistivity method has followed the fundamental physical law of Ohm's Law and determined the value of resistivity in Ohm meter (Ωm). Furthermore, to calculate the resistance of the soil, Archie's Law formula is use which relates, for a clay-free sediment, the electrical resistivity (ρ) of a porous rock containing water and cement towards the fraction of the pore space that is filled with water. However, as the sample used in this study is in a form of silt and clay distribution, a revise version of Archie's Law is used which is Waxman and Smits model that includes cation exchange into the formula. Electrical resistivity values are fairly dependent on the constituent mineralogy of the clay material at the moist side. It is essential to understand the possible range of resistivity values and trends of variations of a specific clay mineral under different saturations and physio-chemical properties (such as cation exchange capacity). Lastly, previous study conducted on distribution of minerals in a soil sample was where the mineral mixture design was based. The minerals are characterized into two categories which is the major mineral (dominant mineral found in the soil) and minor mineral (non-dominant mineral found in soil). The study on soil based on geotechnical, geophysical and integrated method is still able to be enhanced due to the uncertenties nature of the soil. A detailed study on minerals in soil could well be established including the quatitative study with degree of saturation and ion excahnge using an integration of electrical resistivity value (ERV) with water content and cation exchange capacity (CEC).

Chapter 3 elaborate the methodology to achieve the research objectives based on the flowchart of the overall methodology used, type of minerals, experimental involved related to the mineral mixture, characterization of index properties, cation exchange capacity, and electrical resistivity test. A detailed explanation of the experiment procedure was discussed including the determination of mineral compound, physical properties testing, the electrical resistivity test, and cation exchange capacity test of the minerals and the mixtures. Then, the analyses involving electrical resistivity, cation exchange capacity, and geotechnical data (water content, saturation, and porosity) were explained based on the formulae. Finally, electrical resistivity value (ERV) for water content (WC) and cation exchange capacity (CEC) were analyzed and correlated between the mineral mixtures.

Chapter 4 began by the determination of the particle size distribution of the mineral clay where the particle size was sieved, passing 0.065 mm. The particle size of the mineral was in the silt and clay category. Figure 4.1 shows the mineral particle distribution of the sample. The mineral clay had to undergo XRD testing to confirm the mineral used was the dominant mineral element used in the samples which was exclaimed and to ensure that the mineral was not an amorphous sample. In Figure 4.2 to Figure 4.7, the peak of the graphs generated showed the dominant mineral element from Kaolinite, illite, montmorillonite, mica, feldspar, and quartz sample, respectively. Atterberg limits were known as water content limits involving plastic index (PI), plastic limit (PL), and liquid limit (LL). The PI was the water content range for the soils of a plastic nature, while PL was known as the minimum water content for soils that was kneaded to a diameter of 3 mm without undergoing dissolution. Furthermore, LL was the minimum water content for a soil that can flow with its own weight. Table 4.2 to Table 4.5 show the LL, PL, and PI results obtained for individual and mixed minerals. From the table shown, it was clear that montmorillonite had the highest LL followed by kaolin, mica, illite, quartz, and feldspar. Therefore, in a mineral mix proportion, the increase of the percentage of minerals with a high LL value would increase the LL value of the mixed mineral. Furthermore, the result of PL obtained from this study showed that quartz was non-plastic and the increase of montmorillonite in the clay mixture affected the increase in the PI value. Specific gravity values were obtained through the pycnometer test. The specific gravity value for individual mineral, major mineral, minor mineral, and the mixture of major and minor minerals are shown in Table 4.6 to Table 4.9. The specific gravity value ranges from 1.97 to 2.66. The presence of montmorillonite in a clay mineral mixture decreased the specific gravity value of the sample. This showed that the specific gravity of a clay mineral was affected by the amount of minerals elements contained in the soil sample. Figure 4.8 to Figure 4.11 show the porosity graph of the sample from unsaturated condition to fully saturated condition for individual mineral, major mineral mixture, minor mineral mixture, and both major and minor mineral mixture, respectively. The porosity values obtained for all the minerals (either individual or mixture) were from 0.5 to 0.6. There was a correlation between the values and water content for the ERV. Therefore, with the increasing water content, the resistivity and chargeability value decreased and became plateau until it reached the LL. The type of mineral and the ratio of mineral mixure also contribute to the ERV, as highlighted in Figure 4.12 to Figure 4.27. The CEC was a part of the chemical properties of clay minerals. The exchangeable cation calcium (Ca2+), magnesium (Mg2+), and potassium (K+) were extracted by electrostatic force using ammonium acetate solution and AAS. Using the formula 3.6, the value of CEC was determined with the unit (meq/100g). Table 4.10 to Table 4.13 show the individual and mix mineral sample results obtained. The result obtained from this CEC testing showed that a high percentage of mineral content with a high CEC value mixed in a mineral mixture such as montmorillonite and illite, would increase the CEC value of the mixture. Lastly, based on the data achieved from this study, a correlation was made by referring to the Archies' law in Eq 2.3. However, Archies' law was applicable only to clean or clay mineral-free sand or rocks. Hence, Waxman and Smits model was used as in Eq 2.4, where the equation was the extension of the Archies' equation, taking into account the different resistivity caused by clay minerals such as the CEC. Figure 4.28 to Figure 4.35 and Table 4.14 to Table 4.17 show the analytical results of the relationship between the resistivity value and the CEC value. With the increasing percentage amount of mineral with high CEC value, the lower the resistivity value of the mineral mixture was.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The relevant pieces of literature related to this study were discussed in this chapter. It began with an explanation of geophysics, followed by the explanation of electrical resistivity theory of soil, electrical resistivity method and the cation exchange capacity. Lastly, this chapter summarized all literature-related studies, thus, contributing to research gaps and novelty of the study.

2.2 Geophysics

Geophysics is a subsurface site characterization of geology, geological structure, groundwater, and contamination beneath the Earth's surface. It also involves a non-invasive investigation of subsurface conditions in earth by measuring the analysis and interpreting physical fields at the subsurface.

Over the years, with the introduction of several methods and techniques, geophysics technology has been rapidly improved. Table 2.1 shows the classification of Geophysical Technique by Herckenrath and Government 2016. In geological and geotechnical investigation settings, a large area is usually investigated. Therefore, the geophysical method will provide valuable tools in helping the survey of earth without expanding many resources. However, in this study, the electrical resistivity method (ERM) was used to determine the resistivity of the fine-grained artificial minerals.

Table 2.1: Classification of Geophysical Technique (Herckenrath & Government, 2016)

Method	**Measure parameter**	**Operative physical property**
Seismic	Travel time of reflected/refracted seismic waves	Density and elastic moduli which determine the propagation velocity and seismic wave
Gravity	Spatial variation in the strength of the gravitational field of the earth	Density
Magnetic	Spatial variation in the strength of the geomagnetic field	Magnetic susceptibility and remanence
Electrical Resistivity	Earth resistance	Electrical conductivity
Induced polarization	Polarization voltage of frequency-dependent ground resistance	Electrical capacitance
Self-potential	Electrical potential	Electrical conductivity
Electromagnetic	Response to electromagnetic radiation	Electrical conductivity and inductance
Radar	Travel time of reflected radar pulse	Dielectric constant

2.3 Electrical Geophysical Technique

Electrical methods are probably the most widely used geophysical technique (Binley, 2015). This is because the subsurface electrical properties are often well correlated to the physical and chemical properties of fluid within the pore space such as saturation and salinity and the theoretical concepts are straightforward. Furthermore, Field measurement techniques are highly scalable, allowing an investigation towards the depths of tens to hundreds of meters, where the data analysis techniques have matured.

2.3.1 Electric Resistivity Method (ERM)

The electrical resistivity method (ERM) involves the measurement of the apparent resistivity of soils and rock as a function to determine the depth or position. A conventional method such as drilling was used to obtain groundwater position and determine soil sampling. However, this method is weak as it is expensive, time-consuming, and has limited data coverage (Baharuddin *et al*., 2015). During resistivity surveys, a current is injected into the earth through a pair of electrodes. It utilizes direct current or low-frequency alternating currents to investigate the subsurface's electrical properties (resistivity). ERM follows the fundamental physical law of Ohm's Law and determines the value of resistivity in Ohm meter (Ωm) (Madun, et al./, 2019). Moreover, it provides a large-scale characterization of the physical properties under undisturbed conditions (Baharuddin *et al*., 2015). However, the lack of cooperation with an expert may cause unreliable results due to the weak interpretation and justification (Hazreek *et al*., 2015).

As per the understanding, electrical resistivity experiments have been performed to establish a relationship between the electrical resistivity and soil characteristics. In short, the voltage will act as a pressure to push the electricity towards any materials. The current is the number of electrons flowing through a circuit whilst the resistance is a measure of how the material reduces the electric current flow through it. There are usually two types of experiments where this experiment will be conducted (either in the lab or on site). Figure 2.1 shows the concept of ERM done on-site and Figure 2.2 shows the concept of ERM done in the Lab. In the lab, an analog resistivity meter is used where a specific type or combination of soil and mineral can be used to investigate the probability of electrical resistivity on the combination of soil ratio. Water is added to the soil sample to encourage low electrical voltage to flow in between the soil sample to get an abundant result.

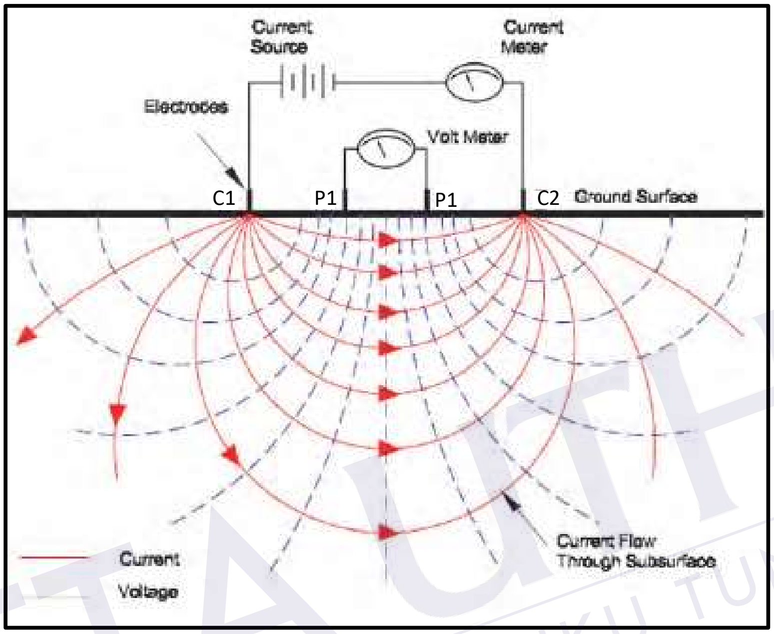

Figure 2.1: Basic Concept of Electrical Resistivity Subsurface Measurement (adopted from Sharma, 1992)

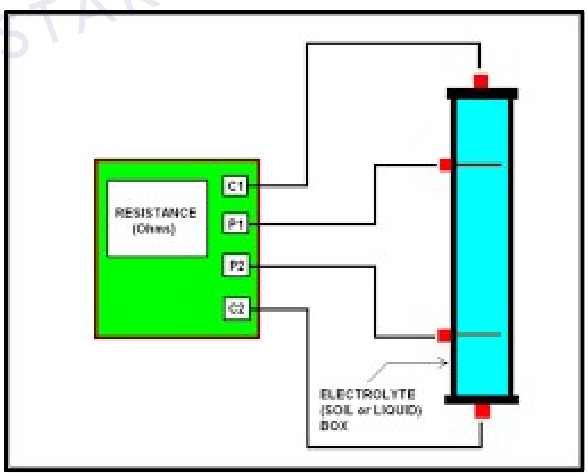

Figure 2.2: Concept of Electrical Resistivity Measurement Done in Lab

REFERENCE

Aminaton, M.and Fauziah, K.. (2003). “Characterisation of Malaysia Residual Soils For Geotechnical and Construction Engineering”

Abdelaal, A. (2015). IWA Specialist Conference ‘ Water and Wastewater Treatment Plants in Towns and Communities of the XXI Century : Technologies , Design and Operation ,’ (June 2010).

Aja, A. A., & Randy, G. J. (2017). Physical Properties of Kaolin Used in Soap Production in Nigeria Physical Properties of Kaolin Used In Soap Production In Nigeria, (October 2013).

Aparicio, P. (2006). Mineralogical Interference on Kaolinite Crystallinity Index Measurements. *Clays and Clay Minerals*, *47*(1), 12–27. https://doi.org/10.1346/ccmn.1999.0470102

Arjwech, R., & Everett, M. E. (2015). Application of 2D electrical resistivity tomography to engineering projects : Three case studies, *37*(6), 675–681.

Baharuddin, M. F. T., Md Ali, N., Abidin, M. H. Z., Madun, A., Zawawi, M. H., & Ahmad Tajudin, S. A. (2015). Groundwater Seepage Mapping Using Electrical Resistivity Imaging. *Applied Mechanics and Materials*, *773–774*, 1524–1534. https://doi.org/10.4028/www.scientific.net/amm.773-774.1524

Bery, A. A., & Ismail, N. E. H. (2018). EMPIRICAL CORRELATION BETWEEN ELECTRICAL RESISTIVITY AND ENGINEERING PROPERTIES OF SOILS, *54*(6), 425–429. https://doi.org/10.1007/s11204-018-9491-7

Binley, A. (2015). *Tools and Techniques : Electrical Methods*. *Treatise on Geophysics*. Elsevier B.V. https://doi.org/10.1016/B978-0-444-53802-4.00192-5

Bunaciu, A. A., Udriştioiu, E., Aboul-enein, H. Y., Bunaciu, A. A., Udriştioiu, E., Aboul-enein, H. Y., … S, E. G. U. (2015). Critical Reviews in Analytical Chemistry X-Ray Diffraction : Instrumentation and Applications X-Ray Diffraction : Instrumentation and Applications, 8347.

https://doi.org/10.1080/10408347.2014.949616

Burns, S. E. (2015). Shear wave velocity of granular mixtures of silica particles as a function of finer fraction , size ratios and void ratios. *Granular Matter*. https://doi.org/10.1007/s10035-015-0580-2

Choo, H., Song, J., Lee, W., & Lee, C. (2016). Journal of Petroleum Science and Engineering E ff ects of clay fraction and pore water conductivity on electrical conductivity of sand-kaolinite mixed soils. *Journal of Petroleum Science and Engineering*, (August), 0–1. https://doi.org/10.1016/j.petrol.2016.10.009

Climate, B., & Development, G. M. (2013). The role of microorganisms at different stages of ecosystem development for soil formation, 3983–3996. https://doi.org/10.5194/bg-10-3983-2013

Connolly, J. R. 2007 Introduction to X-Ray Powder Diffraction; Spring,

Dohnalová, Ž., Svoboda, L., & Šulcová, P. (2008). Characterization of kaolin dispersion using acoustic and electroacoustic spectroscopy. *Journal of Mining and Metallurgy, Section B: Metallurgy*, *44*(1), 63–72. https://doi.org/10.2298/JMMB0801063D

Electrical Conductivities in Oil-Bearing Shaly Sands. (n.d.).

Fleming, R. J. (1989). An investigation of the effects of hydroxyl concentration and bubble formation on the electrical conductivity of synthetic quartz, *158*, 335–342.

Flóvenz, Ó. G., Hersir, G. P., Sæmundsson, K., Ármannsson, H., & Friðriksson, Þ. (2012). *Geothermal Energy Exploration Techniques*. *Comprehensive Renewable Energy* (Vol. 7). Elsevier Ltd. https://doi.org/10.1016/B978-0-08-087872-0.00705-8

Ganor, J., Roueff, E., Erel, Y., Blum, J.D., (2005). The dissolution kinetics of a granite and its minerals — implications for comparison between laboratory and field dissolution rates. Geochim. Cosmochim. Acta 69 (3), 607–621.

Giuseppe, M. G. Di, Troiano, A., Fedele, A., & Caputo, T. (2015). Electrical resistivity tomography imaging of the near-surface structure of the Solfatara crater , Campi Flegrei (Naples , Italy). https://doi.org/10.1007/s00445-015-0910-6

Gunn, D. A., Chambers, J. E., Uhlemann, S., Wilkinson, P. B., Meldrum, P. I., Dijkstra, T. A., … Glendinning, S. (2015). Moisture monitoring in clay embankments using electrical resistivity tomography. *Construction and Building Materials*, *92*, 82–94. https://doi.org/10.1016/j.conbuildmat.2014.06.007

Hazreek, Z. A. M., Rosli, S., Chitral, W. D., Fauziah, A., Azhar, A. T. S., Aziman, M., & Ismail, B. (2015). Soil identification using field electrical resistivity method. *Journal of Physics: Conference Series*, *622*(1). https://doi.org/10.1088/1742-6596/622/1/012030

Herckenrath, D., & Government, Q. (2016). Informing groundwater models with near-surface geophysical data Daan Herckenrath, (March 2012). https://doi.org/10.13140/2.1.3664.9289

Introduction, A. (n.d.). Montmorillonite : An Introduction to Properties and Utilization Utilization, 3–24. https://doi.org/10.5772/intechopen.77987

Kibria, G., & Hossain, S. (2017). Electrical resistivity of compacted clay minerals, (1996), 1–8.

K. Maher, (2010) The dependence of chemical weathering rates on fluid residence time. Earth Planet. Sci. Lett. 294, 101–110. doi:10.1016/j.epsl.2010.03.010

K. Maher, (2011) The role of fluid residence time and topographic scales in determining chemical fluxes from landscapes. Earth Planet. Sci. Lett. 312, 48–58. doi:10.1016/j.epsl.2011.09.040

Krzesi, M., Celzard, A., Grzyb, B., & Marˆ, J. F. (2006). Elastic properties and electrical conductivity of mica / expanded graphite nanocomposites, *97*, 173–181. https://doi.org/10.1016/j.matchemphys.2005.08.003

Lima, O. A. L. De, & Sharma, M. M. (1992). A generalized Maxwell-Wagner theory for membrane polarization in shaly sands, *57*(3), 431–440.

Madun, A., Abu Talib, M. K., Sahdan, M. Z., Md Dan, M. F., & Ahmad Tajudin, S. A. (2019). Electrical resistivity and induced polarization techniques for groundwater exploration. *International Journal of Integrated Engineering*, *10*(8), 56–60. https://doi.org/10.30880/ijie.2018.10.08.005

Maher, K. (2010). The dependence of chemical weathering rates on fl uid residence time. *Earth and Planetary Science Letters*, *294*(1–2), 101–110. https://doi.org/10.1016/j.epsl.2010.03.010

Maher, K. (2011). The role of fluid residence time and topographic scales in determining chemical fl uxes from landscapes. *Earth and Planetary Science*

Letters, *312*(1–2), 48–58. https://doi.org/10.1016/j.epsl.2011.09.040

Malmstrom, M.E., Destouni, G., Banwart, S.A., Stromberg, B.H.E., (2000). Resolving the scale-dependence of mineral weathering rates. Environ. Sci. Technol. 34 (7), 1375–1378.

Michot, D., Thomas, Z., Adam, I., Michot, D., Thomas, Z., & Adam, I. (2018). Nonstationarity of the electrical resistivity and soil moisture relationship in a heterogeneous soil system : a case study To cite this version : HAL Id : hal-01686648 Nonstationarity of the electrical resistivity and soil moisture relationship in a heterogeneous soil system : a case study. https://doi.org/10.5194/soil-2-241-2016

Nwosu, F. O., Ajala, O. J., Owoyemi, R. M., & Raheem, B. G. (2018). Preparation and characterization of adsorbents derived from bentonite and kaolin clays. *Applied Water Science*, (October). https://doi.org/10.1007/s13201-018-0827-2

Ore, M. (2015). Beneficiation of Mica-Containing Ore, 173–184. https://doi.org/10.1016/B978-0-444-53083-7.00038-5

Prasad, M. S., Reid, K. J., & Murray, H. H. (1991). Kaolin : processing , properties and applications, *6*, 87–119.

Revil, A., & Glover, P. W. J. (1998). Nature of Surface Electrical Conductivity in Natural sands, sandstones and clay. *GEOPHYSICAL RESEARCH LETTER*, *25*(5), 691–694.

Safety, R., Industrial, S., & Gmbh, M. (2014). COMPARISON OF THREE SMALL-SCALE DEVICES FOR THE INVESTIGATION OF THE ELECTRICAL CONDUCTIVITY / RESISTIVITY OF SWELLING AND OTHER, *62*(1), 1–12. https://doi.org/10.1346/CCMN.2014.0620101

Shetti, N. P., Nayak, D. S., Reddy, K. R., & Aminabhvi, T. M. (2019). *Graphene – Clay-Based Hybrid Nanostructures for Electrochemical Sensors and Biosensors*. *Graphene-Based Electrochemical Sensors for Biomolecules*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-815394-9.00010-8

Street, Y. (2014). Effects of Bentonite Content on Electrical Resistivity of Soils, 2404–2413.

Teorica, G., & Vol, A. (2005). Time-lapse geophysics for monitoring an infiltration test in the vadose zone, *46*(September), 201–216.

Ugbo, J. O., Kelly, B. F. J., & Ward, C. R. (2009). ESTIMATION OF AN

EQUIVALENT SHALINESS PARAMETER USING RESISTIVITY AND SPECTROSCOPY LOGS : A TOTAL EXPANSIBLE CLAY APPROACH, *32*(October), 383–406.

Weisenberger, T. B., Ingimarsson, H., Gylfi, P., & Fl, Ó. G. (2020). Cation-Exchange Capacity Distribution within Hydrothermal Systems and Its Relation to the Alteration Mineralogy and Electrical Resistivity, 1–19.

Zhan, L. tong, Xu, H., Jiang, X. ming, Lan, J. wu, Chen, Y. min, & Zhang, Z. ying. (2019). Use of electrical resistivity tomography for detecting the distribution of leachate and gas in a large-scale MSW landfill cell. *Environmental Science and Pollution Research*, *26*(20), 20325–20343. https://doi.org/10.1007/s11356-019-05308-6

Zhou, C., Tong, D., & Yu, W. (2019). *Smectite Nanomaterials: Preparation, Properties, and Functional Applications*. *Nanomaterials from Clay Minerals*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-814533-3.00007-7