INVESTIGATING LINKAGES BETWEEN ENGINEERING AND PETROPHYSICAL PROPERTIES OF UNCONSOLIDATED GEOMATERIALS AND THEIR GEOELECTRICAL PARAMETERS

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Dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Civil and Environmental Engineering in the Graduate School of Duke University

2011
ABSTRACT

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**Abstract**

The need for an improved ability to “see into the earth” has resulted in the use of geophysical techniques, especially the electrical resistivity method, in engineering and environmental investigations. The major challenge in the use of electrical resistivity measurements however is the interpretation of the electrical response. This is due to the lack of adequate understanding of the relationships between the physical factors controlling the engineering behavior of geomaterials (earth materials) and their measurable electrical parameters. This research work therefore sets out to investigate the linkages between engineering and petrophysical properties of geomaterials and their geoelectrical parameters and to provide a methodology by which the engineering behavior of the subsurface can be predicted non-invasively. This goal is achieved through the development of laboratory equipments and the conduction of both laboratory and field studies. The laboratory experiments involve the measurement of the complex resistivity responses of natural and artificial soil samples under varying effective stress conditions. The field study involves the characterization of subsurface fracture parameters from field electrical measurements in complex fractured terrains at selected farming communities in Ghana.

The results from this study improve on our knowledge and understanding of the influence of fundamental engineering properties of geomaterials on their electrical
responses. The results will aid in the interpretation of field electrical measurements and provide a means for engineering properties of geomaterials to be estimated from measurable electrical parameters. It will also contribute towards using non-invasive electrical measurements to assess and monitor the stability conditions of soil units and examine the role of subsurface fractures in the contamination of groundwater resources in complex fractured terrain.
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1 Introduction

1.1 Motivation

The shallow earth’s subsurface consisting of weakly consolidated soils and fractured rock mass support a variety of loads from engineering structures. It also provides flow paths for water and contaminants, and acts as storage reservoirs for various kinds of wastes. Most of these processes occurring in the earth subsurface may ultimately modify the engineering properties and behavior of these natural earth materials. Proper characterization and investigation of the earth subsurface is therefore necessary to determine its engineering and petrophysical properties; evaluate its stability conditions; assess and monitor risks posed by site conditions; and ascertain its suitability for earthworks.

The conventional way by which the earth’s subsurface is characterized and investigated for geotechnical engineering purposes involve field measurements and laboratory analysis of field samples. The information obtained from field (in-situ) measurements such as borehole drilling is limited in spatial extent (1-D information). Also, the analysis of field samples in the laboratory are often very expensive, laborious and time consuming, thereby limiting the number of samples analyzed. Consequently, information obtained about the subsurface condition from these conventional methods is usually inadequate. It is therefore not surprising that a committee convened by the
National Research Council of the National Academics of Science and Engineering (NRC) to develop a vision for 21st century geo-engineering, indicated an improved ability to “see into the earth” as perhaps the most important need in geotechnical engineering (Mitchell and Kavazanjian, 2007). In addition, there is the need for a better ability to characterize the spatial variability of subsurface geomaterial properties and the uncertainties thereof. These needs indeed make geophysical methods very useful for advancing geotechnical knowledge and practice. This is because of its non-invasiveness, its low operational cost and minimal time requirement, and its ability to provide large scale information of the earth subsurface.

Over the past two decades, geophysical techniques have been introduced into near surface investigations involving engineering, groundwater and environmental projects. It is also being steadily utilized in geotechnical and geohazard investigations such as site characterization, slope stability studies and landslide analysis. Out of the numerous geophysical methods available, the electrical resistivity method is one of the most used in shallow investigations (Telford et al., 1990; Reynolds, 1997). It is fast and easy to perform, and has the ability to detect simultaneously lateral and vertical variations in subsurface soil properties with less data to process.

The employment of electrical resistivity method in geotechnical engineering and subsurface investigations however, comes with its own challenge: interpretation of
electrical responses. This is because of the lack of adequate research work relating physical factors controlling the engineering behavior of earth materials to their measurable electrical parameters. Thus, for electrical resistivity measurements to be useful in geotechnical engineering and subsurface investigations, there is a need for a good understanding of how physical factors (external and internal) which influence the behavior of earth materials, relate to their electrical responses. Fundamentally, the physical factors which influence the engineering and hydraulic behavior of geomaterials are invariably, the same factors that affect their electrical responses (Schön, 2004). This makes the use of electrical methods in assessing and monitoring the engineering and hydraulic behavior of soils non-invasively very appealing. Electrical resistivity measurements can be performed in the laboratory and in field environments quickly and inexpensively. There is also less data to process and is applicable in built up areas.

One of the goals of this research work is to develop a methodology by which the engineering and hydraulic properties of the subsurface can be characterized non-invasively using complex electrical resistivity measurements. The mechanisms by which these properties influence the electrical resistivity responses are complex and coupled. This research work therefore develops a comprehensive laboratory testing program to explore the linkages between relevant engineering properties of geomaterials and their electrical responses. Field electrical measurements are also carried out to characterize the
hydraulic properties of fractured rock mass in the shallow subsurface. Valuable information from the electrical resistivity responses that can be used to predict engineering and hydraulic properties of the subsurface are explored. The possibility of extracting electrical signatures that can be used to assess and monitor changes in the internal structure of soils under applied loads are also investigated.

1.2 Literature Review

1.2.1 Engineering and Petrophysical Properties of Geomaterials

The engineering and petrophysical properties of geomaterials which are of interest in this research work are the physical properties of soils and rocks essential for characterizing the subsurface conditions for engineering purposes. These properties influence the engineering and hydraulic behavior of the earth’s subsurface (Mitchell and Soga, 2005). Laboratory and field tests are usually conducted on geomaterials to assess its engineering properties and quantify its strength, compressibility, and permeability. Geomaterials with excellent engineering properties exhibit high shear strength, low compressibility and are usually appropriate for earthworks. Being able to adequately determine the engineering and petrophysical properties of the subsurface is therefore essential in the assessment of subsurface behavior and stability conditions.
1.2.1.1 Strength Properties and Mechanical Behavior of Geomaterial

Knowledge of the strength and mechanical behavior of geomaterials is required for numerous subsurface stability analyses. The strength of geomaterials gives a measure of the capacity of the material to withstand stresses/forces without giving way to those stresses by rupturing or becoming deformed. In geotechnical engineering, the strength of soils is given by engineering properties such as shear strength, penetration resistance, bulk density, and elastic modulus. The Mohr-Coulomb failure criterion provides soil strength parameters (cohesion and angle of internal friction), used for soil strength analysis. The cohesion parameter is a combination of ‘true cohesion’ and other physical properties of soils such as: soil moisture, grain size distribution, and relative density. The angle of internal friction represents the degree of interlocking of individual grains or aggregates and is influenced by the shape, size, and packing arrangement of these particles (Sidle and Ochiai, 2006).

Though these strength parameters are widely used in soil strength analysis, there are indeed many basic physical factors (internal and external) that influence the strength properties and mechanical behavior of soils (Mitchell and Soga, 2005; Poulos, 1988). These factors include soil composition (grain size and distribution, mineralogy, pore fluid type and content), structure (voids, inclusions), initial state (effective stress, water content), and loading method (drained/undrained, static/dynamic) (Poulos, 1988).
strength of geomaterials is therefore a highly variable property which may change as these fundamental factors change.

Duncan and Wright (2005) however indicated that the magnitude of interparticle contact forces (effective stress) and density are probably the most important factors governing the strength of soils. Larger interparticle contact forces (relatively higher effective stress) and higher densities results in higher strength. Effective stress is the total stress on a soil mass minus the pore water pressure. Increasing pore water pressure generally results in a decrease in effective stress and thus a decrease in soil strength. Increase in pore water pressure may be caused by an increase in total stress if the water in the pores is not able to flow freely out of a soil mass during the time the soil is subjected to the stress change.

1.2.1.2 Transport Properties and Hydraulic Behavior of Geomaterials

The hydraulic behavior of the subsurface depends very much on soil fabric, both microstructure (i.e. arrangement of individual particles) and macrostructure (such as stratification and fractures). The physical properties of soils and rocks such as porosity, void ratio, specific surface area and grain size distribution therefore determines the hydraulic behavior of the subsurface. Hazen (1911) proposed a relationship between hydraulic conductivity and effective grain size. Boadu (2000) reasonably predicted the hydraulic conductivity of soils from soil physical properties including fractal dimension,
porosity and fines content. Application of stress also influences the hydraulic behavior of geomaterials because of the modification in their pore spaces.

The pores and fractures in geomaterials of the subsurface provide flow paths for fluids and contaminants which may alter the engineering properties of the geomaterials and/or pollute the groundwater resources. Knowledge of the changes in the hydraulic behavior of the subsurface which are manifestations of changes in the structural properties of the subsurface is therefore very important in engineering and environmental investigations.

1.2.2 Complex Electrical Resistivity

Electrical conduction (inverse of electrical resistance) in a porous media such as soils is caused by movement of ions through the pore fluid (e.g., water and air) coupled with the movement of adsorbed ions along the surfaces of pores and conduction through the soil solids. The electrical resistance of soils is obtained by imposing an electric current $I$ on a soil sample and measuring the resulting electric potential or voltage $V$. The electrical resistance or impedance is affected by the soil sample geometry. This effect is corrected for by multiplying the measured resistance by a geometric factor to give a parameter called Resistivity which is an inherent material property independent of the geometry. The resistivity ($\rho$) is related to the resistance or impedance ($Z$) via the
area (A) to length (L) ratio of the sample, and thus $\varrho = Z \times (A/L)$, with $(A/L)$ being the geometric factor.

The applied current in electrical resistivity measurements can be direct current (DC), where the signal is constant in time, or it can be frequency dependent. Unlike direct current measurements where only resistance of the soil medium is measured, the capacitance properties of the medium manifest themselves in addition to the pure resistance in frequency dependent measurements. The output voltage of the frequency dependent measurements can be expressed as a vector sum of both in-phase (real) and out-of-phase (imaginary) components resulting in the term complex resistivity. The real part is influenced by both pore volume (electrolyte) and interface properties, while the imaginary part is influenced solely by the interfacial properties (Schön, 2004). The measured complex resistivity can be transformed into polar coordinates as Resistivity Magnitude and Phase.

Measured soil complex resistivity is influenced by a combination of soils physico-chemical properties including clay/fines content, fluid content and degree of saturation, void ratio/porosity, and stress (Thevanayagam, 1993; Seabrook and Boadu, 2002; Schön, 2004). Electrical parameters obtained from the complex resistivity response are therefore sensitive to different composition, structure and state of the soil. Examples of electrical parameters which can be extracted from the complex resistivity response
include resistivity amplitude \( \rho(\omega) \), phase \( \theta(\omega) \), capacitance \( C(\omega) \), percentage frequency effect (PFE) and loss tangent \( \tan \delta(\omega) \). The phase is sensitive to the distribution and amount of polarizing sources present; the capacitance is sensitive to microstructure, specific surface area and double layer thickness; the loss tangent or dissipation factor, is related to the ratio of the energy dissipated in the material to the energy stored at the peak of polarization by the electric field.

### 1.2.3 Review of Electrical Measurements in Subsurface Investigations

The past two decades have seen the utilization of electrical measurements in subsurface investigations to assess and estimate geotechnical properties. Pellerin (2001) reviewed the applications of electrical methods for environmental and geotechnical applications. A comprehensive review of literature involving the use of electrical measurements in the evaluation of geotechnical parameters has also been done by Bryson (2005).

Electrical response of soils have been shown to be dependent on water content, degree of saturation, bulk density and pore structure (Schon, 2004) and have been suggested as a means to evaluate hydraulic conductivity (Slater and Lesmes, 2002; Boadu and Seabrook, 2000). The magnitude of dielectric dispersion, an electrical parameter, has been correlated with compression index (Arulanandan et al., 1983) whiles McCarter and Desmazes (1997) investigated changes in soils’ electrical conductivity in...
response to one-dimensional consolidation. Other researchers (Rinaldi and Cuestas, 2002; Abu-Hassanein et al., 1996; Kalinski and Kelly, 1994; McCarter, 1984) have utilized electrical resistivity measurements to evaluate soil compaction. Bryson and Abhijit (2009) also predicted geotechnical properties such as void ratio from electrical conductivity measurements of compacted soil samples.

Resistivity measurements have also been used to provide subsurface properties in slope stability studies where there is a contrast in porosity and saturation between the disturbed material and parent rock (Mauritsch et al., 2000; Lapenna et al., 2004). Perrone et al. (2004) applied geoelectrical prospecting techniques to identify the sliding surface and estimated the thickness of the mobilized material in Varco d’Izzo landslide. Meric et al. (2005) also used combined geophysical methods to investigate large gravitational mass movement and their results suggest that monitoring the evolution of rock mass movement with time-lapse geophysical surveys could be beneficial. Neisner (2010) recently investigated the possibility of using repeated resistivity measurements as an integral part in an early warning program for landslides. He concluded that resistivity measurements have the ability to detect potentially unstable conditions of the earth subsurface before actual failure occurs.

Field electrical measurements have further been conducted to relate electrical parameters (mainly resistivity) to soil strength derived from geotechnical tests such as
Standard Penetration Test (SPT) (Cosenza et al., 2006; Braga et al., 1999; Oh and Sun, 2008). The relationships obtained between the electrical parameters and the geotechnical properties (mainly SPT N-values) which are site-specific were however generally poor. These poor relationships were obtained because, the basic physical factors affecting the electrical as well as the soil strength properties especially their interdependencies were neglected. The physics of electrical current flow in subsurface soil suggest that the possible relationship between the engineering and hydraulic behavior of geomaterials and electrical resistivity should be based on the parameters which control the engineering behavior as well as electrical resistivity such as composition, grain size distribution, fluid type and content, porosity and effective stress. It is therefore imperative to investigate and explore the linkages between the properties which influence the engineering and hydraulic behavior of geomaterials and their electrical response.

The ability to conduct such investigations will require the development of geotechnical testing devices capable of concurrently measuring changing geotechnical properties of geomaterials and its attendant electrical responses. These devices can then be used for the conduction of comprehensive laboratory measurements. Information from such investigations will provide a useful direction in the use of electrical
measurements to effectively assess the engineering behavior of geomaterials and will be helpful in the interpretation of field electrical measurements of the earth’s subsurface.

1.2.4 Review of Existing Geotechnical Testing Devices

Testing devices needed to carry out laboratory investigations to understand the relationships between geomaterial properties and behavior and its electrical responses are very few and usually very expensive to acquire. This has limited the number of laboratory studies carried out to improve our knowledge and understanding on the influence of geotechnical properties on the electrical responses of geomaterials. To overcome this limitation, researchers usually resort to developing custom testing devices for their particular geotechnical-electrical investigations. Some of the developed testing devices for geotechnical-electrical investigations are described briefly below.

McCarter and Desmazes (1997) fabricated a test cell from perspex material, fitted with stainless steel electrodes for the bulk characterization of soil-water electrolyte system and to investigate electrical anisotropy. Abu-Hassanein (1994) also developed a test apparatus from polyvinyl chloride (PVC) cylinder to measure the vertical bulk electrical resistivity of compacted clays. A cell consisting of cylindrical glass tubes and two circular copper electrodes coated with nickel was developed by Rinaldi and Cuestas (2002) to investigate the ohmic conductivity of compacted loess specimens. Bryson and Bathe (2009) also developed a testing system for the investigation of anisotropic
electrical measurements of compacted soil samples. McCarter et al. (2005) modified a hydraulic oedometer (Rowe cell) developed by Blewett et al. (2002) to facilitate monitoring of the electrical conductivity of soil, in conjunction with load-deformation characteristics.

1.3 Design of this Study

The premises used in directing this research work is based on the knowledge that the physical factors that influence the engineering and hydraulic behavior of geomaterials are invariably the same properties that influence their electrical responses (Figure 1.1). It is therefore hypothesized that, important characteristic parameters extracted from complex resistivity measurement on geomaterials can be used to assess the engineering properties and behavior of these geomaterials. It is expected that changes in the engineering and hydraulic behavior of geomaterials will result in changes in the electrical response.

Currently, electrical methods are mostly used, in conjunction with conventional geotechnical techniques, in geohazard investigations to help characterize the failure region and understand the mechanisms leading to the failure. It will however be extremely useful if electrical measurements can be used to non-invasively determine the strength and stability conditions of the earth’s subsurface and to predict impending failures. It will also be appealing if electrical resistivity methods can be utilized in the
environmental impact assessment of a project or activity (e.g., impact of farming activity on groundwater resource). These interesting applications of the electrical resistivity method can, however, be possible if a good understanding of the linkages between the engineering and hydraulic properties of geomaterials and their geoelectrical parameters are adequately known.

Figure 1.1: Hypothesis that sensitive parameters extracted from electrical response can be used to assess the engineering and hydraulic behavior of soils.

This research work therefore sets out to answer the following basic questions:

- How do fundamental physical factors (internal and external) which affect the engineering and hydraulic behavior of geomaterials influence their complex resistivity responses?
• Can electrical measurements be used to predict engineering and petrophysical properties of geomaterials, especially those that influence the strength and stability conditions of the earth subsurface?

• Are there any characteristic electrical parameters that are responsive to and can be used effectively to infer the changes in soil state, e.g., the evolution of soil units from frame supported (stable) to near suspensions (unstable) conditions?

• Can the insights and understanding gained in this proposed investigative effort be utilized to assess and monitor the stability conditions of soil units non-invasively using electrical measurements?

• Can electrical measurements be used to characterize subsurface fracture parameters which may provide the medium for groundwater contamination?

To answer these questions, a series of laboratory experiments as well as field measurements were designed and carried out.

### 1.4 Laboratory Design

Two different laboratory measurement systems were designed to measure concurrently the complex electrical resistivity and engineering properties of well characterized artificial and natural soil samples under varying loading (effective stress) conditions. The laboratory systems include the New England Research (NER) Autolab 500 lab system and a geotechnical testing device (modified oedometer) developed to
facilitate the study of the engineering behavior of geomaterials. These laboratory systems were connected to an electrical equipment and computer for electrical resistivity measurements. The electrical equipment, the Zonge GDP-32 receiver and LDT-10 transmitter, is a system consisting of a broadband multi-channel multi-frequency digital receiver and a laboratory transmitter. The transmitter produces a square wave constant current source signal and the receiver measures the complex impedance spectrum (amplitude and phase shift) for the frequency range of $10^{-2}$ to $10^{4}$ Hz. The receiver calculates the standard error of each measurement in real time, which can be used to confirm data quality during measurements.

1.4.1 New England Research (NER) AutoLab 500 Lab System

The NER AutoLab 500 is a high confining pressure system with a core holder assembly for securing prepared soil samples. The coreholder is designed to hold cylindrical soil samples 38 mm in diameter and between 25 mm and 50 mm in length. The equipment provides isotropic confining pressures up to 70 MPa and pore pressures from 0.5 MPa to 30 MPa. The system includes a gas pressurized accumulator which can hold pressures at pre-determined levels constant for over forty-eight hours. Due to the high pressures involved, porous stainless steel discs are used as electrodes. These porous steel discs serve two purposes: first as filters equivalent to porous stones in permeability measurements and secondly as current and potential electrodes. Prepared
soil samples are sandwiched between the four electrode discs, two at each end. The two electrodes at each end are separated from each other by a nylon filter membrane of equal or larger pores to ensure a four-electrode measurement system while not impeding fluid flow. One serves as a current electrode while the other serves as a potential electrode (Figure 1.2). This arrangement of electrode stacks allows measurement of the electrical response of soil samples to be taken at different stress levels. A sketch of the NER equipment connected to the electrical measurement system is shown in Figure 1.3. The full description of the NER equipment, setup, and its calibration has been described in (Seabrook, 2001; Seabrook and Boadu, 2002).
Figure 1.2: A schematic of the core assembly, showing electrical contacts, pore fluid connections and axial deformations LVDT (Seabrook, 2001).
1.4.2 Geotechnical Testing Device (Modified Oedometer)

An alternate measurement system, a geotechnical testing device (modified oedometer), was designed and developed to allow electrical measurements to be taken at low effective stress levels (< 500 kPa) since the NER equipment could not give such low effective stresses. This device is also simply designed to enable undergraduate students to easily use it in their soil mechanics laboratory experiments (incorporating geophysics into geotechnical engineering). The apparatus set up consists of a cylindrical cell with an inside diameter of 100 mm and a loading frame. The cylindrical cell, together with top and bottom platen is fabricated from acrylic plastic material. The cell is
fitted permanently to the base platen while the top platen is free to move down the cell during sample consolidation. The cell can host samples with thickness (heights) ranging from 45 mm to 70 mm. Porous stones are attached to the base and upper platens to serve as filters. O-rings are also placed at the edges of the platens to ensure a tight contact between the platens and the cell to prevent leakage of water and pore pressure dissipation.

The cell has outlets for sample vacuuming, saturation and drainage, and is also equipped with a pore pressure transducer, strain gauge and electrodes for electrical measurements. Axial loads are applied to the samples under lateral confinement using a loading frame similar to the conventional loading in oedometer (consolidation) experiments. The load is transmitted centrally through a loading piston which rests on the upper circular platen, providing a uniform pressure distribution on the soil sample. The apparatus setup is designed to accommodate stresses of up to 2 MPa. A sketch of the device connected to the electrical measurement system is shown in Figure 1.4.
1.4.2.1 Electrode configuration and cell calibration

The electrodes, made from stainless steel, were arranged on the test cell in a manner so as to provide four different measurement or electrode configuration (Figure 1.5). Two electrode configurations (E1 and E2) were obtained by positioning two sets of four electrodes around the perimeter of the cell at two levels. The third electrode configuration (E3) is attained from four electrodes positioned on top of the upper platen. The final configuration (E4) is obtained by placing two electrodes at the bottom and utilizing two of the electrodes at the top platen. Each of the configurations is therefore made up of four electrodes, two serving as current electrodes and the other two as potential electrodes (Figure 1.5). Stainless steel electrodes are used for the device.
because they are considered to be sufficiently inert for soil resistivity measurements (Bohn et al., 1982). They are also appropriate for this cell due to the time required to complete a measurement cycle, the need for the cell to be used for several measurements, and the amount of loading being applied.

Figure 1.5: Different electrode positions providing four different electrode configurations E1, E2, E3 and E4. C represents the current electrodes and P represents the potential electrodes

For the device to produce correct resistivity measurements, which are representative of the inherent soil property, and not the sample and measurement
geometry, the test cell was calibrated. The calibration was done to obtain calibration factors for the various electrode configurations. It must be noted that the top platen slides down during sample consolidation which changes the geometry and varies the distribution of electric field. As such the electrode system was also calibrated for various positions of the top platen within the cell.

The calibration of the cell was conducted using different concentrations (0.0001M, 0.0005M, 0.001M, and 0.01M) of KCl solution whose conductivities span through the expected conductivities of the various soil samples to be measured. The prepared solutions were poured into the oedometer cell and their electrical conductance measured at various positions of the upper platen for all the electrode configurations. The calibration factors are then obtained from the ratio of the measured conductance to the true conductivity. The true conductivities of the KCl solutions were obtained from manufacturer’s conductivity standards. Figure 1.6 shows the calibration factors for the four electrode configurations at various positions of the top platen.
1.5 Field Measurement

Field measurements were designed to characterize subsurface fracture parameters and ascertain their role in groundwater contamination. The field studies include geological, geophysical and geochemical measurements. Geological mapping of exposed fractured rocks and subsequent electrical resistivity measurements provided a means by which subsurface fracture characteristics can be determined from electrical resistivity surveys. Fractures, which provide the medium for fluid and contaminant flow, are sensitive to electrical responses. As such, knowledge of and the ability to estimate the fracture characteristics of geomaterials of the subsurface, may provide information on the vulnerability of underlying groundwater resource to contamination from anthropogenic activities on the earth’s surface.
1.6 Objectives of this Study

The aim of this research work is to develop a methodology by which engineering and petrophysical properties as well as changes in the structure of geomaterials and hence subsurface stability conditions can be assessed and monitored non-invasively from complex electrical resistivity measurements. This research effort improves our knowledge and understanding of the influence of geomaterial properties, especially those that affect their engineering and hydraulic behavior, on their electrical resistivity responses. It also contribute towards our quest of using geophysical methods in assessing and monitoring non-invasively, the strength properties and stability conditions of the earth’s subsurface.

The research objectives were addressed through the design of the following specific laboratory experiments and field investigations:

- Obtain a large number of soil samples to be used in the experimental analyses so reliable relationships between electrical and engineering properties of soils may be established.
- Design and conduct laboratory experiments for concurrent measurements of the compressibility characteristics and spectral electrical responses of soils. Characteristic changes in the features of the electrical response, which are manifestations of changes in composition and structure of the soil, are analyzed.
• Explore the relations between electrical parameters describing soils as multi-component, multi-phase porous media and the properties describing their engineering behavior such as void ratio, elastic modulus, compressibility, and dry density.

• Characterize subsurface fracture parameters using electrical measurements and ascertain the role these fractures play in groundwater contamination.

1.7 Overview of Dissertation

This dissertation is organized into six chapters. The motivation, literature review, and objectives for the study are given in Chapter 1 as introduction whiles the conclusions and contributions of the study are presented in Chapter 6. Chapters 2, 3, 4 and 5, presents independent studies (experiments) carried out to provide information on the linkages between engineering and petrophysical properties of geomaterials and their electrical parameters.
2 Effect of Clay Content and Effective Stress on the Spectral Electrical Response of Sand-Clay Mixtures


2.1 Abstract

The strength and stability conditions of unconsolidated geomaterials, for example soils, are influenced by modifications of their micro-structure, texture, mineralogy and normal effective stress levels. These modifications in the internal structures of the soils often result in geohazards (e.g., landslides, liquefaction, and debris flow) which often claim so many lives, destroy the environment and cause considerable amounts of property damage. Characterization and monitoring of such geohazards demand knowledge about the physical and mechanical properties of unconsolidated near surface geomaterials of interest.

The fundamental relations between geoelectrical parameters and the geotechnical properties which influence the mechanical behavior of soils are investigated by performing controlled laboratory experiments on sand-clay mixtures under stress. Spectral electrical response (SER) measurements are performed on these mixtures over a range of frequencies (0.001 Hz-1 kHz) with concurrent measurements of their geotechnical properties. Electrical parameters, that is, the phase, resistivity

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amplitude, capacitance and loss tangent are extracted from the SER measurements, and geotechnical properties of the mixtures which include the void ratio, dry density and the modulus of elasticity are obtained from laboratory measurements. Cross-plots of geotechnical properties and geoelectrical parameters indicate significant correlations. The phase and capacitance values decrease with an increase in the dry density, whilst the loss tangent and the resistivity values increase with increase in dry density. The phase and capacitance values however decrease with an increase in the values of the modulus of elasticity whereas the loss tangent and the resistivity values increase with increase in elastic modulus. These relations can be useful in non-invasive prediction of the geotechnical properties of unconsolidated geomaterials relevant in the assessment, monitoring and mitigation of geohazards.

2.2 Introduction

The electrical properties of geomaterials such as soils are influenced by their petrophysical properties including pore volume, type of pore fluid and saturation conditions, as well as composition, for example, clay content. Knowledge about these properties is required to investigate and solve geotechnical, hydrogeological and ecological problems. Generally, the shallow earth’s subsurface consists of unconsolidated geomaterials (soils) mainly composed of mixtures of sand and clay particles. Several natural phenomenons, e.g., landslides, liquefaction and debris flow
which all pose as geohazards, occur near the fluid/solid transitions of suspensions and saturated sediments. Characterization and monitoring of such geohazards demand knowledge about the physical and mechanical (strength) properties of unconsolidated near surface geomaterials of interest.

The strength properties of soils have been found to be directly related to the grain size and distribution, number of grain contacts, specific surface area, amount of fines and the interaction between the solid and fluid phase of soils (Holtz and Kovacs, 1981). For example, Igwe et al. (2007) showed that well graded soils have higher shear strength than poorly graded soils. The relative amount of clay sized particles and their mineralogy has been shown to be related to the shear strength of soils (Wroth and Wood, 1978) whilst Youssef et al. (1965) showed a decrease in shear strength with an increase in water content. A number of empirical relationships between the elastic modulus and parameters characterizing soil strength such as standard penetration tests (SPT) N values and tip resistance have also been proposed (Bowles, 1996; Meyerhof and Fellenius, 1985). The elastic modulus was found to be directly proportional to the tip resistance. Duncan and Wright (2005) have indicated that the magnitude of interparticle contact forces (effective stress) and density are probably the most important factors governing the strength of soils. The ability to locate and monitor weaker soil/rock units
in the subsurface using geophysical methodologies would be cardinal to the assessment of the lifetime integrity of sensitive structures.

Using geophysical methods to assess and monitor geotechnical properties would be extremely useful as they are non-invasive, cheaper to perform than drilling many sampling wells and faster in operation. One of the commonly used geophysical methods in engineering investigations is the electrical resistivity method (Telford et al., 1990; Reynolds, 1997). The most common and simplest type of electrical measurement is that of conductivity of direct current which is convenient for characterizing the pore structure of clay free unconsolidated materials such as sand and gravels. In complex porous media such as sand-clay mixtures with varying particle sizes, shapes and surface characteristics, another mode of electrical conduction referred to as surface conductivity exist. It involves the movement of surface charges at the interface between the soil particles and the pore water (Reynolds, 1997; Ruffet et al., 1995). The use of direct current measurement in such a medium is therefore ineffective since it does not exploit the interfacial properties of the medium which are more related to the geotechnical properties of the soil (Bryson, 2005).

The interfacial properties which induce polarization of ions in a soil medium influence the phase response of spectral electrical response (SER) measurements (Garouch and Sharma, 1994; Schön, 2004). Thus, SER measurements can be useful in
discriminating between the influence of internal physical factors (e.g., composition, pore fluid content, void ratio) and external factors (effective stress) on the electrical responses of soils (Schön, 2004; Olhoeft, 1985; Seabrook and Boadu, 2002). Garouch and Sharma (1994) showed that clay content, salinity and ionic mobility control the dielectric spectra of rocks in the frequency range of 10 Hz to 10 MHz. SER measurements on soils by Boadu and Owusu-Nimo (2010) indicated that the normalized phase and resistivity amplitude are very sensitive to changes in the amount of fines (silts and clays) with fines content value of 18% being the transition value for the conduction process.

For SER measurements to be useful in the non-invasive assessment and monitoring of soil’s stability conditions, adequate knowledge of the relationships between the physical factors (external and internal) which influences the strength characteristics of unconsolidated materials and the measurable electrical responses are required. The mechanisms by which the physical factors, which in combination define the geotechnical properties, influence electrical measurements are complex and coupled and to understand these processes demand conduction of controlled laboratory experiments.

In this study, controlled laboratory experiments were performed to investigate how the interplays of varying effective stress (normal) levels and clay content concurrently influence the SER of the sand-clay mixtures. In the sequel, the relationships
between geotechnical properties of the mixtures and the relevant electrical parameters were investigated. The geotechnical properties considered include void ratio, dry density and modulus of elasticity whiles the electrical parameters include the phase, resistivity amplitude, capacitance and loss tangent. Information from the laboratory measurements can be used to constrain and improve field interpretation of electrical measurements in the assessment of instabilities in geomaterial, and to reduce the uncertainties in such assessments. This study contributes to our quest of using geophysical methods to assess and monitor non-invasively, the strength properties and stability conditions of the earth’s subsurface.

2.3 Experimental Procedures

2.3.1 Soil Preparation and Electrical Measurements

The experiments were conducted on sand-clay mixtures prepared by mixing Ottawa sand with 0%, 2%, 5%, and 10% of clay (Na- Bentonite) by weight and saturated with de-aired tap water (∼50 Ωm). For each sample, the initial length, diameter and weight were measured and loaded into a pressure vessel (the New England Research (NER) Autolab 500 lab system), and subjected to confining pressures of 1.0, 1.5, 2.0, 2.5 and 3.0 MPa with pore pressure fixed at a value of 0.5 MPa. Full saturation was achieved when the pressure difference from the top to the bottom of the sample remained constant, and the saturation and equilibration times range from a few minutes to several
hours depending on the clay content. A sketch of the laboratory equipment and configuration (Figure 1.3) shows the connection of the core holder in the pressurized chamber (NER unit) to the electrical measurement system (GDP-32 digital multi-frequency controller-transmitter/receiver) and a PC. The controller generates signals at frequencies ranging from $10^{-2}$ to $10^4$ Hz, and the transmitter produces a square wave constant-current source signal. At all effective stress levels ($\sigma' = 0.5, 1.0, 1.5, 2.0$ and $2.5$ MPa), sample deformation (axial and volumetric strains), and the real and imaginary parts of the complex impedance in the frequency range of $10^{-2}$ to $10^3$ Hz are concurrently measured. These effective stresses are the normal effective stress. Measurement procedures for the system have been described in detail in (Seabrook, 2001; Seabrook and Boadu, 2002).

### 2.3.2 Relevant Electrical Parameters

In this study, the important electrical parameters that are responsive to the textural and microstructural characteristics of the sand-clay mixtures are investigated and extracted from the frequency dependent electrical measurements. These characteristic electrical parameters include the phase ($\phi$), capacitance ($c$), loss tangent ($\tan \delta$) and resistivity amplitude ($\rho$), all functions of angular frequency ($\omega$).

The phase [$\phi(\omega)$] is obtained from the real and imaginary parts of the complex impedance which is given as $\arctan [Z''(\omega)/Z'(\omega)]$; where $Z''$ and $Z'$ are the imaginary
and real parts of the complex impedance \((Z^*)\) respectively. The complex resistivity \((\varrho^*)\) is related to the complex impedance \((Z^*)\) via the area \((A)\) to length \((L)\) ratio of the sample, and thus \(\varrho^* = Z^*(\omega) \times (A/L)\). The phase has been shown to be sensitive to the pore size, the distribution and the amount of polarization sources that are inherent in the sample (Boadu and Owusu-Nimo, 2010; Schön, 2004). Generally, the phase values are relatively small when free electrolytic paths (in clay free samples) dominate over ion-selective paths or zones (e.g., clay zones). However, the phase values may be elevated under stress for clay free samples (Boadu and Seabrook, 2006; Seabrook and Boadu, 2002).

The capacitance \(C(\omega)\) is related to the complex impedance via the relation \(C(\omega) = 1/[i\omega Z^*(\omega)]\) (Czichos et al., 2006). The capacitance is sensitive to the micro-structure of the sample and related to the surface area and double layer thickness.

The loss tangent or dissipation factor \([D \text{ or } \tan(\delta)]\) is obtained from the real and imaginary parts of the complex impedance via \(\tan(\delta) = Z'(\omega)/Z''(\omega)\) and is related to the ratio of the energy dissipated in the material to the energy stored at the peak of polarization by the electric field. It is a measure in relative terms, of energy transferred to a sample from the electric field due to DC conduction and polarization processes.

### 2.3.3 Relevant Geotechnical Properties

The fundamental geotechnical properties of unconsolidated geomaterials of interest when assessing the stability and strength conditions of unconsolidated materials
include but not limited to the void ratio \((e)\), dry density \((\gamma_{dry})\) and modulus of elasticity \((E)\). These properties can be useful, for example, in monitoring the transition from frame-supported unconsolidated materials to loose suspensions, in assessing the settlement characteristics of unconsolidated materials, and monitoring densification in geotechnical construction to achieve the required compressibility. The usual strength parameters (cohesion and angle of internal friction) used for soil strength analysis is not used because of the difficulty in obtaining these parameters concurrently with electrical measurements.

The ratio of volume of void space to the volume of solids in a soil unit is defined as the void ratio and serves as a measure of the state of compaction which is characteristic of the strength of unconsolidated materials. Soils with high clay or fines content will have decreased porosity or void ratio and will result in an increase in conductivity. In general, soils with high clay content will tend to have higher specific surface which will improve surface conductance. Void ratio is related to the porosity \((\Phi)\) of the soil via \(e = \Phi/(1-\Phi)\). The porosity and thus void ratio of the samples, at each effective stress is determined as a function of the initial porosity \((\Phi_0)\) and the axial strain \((\varepsilon_i)\) from the equation;

\[
\Phi = \frac{\Phi_0 e^{-\varepsilon_i}}{1-\varepsilon_i} \quad (2-1)
\]
The initial porosity of the samples was determined using the initial volume \( (V_o) \) and the matrix-specific weight via the expression:

\[
\Phi_o = \frac{V_o - W_M / \gamma_M}{V_o} \tag{2-2}
\]

where \( W_M \) and \( \gamma_M \) are, respectively, the total weight and unit weight of the soil matrix obtained after oven drying.

Dry density is defined as the ratio of mass of solids to the total volume of a soil unit. Kokusho et al. (2004) observed the undrained shear strength to increase with increase in the dry density of granular soils. The dry density of the samples at each effective stress was obtained from the ratio of the mass of the soil grains to the volume of the sample at each effective stress level. Low values of dry density imply there is poor particle to particle contact within the soil grains which will influence ohmic conduction and surface conductivity. The enhancements of particle to particle contact in some soils increase its strength which influences the overall electrical conductivity.

The modulus of elasticity \( (E) \) is a measure of the stiffness and strength characteristics of unconsolidated material and is usually obtained from the slope of the stress-strain curve \( (\sigma/\varepsilon) \). The modulus of elasticity of the samples was computed from the ratio of the change in effective stresses to the respective change in strains. Lower values of the elastic modulus indicate soft or weak material, whilst higher values of the modulus imply materials with high stiffness and hence strength. D’Appolonia et al.
(1971) reported that the modulus of elasticity in clays may be formulated as a linear function of undrained shear strength. Palchick (1999) also observed a strong correlation of increasing uniaxial compressive strength with increasing modulus of elasticity with an $R^2 > 0.75$ for sandstones.

### 2.4 Data Analysis and Discussions

The spectral electrical responses were analyzed to extract useful information that exploits the interfacial properties needed to enhance our understanding of how the electrical parameters relate to the geotechnical properties of the mixtures. Figures 2.1 and 2.2 show phase and capacitance values as a function of frequency for varying clay content and stress levels.

Measured phase shifts on soil samples are influenced by the distribution and the amount of polarization sources that are inherent in the sample (Boadu and Seabrook, 2006). Clays generally act as polarization sources (Schön, 2004) and measured values of the phase shift are relatively small when free electrolytic path dominates over ion-selective paths. As shown in Figure 2.1, at low frequencies ($< 10$ Hz), the phase values are low and relatively insensitive to frequencies for the clay free sample. This is the case when electrolytic conduction in the clay free pore spaces dominates the conduction process. Addition of clay to the sand results in a peak in the phase spectra. The frequency at which peak values occur for given clay content is the same at all effective
stress levels, indicating peak frequency is insensitive to stress. However, the peaks shift toward lower frequencies as the clay content increases and consequently become spatially continuous. Increasing clay content results in a higher relaxation time of the ions due to increasing membrane blockage effects. This increase in relaxation time is reflected in the phase peaks shifting to the lower frequencies. It is further observed that the phase values decrease with an increase in effective stress. However, the sensitivity of the phase values with effective stress at higher frequencies (>10 Hz) decrease for samples with higher clay contents.

Figure 2.1: Variation of phase spectra at different effective stress levels and clay content.
The capacitance is observed in Figure 2.2 to be sensitive to clay content variations at low frequencies and virtually insensitive at higher frequencies. When the frequency applied is high, the capacitive properties of the soil medium are lessened and electric charges are able to move more freely. Gashimov and Gasanov (2009) found that under the action of an electric field bentonite clay samples tend to accumulate electric charges and thus values of the capacitance will increase with increase in clay content. For a given value of clay content, the capacitance values decrease with an increase in effective stress. This is due to the reduction in pore volume and/or change in tortuosity (Garrouch and Sharma, 1994) and the attendant decrease in ionic conductivity (Campbell, 1990). For a given clay content, as the pore spaces collapse by increasing the effective stress, the capacitance values decrease because of a reduction in the capacity of the soil medium to store electric charges. It is also observed that at lower frequencies variations in capacitance with frequency and the characteristic changes in the slope are indicative of micro-structural changes associated with application of effective stress.
Figure 2.2: Variation of capacitance spectra at different effective stress levels and clay content.

The amplitude and phase spectra for clay-free and 2% clay samples which are shown in Figure 2.3 indicate that the amplitude values decrease with frequency for both the clay-free sample and sample with 2% clay. The overall amplitudes increase with increase in effective stress for both samples, an indication of closing down or collapse of interconnected pore space which serve to provide the pathway for current flow. The phase values are insensitive to frequency in the lower frequency range for the clay free samples when subjected to different stress levels. For the 2% clay sample, there is a characteristic peak frequency for all applied stress levels. The peak frequency is virtually the same for all stress levels, but the phase values at this peak frequency decrease with
an increase in stress levels. Thus, the occurrence of peak frequency reflects on inclusion of polarization sources such as clay minerals in the sample. Generally, the magnitudes of the phase values decrease for increasing stress levels.

![Graphs showing variation of resistivity amplitude and phase spectra for 0% and 2% clay content.](image)

**Figure 2.3: Variation of resistivity amplitude and phase spectra for 0% and 2% clay content.**

The coupled effects of clay content and effective stress on the phase, resistivity amplitude, capacitance and loss tangent at a selected frequency of 8 Hz were analyzed using 3-D bar graphs in Figures 2.4(a)-(d) below. As observed in Figure 2.4(a), the phase values jump from small values (5 mrad) for clay free conditions to high values (60 mrad) when a small amount of clay (2%) is added to the sample. As discussed earlier, this increase in phase value is indicative of presence of polarizable sources such as clay.
minerals. However, as the clay content increases, it becomes spatially continuous within the mixture and result in decrease in the phase values, but to levels that are still relatively greater than the clay free samples. Thus, one can ascertain that decrease in pore space without increasing the polarization sources, such as application of stress, reduce the phase values.

The influence of effective stress on the amplitude values for varying clay contents is also given in Figure 2.4(b) which illustrates that the amplitudes slightly increase with increase in effective stress for all samples. At a given stress level, the amplitudes decrease with an increase in clay content. For samples with higher clay content, increasing stress levels enhances the clay particle to particle contact, thus providing a continuous conductive path which increases the surface conduction. This increase in surface conduction compensates for the decrease in electrolytic conduction due to closing down or collapse of interconnected pore space.

The capacitance values are also observed in Figure 2.4(c) to increase with increase in the clay content, and the values are extremely low when there are no clay particles. For a given clay content, the capacitance values decrease with increasing stress application as the pore spaces collapse. The capacity for the soil medium to store energy increases with increase in clay content, but decreases with an increase in effective stress.
Increase in effective stress limits the availability of surfaces for ion-exchange processes and charge storage capacity and hence decrease in capacitance.

Figure 2.4: Plot showing effect of clay content and effective stress on (a) phase (b) resistivity amplitude (c) capacitance and (d) loss tangent.

Figure 2.4(d) further shows the variations in the values of the loss tangent with changing effective stress levels and varying clay contents in the samples. The values of the loss tangent for all stress levels are found to be relatively high in the clay free sample and drop significantly on addition of clay since the sand grains are virtually non-conducting and little energy is stored. As clay is added to the sand, surface conduction
process is enhanced resulting in energy storage in the soil medium and thus a decrease in the loss tangent. Further increasing the amount of clay increases the loss tangent marginally due in part to the marginal increase in surface conductivity, as the polarizable sources become continuous and the surface area per unit volume required for efficient ion exchange processes diminish.

2.4.1 Variation of Electrical Parameters with Geotechnical Properties

Variations in electrical response measurements as a result of changes in geotechnical properties are analyzed below. Changes in composition reflect in changes in the geotechnical properties which influence the electrical parameters.

The relationships between the void ratio and the electrical parameters of the samples with different clay contents are given in Figures 2.5(a)-(d). Lower values of void ratio are an indication of densely packed unconsolidated materials resulting in higher soil strength. Thus, knowledge of the relationships between the void ratio and the electrical parameters will be useful in assessing and monitoring the strength properties of such materials from SER measurements.

From Figure 2.5(a), the phase values are observed to generally increase with an increase in the void ratio for samples with the same clay content whereas the amplitude values slightly decrease with an increase in the void ratio [Figure 2.5(b)]. The real part of the capacitance values also increases with increasing values of the void ratio [Figure
2.5(c)] for all clay contents. It is also observed that increases in the void ratio of the unconsolidated samples results in a decrease in the loss tangent [Figure 2.5(d)] for soil samples with the same amount of clay. For a soil sample fully saturated with water, a decrease in void ratio indicates a decrease in water content and thus overall reduction in ionic conduction. Decreasing the void ratio therefore decreases the availability of free ions for the conduction and polarization processes resulting in a decrease in the phase values and an increase in the resistivity amplitude. Also, a decrease in the void ratio decreases the capacity of the soil medium to store charges and also restricts the free flow of ions. This leads to the observed decrease in capacitance and the increase in loss tangent values.

Soil samples with different amounts of clay may however exhibit different electrical relationships with changing void ratios. Considering the soil samples with different clay contents in Figure 2.5(c), the capacitance values are observed to increase with decreasing void ratio as the clay content increases. This indicates that, at the same effective stress level, increase in the amount of clay/ fines which fills the pore spaces and decreases the void ratio, results in an increase in capacitance values. However, for soils with the same clay content, decreasing void ratio due to an increase in effective stress leads to a decrease in capacitance.
Figure 2.5: Effect of changing void ratio on (a) phase (b) resistivity amplitude (c) capacitance and (d) loss tangent. Arrows indicate direction of increasing effective stress.

Figures 2.6(a)-(d) shows the variation of dry density with the electrical parameters for varying amounts of clay content. The phase values increases with decrease in the dry density [Figure 2.6(a)] as the polarization process and the attendant surface conductivity is enhanced due to poor particle to particle contacts in the solids. The resistivity values for soil samples with the same clay content also increase with increase in dry density values [Figure 2.6(b)] as a result of reduction in the ohmic conductance. It can be seen that as the clay fraction increases, the dry density increases due to a possible increase of clay coatings to the sand grains and improving particle to particle contact. Also, as the dry density of the samples decreases due to poor particle to
particle contacts within the soil solids, the capacitance values increase [Figure 2.6(c)], while the values of the loss tangent, which is a characteristic of energy dissipation in the soil medium, decrease for samples with the same clay content [Figure 2.6(d)].

Figure 2.6: Effect of changing dry density on (a) phase (b) resistivity amplitude (c) capacitance and (d) loss tangent. Arrows indicate direction of increasing effective stress.

Variations in the electrical parameters with modulus of elasticity for varying amounts of clay in the mixtures are shown in Figures 2.7(a)-(d). For soil samples with the same amount of clay, both the phase and capacitance values decrease with an increase in values of the modulus of elasticity [Figure 2.7(a) and Figure 2.7(c)]. The resistivity and loss tangent increase with increase in the modulus of elasticity [Figure
2.7(b) and Figure 2.7(d)]. It can be observed that the resistivity variation with elastic modulus as well as capacitance variations with elastic modulus are the relations that clearly separate out the effects of clay content. The values of the modulus of elasticity decrease with an increase in clay content.

Figure 2.7: Effect of changing elastic modulus on (a) phase (b) resistivity amplitude (c) capacitance and (d) loss tangent. Arrows indicate direction of increasing effective stress.

2.5 Conclusions

Controlled laboratory experiments were performed to enhance our understanding of how effective stress, which influences soils’ structure, and mineralogy (clay content) which affect soil texture, concurrently influence the spectral electrical
response and geotechnical properties of unconsolidated soil materials. This understanding is cardinal to our efforts geared toward establishing linkages between geotechnical and geoelectrical parameters. The SER measurements on mixtures of sand and clay were conducted and the relevant electrical parameters that are influenced by the petrophysical and geotechnical properties were extracted from them. These include the spectral content of the phase, resistivity amplitude, capacitance, and loss tangent.

The spectra of the phase and capacitance are observed to be sensitive to structural changes resulting from changes in effective stress and the mineralogical content which affect the geotechnical properties. Characteristically, the phase values decrease with an increase in effective stress and increase with an increase in clay content. The capacitance also increases with an increase in clay content and decreases with an increase in effective stress. The loss tangent however increases with an increase in effective stress and decreases with increasing clay content. In exploring the linkages between these electrical parameters and the geotechnical properties of the samples, it was observed that the phase and capacitance values decrease with an increase in the dry density, whilst the loss tangent and the resistivity values increase with increase in dry density. It was also shown that the phase and capacitance values decrease with an increase in the values of the modulus of elasticity; but the loss tangent and the resistivity values increase with increase in elastic modulus. The void ratio was seen to influence the electrical
parameters such that the phase and capacitance values measured on the samples increase as the void ratio of the samples increase. However, the values of the loss tangent and resistivity decrease with an increase in void ratio. The relations, when explored further could provide useful information for non-invasive prediction of geotechnical properties of the earth's subsurface useful for monitoring and assessing the stability conditions of unconsolidated soil materials.

2.6 Acknowledgements

This work was supported by National Science Foundation Grants (NSF-EAR-03-09626 and NSF-CMS-02-17318) and also by the Donors of The Petroleum Research Fund, administered by the American Chemical Society through the grant (PRF 40160-AC9).
3 Relationships between Textural Properties of Soils and their Complex Resistivity Parameters


3.1 Abstract

The influence of textural properties of unconsolidated near surface earthen materials (soils) on their electrical responses is investigated. Complex resistivity measurements are performed at a constant effective stress on thirty-two soil samples of varying textures and compositions. Textural properties which inherently affect the mechanical and strength behavior of the samples, that is, fines content, pore size parameter, specific surface area, and fractal dimension of the grain size distributions, are obtained from geotechnical analysis. The electrical parameters which describe the electrical response of the samples, that is, resistivity amplitude (\(\rho\)), phase shift (\(\Phi\)), percent frequency effect (PFE), loss tangent (\(\tan \delta\)) and the normalized phase (\(\phi_N\)), are computed from the electrical measurements. Crossplots of the electrical and the engineering parameters provide useful information on how the geotechnical properties of the soil material influence the electrical responses. In particular, \(\rho\) and \(\tan \delta\) values are strongly influenced by variations in the textural properties (\(R^2 > 0.60\)) in comparison with the other electrical parameters. Soils become more dissipative as their specific surface area increases. The PFE values are less sensitive (\(R^2 < 0.55\)) to the textural
properties. Analysis of the correlations also indicates that there exist characteristic or transitional values of the fines content (18%) and pore size (0.03 mm), beyond which the phase and normalized phase values are insensitive to their respective increases. The characteristic value of 18% of fines content is close to values reported in previous studies that signify transition in strength behavior of soils, and thus such relations could be important in non-invasive strength assessment and monitoring of soils. Normalized phase values are used to assess the relative amount of fines in the studied soils.

3.2 Introduction

Utilization of geophysical techniques to solve engineering and environmental problems has been on the ascendency in recent years. These techniques, which are non-invasive and cost effective, can be used to predict useful textural properties of unconsolidated geomaterials (e.g., soils) that are known to affect their geotechnical behavior, that is, stability and strength. Knowledge of such properties is useful in reclamation engineering and evaluation of liquefaction susceptibility of soil as well as assessment of landslides and slope stability.

The effective use of geophysical techniques however demands adequate knowledge of how the fundamental properties of soil, which affect its strength and stability, also influence its geophysical response. Several prior studies have added to the knowledge base of how soil properties influence geophysical responses (e.g., Schön,
The relationship between porosity and bulk resistivity has been known since the work of Archie (1942). Vanhala and Soininen (1995) presented a laboratory technique for measuring the spectral electrical response of fine and coarse grained soil samples. It was shown in this study that the phase spectrum is sensitive to the texture of the soils. The interface conductivity of unconsolidated sediments was shown by Schön (1984) to decrease linearly with mean grain size. Börner and Schön (1991) also reported that the imaginary conductivity of saturated sandstone samples increases linearly with increasing specific surface area. Analysis of spectral electrical responses obtained in the submarine environment by Souza and Sampaio (2001) provided useful information about the grain size and the mineral composition of sub-bottom sediments. Boadu and Seabrook (2006) also investigated the effect of clay content and pore electrolyte concentration on the electrical response of sand-clay mixtures under effective stress. They found that changes in clay content and fluid concentrations resulted in characteristic changes in the amplitude and phase spectra of the electrical response.

Dominance of fines (grain size less than 0.075 mm) in a soil influence its engineering properties such as void ratio, permeability, shear modulus and bulk modulus, particularly when subjected to stress (Chien and Oh, 2000; Chien et al., 2002; Monkul and Ozden, 2007). Observations by Naeni and Baziar (2004) indicate a
significant decrease in the residual strength of a soil with increasing fines content up to 35%. The liquefaction potential of reclaimed soils has been shown to bear a relationship with fines content (Chien et al., 2002) with the observation that the liquefaction resistance decreases as fines content increases. The reduction was observed to be significant when the fines content exceeds 10%. Seed et al. (1985) also showed the influence of fines content on standard penetration test (SPT) blow count values ((N1)60) and indicated that the (N1)60 values decrease as the fines content increases. Studies on the interplay between the clay and sand fractions in defining soil behavior during site reclamation studies were conducted by Fukue et al. (1986) in which they concluded that liquefaction risk of the cohesionless soils might be reduced through the addition of bentonite. It was shown by Yin (1999) that the angle of internal friction decreases with increasing clay content for reconstituted soils. For clayey soils, Skempton (1985) indicated that if the clay fraction is less than about 25%, the soil behaves much like sand or silt, whereas residual strength is controlled almost entirely by sliding friction of the clay minerals when the fraction is above 50%. Tests performed by Salgado et al. (2000) highlighted that fines fully control soil response in terms of dilatancy and shear strength beyond 20% of content.

The bulk electrical conductivity of a soil medium result from movement of ions through soil pores. The ions may however travel through the pore fluid in the macro-
pores (electrolytic conduction) and along surfaces of clay minerals which are negatively charged and blocking the pore channels. Clay minerals permit substitution of ions of lower valencies (cation exchange capacity [CEC]), generating an electrically negatively charged surface and when in contact with ionic solutions generate electrically charged double layer. The surface conduction effects lead to a frequency dependent electrical conductivity (spectral induced polarization [IP]). Thus, the IP is the result of two physical processes: an interfacial polarization process involving free ion displacement in the pore fluid and tangentially at grain surfaces (Maxwell-Wagner effect), and an electrochemical process involving cation exchanges at the surfaces (CEC). These two processes are not exclusive and could simultaneously coexist. The CEC is proportional to the product of the surface charge density and the specific surface area of the soil grains (Bolt and Bruggenwert, 1978; Vanhala, 1997; Borner et al., 1993). When grains with high specific surface area (e.g., silts and clays) are dominant in a soil, they will contribute significantly to the surface conductivity and hence the IP effect (Ruffet et al., 1995; Vanhala, 1997; Schon, 2004).

It is therefore contemplated that there are important textural properties of soils that can be easily obtained from grain size distributions (GSDs) that characteristically affect the geotechnical (strength and stability) behavior of soils, and that, these same soil properties affect the electrical responses of the soils especially their surface or interface
conductivity. The soil properties include the amount of fines, the pore size parameter, specific surface area of the soil per unit mass, and the fractal dimension (Santamarina et al., 2002; Boadu, 2000). The mechanical strength of kaolin has been predicted using specific surface area with a 90% certainty (Semenov and Novozhilova, 1981).

In this paper, laboratory experiments are performed to investigate how the textural properties of soils which affect their stability and strength conditions influence their electrical responses. In particular, the effect of fines content (which has been shown to have profound influence on the stability and strength of soils) on the electrical parameters is investigated. This work serves as a contribution toward the understanding of how engineering properties of unconsolidated geomaterials affect their electrical response. Characteristic electrical parameters are extracted from the electrical responses of the soils, and the variations of these parameters with the textural properties of the soils are investigated and analyzed. Such an investigation is a valuable contribution to the search for elegant ways of using geoelectrical methods to solve complex engineering and environmental problems.

### 3.3 Experimental Procedures

#### 3.3.1 Soil Sampling

Thirty-two unconsolidated soil samples were taken across different geological terrains along transects within North Carolina and Virginia. Thus, the samples have a
wide variation in texture and composition. Most of the samples were obtained from fresh cuts from highway construction activities, and some were obtained with hand augers at depths of approximately 0.75 - 1 m. For each location, disturbed and undisturbed samples were collected close to each other, stored in plastic containers and sent to the laboratory for soil analysis and electrical measurements. The undisturbed samples (50 mm in diameter and 150 mm in length) were used for the electrical measurements and the disturbed samples were used for grain size analysis.

3.3.2 Estimation of Engineering Properties: Soil Textural Properties

Standard laboratory testing procedures were employed to determine the grain size distribution (GSD) using sieve analysis (for fractions > 0.075 mm) and hydrometer analysis (for soil particles smaller than 0.075 mm) [ASTM D422]. The non-fines comprised sand particles (0.075 - 2 mm in size). The fines content (clay and/or silt particles) in each sample was obtained from the amount of soil sample passing through No. 200 sieve (< 0.075 mm). The GSD analysis indicated a range of fines content from 3% to 36%. A similar range of fines content has been obtained for reclaimed soils by Chien et al. (2002). Other fundamental engineering properties of the soils derived from GSD include the mean grain size, pore size, specific surface area, and fractal dimension (Table 1) all of which influence the soils’ engineering behavior as well as their electrical responses.
The mean grain size ($\delta_m$) was used as the representative grain size of a sample. The value is obtained from the grain size distribution curve (ASTM D422), and is the particle diameter at which 50% of the soil sample is finer ($d_{50}$).

The pore size parameter ($\delta_p$) is usually estimated from the mean grain size and porosity $\varphi$ (Hovem and Ingram, 1979) and is given by

$$\delta_p = \frac{\varphi \delta_m}{3(1-\varphi)} \quad (3-1)$$

The parameter is directly related to the hydraulic radius, defined as the volume of pore filled with fluid per unit wetted surface (Hovem and Ingram, 1979), and its values tend to increase with increasing mean grain size or decreasing fines content.

The specific surface area is a fundamental and intrinsic property of soils that has been found to correlate with their cation exchange capacities (Patchet, 1975; Schön, 1984), their hydraulic properties (Hillel, 1998) and their mechanical behavior (Santamarina et al., 2002; Mitchell and Soga, 2005). The specific surface area per unit mass $S_m$ was simply determined from the GSD by using an expression given by Hillel (1998);

$$S_m = \frac{6}{\rho_s} \sum \left( \frac{x_i}{d_i} \right), \quad (3-2)$$

where $x_i$ is the mass fraction of grains of average diameter $d_i$, and $\rho_s$ is the density of soil grains. Thus, $S_m$ increases with an increase in fines content.
Fractal dimension $D_f$ values associated with the GSD were estimated using the mass-based relation derived by Tyler and Wheatcraft (1992) as follows:

$$\frac{M(r < R)}{M_T} = \left(\frac{R}{R_{UL}}\right)^{3-D_f},$$

where $M(r < R)$ is the mass of soil particles with radius less than $R$, $R_{UL}$ is the upper size limit of the grain sizes from sieve analysis, and $M_T$ is the total mass of soil. They found the range of soil fractal dimension to be strictly limited to 0 - 3 with most natural soils appearing to have $D_f > 2.0$. The above relation can be arranged in a log-log scale, which provides a way of finding $D_f$ from the slope of log $M(r < R/M_T)$ versus log $R$ (Tyler and Wheatcraft, 1992; Boadu, 2000). Lower values of fractal dimension imply that a particular size range dominates the distribution, whereas higher values suggest a range in grain sizes. The estimated fractal dimension can also be used as a measure of fragmentation (Boadu and Long, 1994). Higher fractal dimension values would imply greater fragmentation and therefore a tendency to create higher fines content. As indicated by Boadu (2000), the hydraulic conductivity of soils which is influenced by the fines content decreases with an increase in fractal dimension.
Table 3.1: Textural properties of soils.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fines content (%)</th>
<th>Mean grain size (mm)</th>
<th>Pore size (mm)</th>
<th>Specific surface area (m²/kg)</th>
<th>Fractal dimension</th>
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<td>0.0236</td>
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</table>
3.3.3 Electrical Measurements

The undisturbed field samples were prepared for the electrical measurements by cutting them to their measurement sizes using a split metallic tube of length 40 mm and diameter 38 mm. These samples were then fitted into a tough cylindrical rubber jacket and loaded into a pressure vessel (the New England Research (NER) Autolab 500 system) and then saturating them with de-aired freshwater ($\approx 78$ $\Omega$m). Full saturation was achieved when the pressure difference from the top to the bottom of the sample remained constant. The initial porosities ($\varphi$) of the soil samples were determined using the initial volume of the sample and its matrix specific weight from the expression:

$$
\varphi = \frac{V_T - W_M / \gamma_M}{V_T}
$$

where $V_T$ is the initial volume of the sample, $W_M$ and $\gamma_M$ are respectively the total weight and unit weight of the matrix obtained after oven drying. A four-electrode measurement array was employed in the electrical measurements of the samples. A full description of the laboratory equipment, setup, and its calibration has been described in Seabrook and Boadu (2002).

Each sample was subjected to a confining pressure of 2000 kPa and a pore pressure of 900 kPa. A sketch of the laboratory equipment and configuration in Figure 1.3 shows the connection of the core holder in the pressurized chamber (NER unit) to the electrical measurement system (GDP-32 digital multifrequency controller-
transmitter/receiver) and a PC. The controller generates signals at frequencies ranging from $10^{-2}$ to $10^4$ Hz, and the transmitter produces a square wave constant-current source signal. The real and imaginary parts of the complex impedance for each of the samples were measured in the above frequency range. Measured values at a selected frequency of 4 Hz are utilized. The measured change in sample length at the 1100 kPa effective stress together with the information on the initial porosity was used to estimate the porosity or void ratio at this effective stress using the formulation in (Seabrook and Boadu, 2002). The effective stress is the normal effective stress.

### 3.3.4 Electrical Parameters

The relations between the textural properties of the natural soils and the electrical parameters characterizing their electrical response are investigated. The fundamental electrical parameters were extracted from electrical measurements at 4 Hz and at an effective stress of 1100 kPa. The parameters are the resistivity amplitude ($\rho$), phase ($\Phi$), percent frequency effect (PFE), loss tangent ($\tan \delta$), and the normalized phase ($\Phi_N$).

The resistivity amplitude ($\rho$) and phase ($\Phi$) are obtained from the real and imaginary parts of the measured complex resistivity and given as:

$$
\rho = \sqrt{(Z'(\omega))^2 + (Z''(\omega))^2} \quad (3-5)
$$

and

$$
\Phi = \tan^{-1}\left(\frac{Z''(\omega)}{Z'(\omega)}\right)
$$
\[ \Phi = \arctan(z''(\omega)/z'(\omega)), \]  

(3-6)

where \( \omega \) is the angular frequency, and \( z' \) and \( z'' \) are the real and imaginary parts of the complex resistivity.

The percent frequency effect (PFE) is estimated from the difference in resistivity amplitude (simply referred to as resistivity hereafter) measured at two frequencies \( f_1 \) (low) and \( f_2 \) (high) \([f_1 < f_2]\), normalized by the resistivity taken at the higher frequency (Reynolds, 1997). The low and high frequencies were selected to be 1 Hz and 8 Hz respectively.

The loss tangent \( \tan \delta \) is a measure of the amount of energy transferred to the soil sample from the electric field due to DC conduction and polarization processes. It is defined as the ratio of the real part of complex resistivity to the imaginary part of complex resistivity. The normalized phase is simply the ratio of the phase shift to the resistivity amplitude.

### 3.3.5 Statistical Methods

The relationships between the electrical parameters and the textural properties were explored using statistical analysis. In using the measured electrical parameters to predict the textural properties of the soils, the accuracy and reliability of the relationships are quantified using the coefficient of determination \( R^2 \) (equivalent to the square of the correlation coefficient) and the standard error of estimate \( Se \) or the root
mean squared error. The coefficient of determination equals the percentage of the variance in the estimated criterion variable that is explained by the predictor variables and thus is an indicator of the accuracy of predictions and reliability of the model equations. The magnitude of the standard error of the estimate on the other hand is a physical indicator of the error between the measured and predicted values (Draper and Smith, 1981). In quantifying the relationships, the notation $R^2$, $Se$ is used to indicate a relationship with the respective coefficient of determination and standard error of the estimate.

3.4 Electrical and Textural Properties Relationships: Analysis and Discussions

The sections that follow discuss the influence of the textural properties, that is, fines content, pore size parameter, specific surface area and fractal dimension of the GSD on the electrical parameters describing the electrical behavior. Cross-plots of the electrical parameters and textural properties are used to provide valuable insights into the relationships and dependencies between the two parameter groups.

3.4.1 Resistivity Amplitude Relations

The influence of fines content, pore size parameter, specific surface area and the fractal dimension of the GSD on the amplitude of resistivity are shown in Figures 3.1(a)-(d). Generally resistivity is found to decrease with increasing fines content ($F_c$) with two recognizable trends. The first segment $F_c < 18\%$ has a negative slope of 4.9 whiles the
second segment $F_c > 18\%$ has a lower negative slope of 1.6. For samples with fines content less than 18\% (open circles), the resistivity values decrease sharply with increasing fines and thus a small addition of fines in this range causes a large decrease in resistivity. However, as the fines content increases beyond 18\% (dark circles), the sensitivity lessens and the resistivity values decrease slowly with increases in fines. Resistivity or conductivity is influenced by both electrolytic and surface conduction processes (Reynolds, 1997), and the general decrease in resistivity observed is as a result of an additional increase in overall conductivity due to an increase in surface conductivity.

Figure 3.1: Plot showing variation of resistivity amplitude with (a) fines content ($\rho = 147\exp[-0.08\, F_c]$, $R^2 = 0.89$, $Se = 9.7$) (b) pore size parameter ($\rho = 1393\, \delta_p^{-15}$, $R^2 = 0.83$, $Se = 11.9$) (c) specific surface area per unit mass ($\rho = 189\exp[-0.03S_m]$, $R^2 = 0.87$, $Se = 10.5$) and (d) fractal dimension of the GSD ($\rho = 470 - 173D_f$, $R^2 = 0.75$, $Se = 15$). Legend applies to all parts of the figure.
The variation of resistivity with fines content can be explained in the context of how the amount of fines influences the void ratio. At higher void ratios, the conduction process is largely electrolytic due the availability of open pores and low percentage of fines. However, as the void ratio decreases due to increase in fines (Figure 3.2) which has smaller grain sizes, pores get filled and increases the tortuosity. The electrolytic conduction process thus gives way to surface conduction due to an increase in polarization sources (fines) and the potential constriction of pores. One can ascertain that there is a critical fines content (or void ratio) at which this transition in conduction process manifest and this critical transition value is roughly about 18% fines content ($\approx 0.46$ void ratio). This may well be the reason why the sensitivity of resistivity to changes in fines content in soils is greater when the fines are less than 18% by weight, that is, when few polarization sources are present. Given that the value of 18% is within the range of values (17-34%) of fines content reported in the literature to alter the strength behavior of soils (Monkul and Ozden, 2007; Yang et al., 2005; Chien et al., 2002), this relation could be important in strength assessment of soils.
Figure 3.2: Plot illustrating variation of void ratio with fines content for the studied soil samples at a constant stress level.

The variation of pore size with resistivity is shown in Figure 3.1(b) where resistivity increases linearly (0.83; 11.9) with pore size. The ability of pores to hold or transmit fluid in the soils depends on their sizes. In general, fine textured soils with relatively high fines content have relatively smaller pore sizes while coarse textured soils have larger pores. Higher fines content and smaller pore sizes imply less likelihood of interconnected pores and thus conductivity is largely due to surface conductance rather than electrolytic conductance. As pore size increases, electrolytic conductance dominates. The relationship of pore size with resistivity may provide some valuable information about inter-connectivity of the pore spaces.
Figure 3.1(c) shows the variation of resistivity with increasing specific surface area ($S_m$) in which the resistivity decreases with increasing $S_m$. The specific surface area increases with increasing fines content and has been shown to correlate with residual strength (Tiwari and Marui, 2005). The $\rho$-$S_m$ relationship tends to have the same trend as resistivity-fines content relation with the transition point around 18% fines content. It can also be observed that beyond the $S_m$ value of 100 m$^2$/kg, the resistivity values are virtually insensitive to increase in $S_m$.

The relationship between resistivity of the soils and the fractal dimension of their GSD is also investigated [Figure 3.1(d)]. Resistivity is found to decrease linearly (0.74; 15) with an increase in the fractal dimension. Conceptually, fragmentation processes described by Turcotte (1986) suggest that a multiplicative cascade process with a high fragmentation rate produces fragments (soil grains) with a higher fractal dimension. The fractal dimension obtained could thus be used as a measure of fragmentation. A higher fractal dimension would imply greater fragmentation and a tendency to create higher fines content. This concept has been used by Boadu and Long (1994) to explain fragmentation processes in rocks. An increase in the rate of fragmentation will relatively increase the fines content as well as the fractal dimension (Boadu and Long, 1994) which will result in a decrease in resistivity. Fractal dimension has been found to bear a reasonable correlation with the hydraulic properties of soils in comparison to say their...
mean grain size (Boadu, 2000). Fractal character of the GSD of the soils implies that across a wide range of scales, the solid particles appear to be self-similar.

### 3.4.2 Phase Relations

The phase characteristics of complex resistivity measurements on the soil samples are influenced by the distribution and the amount of polarization sources that are inherent in the sample. Clay minerals in the fines act as polarization sources due to their high CEC and specific surface area and contribute to the phase shift. The silt particles with their high specific surface area also induce polarization (Schön, 2004) and contribute to the overall phase shift. The values of the phase shift are relatively small when free electrolytic paths dominate over ion-selective paths. The ion-selective paths could be zones which are typically an aggregate of clay minerals or contact between two adjacent clay-coated sand grains. As shown in Figure 3.3(a), phase values barely increase with increasing fines content up to 18%. However, beyond 18% fines content, the phase increases more sharply with an increase in the amount of fines.

Complex resistivity measurements on sandstones by Scott and Barker (2003) indicate that the peaks of the phase spectra closely correlate to their pore-throat sizes. It is observed here that for smaller pore sizes (< 0.03 mm), the phase values decrease sharply with increase in pore size with a huge negative slope of 3202 [Figure 3.3(b)]. However, for sizes greater than 0.03 mm, the phase values are virtually insensitive to
increase in pore size with a relatively insignificant negative slope of 7.3. This is the situation where total conductivity is expected to be largely dominated by electrolytic conductance due to through-going or connected pores, with minimal contribution due to surface conduction process. Existence of smaller pore sizes is generally indicative of higher fines content, thus a greater likelihood to constrict pores and enhance membrane polarization. This situation will produce relatively higher phase values (Schön, 2004).

Figure 3.3: Plot showing variation of phase shift with (a) fines content ($\Phi = 11.67 \exp[0.087 F_c]$, $R^2 = 0.76$, Se = 37.5) (b) pore size parameter ($\Phi = 1.19 \delta_p^{[-1.19]}$, $R^2 = 0.65$, Se = 45.1) (c) specific surface area per unit mass ($\Phi = 39.3 \exp[0.011 S_m]$, $R^2 = 0.38$, Se = 59.6) and (d) fractal dimension of the GSD ($\Phi = 0.0004 \exp[4.8 D_f]$, $R^2 = 0.64$, Se = 45.4). Legend applies to all parts of the figure.
The specific surface area $S_m$ - phase relationship is observed in Figure 3.3(c) in which phase values increase with increasing $S_m$ for values up to 70 m$^2$/kg, beyond which there is a considerable scatter. The overall $R^2$ value is 0.38 with a Se of 59. The erratic scatter in the relationship implies that beyond this transitional $S_m$ value, other relevant physical factors may be contributing strongly to the phase relationship. A similar relationship has been observed between imaginary conductivity and specific surface area per unit volume for sand-clay mixtures by Schön (2004). The specific surface area is influenced by the fines contents and density of the solids and it is inversely proportional to permeability of the soils.

Variations of the fractal dimension associated with the distribution of the soil particles and the phase shifts are illustrated in Figure 3.3(d). The phase is observed to increase exponentially (0.64; 45) with increasing fractal dimension. There is a minimal change in phase values as the fractal dimension approaches 2.4, beyond which there is a large increase in phase values with fractal dimension. Higher fractal dimension is indicative of large range of composition of grain sizes; and as the soils become more heterogeneous, the polarization process is enhanced by virtue of the phenomenon known as the Maxwell-Wagner effect, resulting in an increase in the phase values (Reynolds, 1997; Schön, 2004).
3.4.3 Percent Frequency Effect Relations

The percent frequency effect (PFE) is plotted as a function of the textural parameters, that is, fines content [Figure 3.4(a)], pore size [Figure 3.4(b)], specific surface area [Figure 3.4(c)], and fractal dimension [Figure 3.4(d)]. As can be observed there is considerable scatter in all four crossplots, unlike the crossplots for resistivity and phase relations. The PFE represents changes in amplitude spectrum with frequency, and low values indicate insensitivity of the amplitude to frequency changes. Weakly, PFE increases exponentially with increase in fines content (0.53, 5.7), decreases with an increase in pore size (0.34, 6.8), increases with increase in specific surface area (0.44, 6.3) and increases with increase in fractal dimension (0.41, 6.4). These inherently weak relationships imply that PFE as a characteristic electrical parameter may not be particularly very useful in predicting or assessing the textural properties of soils.
3.4.4 Loss Tangent Relations

The influences of textural properties of the soil samples on their loss tangents or dissipation factors are observed in Figure 3.5(a)-(d). As the amount of polarizable sources (fines content) increases, energy dissipation is expected to lessen since the capacity of the soil medium to store energy increases. This phenomenon is observed in Figure 3.5(a) as the loss tangent decreases linearly with increasing fines content (0.76; 6.1). Increasing pore size is associated with loss of fines and increases the energy dissipation as soils lose their capacity to store energy. Thus the loss tangent increases with an increase in pore size [Figure 3.5(b)]. Soils also become less dissipative as their
specific surface area increases as shown in Figure 3.5(c), in which the loss tangent decreases with increase in $S_m$. Increase in $S_m$ increases the number of particles per unit volume with the tendency to narrow or constrict the pores. This potentially reduces the permeability or ease of fluid flow through such soils with a corresponding decrease in loss tangent. Increasing heterogeneity of soils as indicated by fractal dimension due to an increase in fines results in lower dissipation of energy (lower loss tangent), as seen in Figure 3.5(d). The loss tangent decreases linearly with increase in the fractal dimensions characterizing the distribution of the grain sizes with an $R^2$ of 0.62 and $Se$ of 7.7.

Figure 3.5: Plot showing variation of loss tangent with (a) fines content ($\tau = 48.2 - 1.23 \times FC$, $R^2 = 0.76$, $Se = 6.1$) (b) pore size parameter ($\tau = 430.7\delta_p + 3.2$, $R^2 = 0.59$, $Se = 8.1$) (c) specific surface area per unit mass ($\tau = 63.9 \exp[-0.02 \times S_m]$, $R^2 = 0.68$, $Se = 7.1$) and (d) fractal dimension of the GSD ($\tau = 181.6 - 64.4 \times D_f$, $R^2 = 0.62$, $Se = 7.7$). Legend applies to all parts of the figure.
3.4.5 Normalized Phase Relations

Normalized chargeability as proposed by Keller (1959) has been found to be closely related to lithologic factors and has been used to distinguish IP effects due to lithology from IP effects due to salinity (Lesmes and Frye, 2001). In this work, the ratio of the phase angle to the resistivity amplitude (\(\Phi/\rho\)), termed normalized phase (\(\phi_N\)), was extracted from the complex resistivity measurements made on the soil samples, and its relations with the textural properties were analyzed. Normalizing induced polarization (IP), e.g., chargeability with resistivity helps to detect the changes in lithology (Slater and Lesmes, 2002) because the normalized IP is more directly related to the pore/grain surface properties. The relationships observed between the normalized phase and soil properties are shown in Figures 3.6(a)-(d).

The relationship between the normalized phase (\(\phi_N\)) and fines content is observed in Figure 3.6(a), in which \(\phi_N\) is insensitive to increase in fines content till a critical value of roughly 18% when it starts to increase exponentially with an increase in fines content. The increase in values of \(\phi_N\) with fines content is very smooth and non-chaotic with an \(R^2\) of 0.98 and \(Se\) of 2.9, indicating that the variation in \(\phi_N\) is well explained by the amount of fines in the soil. The values of \(\phi_N\) drop sharply to small values (i.e., from 100 to 3) as the pore size parameter increases to a value 0.03 mm [Figure 3.6(b)]. Beyond this value, the \(\phi_N\) values remain small and insensitive to
increases in pore size values. Higher values of $\phi_N$ are associated with fines-rich soils of smaller pore sizes. Variations of $\phi_N$ with specific surface area [Figure 3.6(c)] indicate that for relatively small values of the specific surface area ($< 70 \text{ m}^2/\text{kg}$), values of $\phi_N$ are relatively small and insensitive to increases in the values of the specific surface area. The relationship however becomes chaotic beyond this value of 70 m$^2$/kg. Low values of $\phi_N$ are associated with soils having fractal dimension less than 2.5 [Figure 3.6(d)]. For soils with fractal dimension greater than 2.5, values of $\phi_N$ increases but with no defined relation with the fractal dimension.

Figure 3.6: Plot showing variation of normalized phase with (a) fines content ($\phi_N = 0.013\exp(0.24F_C)$, $R^2 = 0.98$, $Se = 2.9$) (b) pore size parameter ($\phi_N = 149\exp(-95\delta_p)$, $R^2 = 0.38$, $Se = 17.2$) (c) specific surface area per unit mass ($\phi_N = 3.24\exp(0.018S_m)$, $R^2 = 0.29$, $Se = 18.3$) and (d) fractal dimension of the distribution of the grain sizes ($\phi_N = 0.0000012\exp[6.3D_f]$, $R^2 = 0.32$, $Se = 17.9$). Legend applies to all parts of the figure.
In assessing the relations between $\phi_N$ and the textural properties of soils, one can ascertain that the $\phi_N$ tends to be enhanced by the properties contributing to polarization of the medium. Thus, the crossplot of the real part of complex resistivity and phase is used to provide a distinctive discrimination of ranges in the fines content in soils as shown in Figure 3.7. This allows enhancement of textural discrimination and isolates the high and low ranges of fines content in the real resistivity - phase plane. Soils with high fines content (> 18%) plot in the interval 45-270 mrad and 0-25 Ωm whereas soils with low fines content (< 18%) plot in the interval 0-55 mrad and 25-110 Ωm.

Figure 3.7: Cross plot of real resistivity and phase illustrating how the amount of fines can be qualitatively assessed in the real resistivity - phase space.
3.5 Conclusions

Geophysical techniques are non-invasive and cost effective. These techniques if carefully utilized can be useful in assessing and monitoring the textural properties of near surface unconsolidated geomaterials (e.g., soils) that are known to affect their stability and strength. The properties of the soils in question include fines content, void ratio, pore size parameter, specific surface area and fractal dimension of the GSD of the soil. Measurements of complex resistivity on thirty-two soil samples obtained from sites with parent rocks of different geologic origins have been undertaken. The soils have been characterized by extracting their textural properties in question. Through laboratory experiments, the influence of these useful textural properties on the electrical parameters describing the electrical behavior of the soils at 4 Hz and constant effective stress of 1100 kPa is investigated. The electrical parameters which describe the electrical behavior of the samples - resistivity amplitude (ρ), phase (Φ), percent frequency effect (PFE), loss tangent (tan δ), and the normalized phase (φ$_N$) - are obtained from the electrical measurements. It is observed that ρ and tan δ values are influenced by variations in the textural properties ($R^2 > 0.60$), whereas the PFE values are fairly insensitive ($R^2 < 55$). There are characteristic transitional values of the fines content (18%) and pore size (0.03 mm), beyond which the phase and normalized phase values are insensitive to their increases. This characteristic transitional value of 18% of fines content
is close to reported values in prior studies at which significant changes in the mechanical properties of soils occur. Hence, the identification of the resulting changes in these electrical properties associated with the transitional values of the textural properties could be useful in non-invasive assessment and monitoring of the mechanical response and strength of soils. The phase and real resistivity values are used to assess the relative amount of fines in soils and such an assessment can be useful in stability analysis and in evaluation of the liquefaction potential of soils. This study will contribute to the knowledge of how fundamental engineering properties of soils influence their electrical responses and will be very useful in the geophysical interpretation of field measurements.

3.6 Acknowledgements

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4 Investigating the Deformational and Structural Changes in Unconsolidated Earth Materials using Complex Resistivity Measurements

4.1 Abstract

The internal structural modifications of near surface earth materials, due to changes in its water content and effective stress condition, influence their geotechnical engineering behavior and stability conditions. The ability to characterize and monitor these modifications non-invasively using geophysical techniques would be useful in geotechnical engineering investigations. In this study, the deformational characteristics and complex resistivity response of sand-clay mixtures subjected to external loading are concurrently measured at various effective stress levels. The experimental setup consists of a modified oedometer with outlets for sample vacuuming, saturation and drainage, and is also equipped with pore pressure transducer, strain gauge and electrodes for electrical measurements.

Relevant electrical parameters including resistivity amplitude, phase, capacitance, and loss tangent extracted from the complex resistivity measurements, were observed to be sensitive to the structural changes occurring in the soil during the consolidation process. The resistivity amplitude and capacitance were found to reveal a characteristic transition when the effective stress conditions of the soils progresses from
low to high levels. This transition occurs around the liquid limits of the samples. Liquid limit has been reported in previous studies to indicate the water content at which a slow drying clay slurry start to develop shear strength, and thus this relation could be useful in monitoring the strength of soils.

Analysis of the plot of $\frac{d e}{d \log \sigma}$ (ratio of the change in void ratio to the change in logarithm of effective stress) versus $\sigma$ (effective stress) revealed two different zones, with the variation (or shape) of the $\frac{d e}{d \log \sigma}$ with $\sigma$ in the first zone dependent on the clay content and initial void ratio. The relationship between strain and effective stress and that of resistivity and effective stress are found to follow the same trend, suggesting the possibility of using resistivity amplitudes in estimating the compressibility of soils. Significant relations are also found between the electrical parameters and the deformational properties such as strain, as well as the dry density of the sample. These soil properties influence the engineering behavior of earth materials, and thus the observed relations provide a means for using electrical measurements in assessing and monitoring the engineering behavior of the subsurface.

4.2 Introduction

Modifications in the internal structure of near surface earth materials, due to changes in its water content and effective stress condition, influence their geotechnical engineering behavior and stability conditions. The ability to characterize and monitor
these modifications is essential to ensuring the lifetime integrity of sensitive structures and mitigating geohazards. It would even be more valuable if geophysical techniques, which are cheaper to perform and provide large scale information of the earth subsurface non-invasively, could be utilized for such investigations. Surface geophysical methods have been useful in providing preliminary surveys to locate potentially problematic geologic or soil conditions, and in identifying and delineating specific features of interest (e.g., sinkholes). Meric et al. (2005) used combined geophysical techniques to investigate large gravitational mass movement and their results suggest that monitoring the evolution of rock mass movement with time-lapse geophysical surveys could be beneficial. Neisner (2010) recently confirmed the feasibility of using repeated resistivity measurements as an integral part in an early warning program for landslides. He indicated that resistivity measurements have the ability to detect potentially unstable conditions of the earth subsurface before the actual failure occurs.

To effectively use electrical resistivity measurements to monitor the stability conditions of the earth subsurface will however require adequate understanding of how changing state of soil and its deformational characteristics relate to their electrical responses. Mitchell and Soga (2005) indicated that, the frictional resistance between soil particles in contact is one of the basic factors responsible for soil strength. The magnitude of this resistance is however dependent on external constraints such as
applied stress and internal factors including texture, mineralogy, void ratio, pore fluid type and content. For sands, void ratio is perhaps the most important parameter that affects its strength (Holtz et al., 2010). Thevanayagam (1998) reported that intergranular void ratio play an important role on the undrained shear strength of silty sands while Bell (2000) indicated that, water content is a major factor influencing the strength of soils.

For fully saturated soils, changes in its water content generally correspond to changes in the void ratio provided adsorbed water, usually attracted to its clay constituent, are not expelled out. Relationships between water content and shear strength showed that soils with higher liquid limits generally have lower shear strengths (Youssef et al., 1965). Liquid limit is the water content beyond which soil changes from plastic state to liquid state (Holtz et al., 2010). Wroth and Wood (1978) also found the undrained shear strength of soil to be dependent on its liquidity index (an index for scaling the natural water content of soils), with higher liquidity index values implying lower strength. The aforementioned research works show that changes in the structure and pore content of soils which manifest as measurable deformational and hydraulic properties will affect the stability conditions of soils.

Electrical conduction in a saturated soil medium results from the movement of free and adsorbed ions in its pore space (ionic conduction), and polarization along pore
grain interfaces (surface conductance) [Schön, 2004; Reynolds, 1997]. The volume and content of the pore space of soils therefore influences its electrical responses. Consequently, characteristic changes in the pore space and structure of porous media, which have been noted to control their engineering behavior and stability conditions, will give rise to distinctive electrical resistivity responses (Schön, 2004). Arulanandan et al., (1983) observed a linear relationship between the magnitude of dielectric dispersion, an electrical parameter, and the compression index. The compression index is used in estimating the amount of settlement of soils. A few studies have also been reported relating electrical resistivity measurements to degree of compaction and consolidation behavior for specific soil types (McCarter and Desmazes, 1997; McCarter et al., 2005). Boadu and Owusu-Nimo (2010) have also explored the relations between fundamental electrical parameters of soils and their engineering properties.

In this study, laboratory measurements were conducted on saturated sand-clay mixtures subjected to loading and under controlled drainage. The deformational characteristics and complex resistivity responses of the soils were concurrently measured at various effective stress levels. The influences of changing effective stress conditions of the various soil samples on their electrical resistivity responses were investigated. The relationships between electrical parameters derived from the electrical responses and the deformational and hydraulic properties measured during the
consolidation process were also analyzed. The electrical parameters considered include resistivity amplitude, phase, capacitance and loss tangent, and the deformational and hydraulic properties include axial strain, dry density, void ratio, and intergranular void ratio. The study provides a better understanding of how changing state of soil and its deformational characteristics can be captured from electrical response measurements. The insights and understanding gained from the laboratory measurements will be useful in achieving the ultimate goal of using non-invasive geophysical methods in the assessment and monitoring of potential instabilities in unconsolidated geomaterials.

4.3 Experimental Testing System

To adequately carry out this investigation, a testing cell with features to allow concurrent measurement of the deformational properties of soils during consolidation and their attendant complex resistivity responses was developed. The testing cell incorporates most of the features in other custom testing systems developed by other researchers (McCarter and Desmazes, 1997; Bryson and Bathe, 2009; Comina et al., 2008) and a full description and its calibration is given in section 1.4.2.

4.4 Experimental Procedure

Samples for the experiment were prepared by mixing Ottawa sand with 0%, 2%, 5% and 10% clay (Na-Bentonite) by weight and saturated with a known amount of de-aired tap water (~ 50 Ωm). Each of the sand-clay mixtures was placed in the modified
oedometer cell and further saturated with water to beyond its liquid limit. The top platen is placed in position and the sample is subjected to an axial stress of 500 kPa while sample is kept undrained. An initial pore pressure equivalent to the applied stress is generated in the sample because of its high water content. The initial water content of the sample is estimated based on the amount of water used for saturation and the weight of solids used. The initial length of the sample after loading is also measured.

The experiment is then conducted under controlled drainage, where water is gradually expelled from the sample. Under a given load, expelling water from the sample reduces its pore water pressure and increases its effective stress. Water is expelled to generate effective stresses of about 20, 30, 50, 100, 200, 350 and 480 kPa. At each of the effective stresses, the strain and amount of water expelled from the sample is noted and the complex resistivity of the sample after the pore pressure has equilibrated is measured. The effective stresses are the normal effective stresses. The final water content of the sample after completion of the experiment is also determined. The electrical measurements were conducted utilizing E1 electrode configuration (Figure 1.5) at a frequency of 8 Hz with a GDP 32 transmitter –receiver. The receiver calculates the standard error of each measurement in real time, which can be used to confirm the data quality during measurements. A sketch of the oedometer apparatus connected to the electrical measurement system (GDP-32 digital multifrequency controller-
transmitter/receiver) and a PC is shown in Figure 1.4. The laboratory setup simulates a field condition of changing effective stress or soil state at a particular depth in the earth subsurface.

4.4.1 Estimating Soil Properties

The soil properties obtained during the consolidation process include axial strain, dry density, void ratio, and intergranular void ratio. The axial strain ($\varepsilon_i$) at an effective stress level $i$, which gives a measure of sample deformation, was determined from the ratio of the change in length or vertical deformation at that effective stress to the initial length of the sample. The porosities ($\Phi_i$) of the samples at each effective stress level were then determined from the measured axial strains ($\varepsilon_i$) and the initial porosity ($\Phi_o$) using the equation;

$$\Phi_z = \Phi_o - \varepsilon_i \frac{1}{1-\varepsilon_i}. \quad (4-1)$$

The initial porosities of the samples were determined from their initial volumes ($V_T$) and their matrix-specific weight using the expression;

$$\Phi_o = \frac{V_T - W_M/\gamma_M}{V_T} \quad (4-2)$$

where $W_M$ and $\gamma_M$ are, respectively, the total weight and density of the soil matrix used for the experiment. The void ratio ($e$) is related to the porosity of the soil via $e = \Phi/(1-\Phi)$. 

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The dry density, which indicates the extent of inter-particle contacts within the soil grains, was obtained from the ratio of the mass of the soil grains to the volume of the sample at each effective stress level.

The liquid limits of the samples were obtained from cone penetrometer test and the water content was obtained by weighing samples before and after oven drying.

4.5 Results and Discussions

The influence of characteristic structural changes occurring in the soil medium during the consolidation process on the electrical response measurements are explored and analyzed. Electrical parameters including resistivity amplitude, phase, loss tangent and capacitance were extracted from the complex resistivity measurements. The resistivity amplitude ($\rho$) and phase ($\varphi$) are obtained from the real and imaginary parts of the measured complex resistivity and given as:

$$\rho = \sqrt{(Z'(\omega))^2 + (Z''(\omega))^2} \quad (4-3)$$

and

$$\varphi = \arctan(Z''(\omega)/Z'(\omega)) \quad (4-4)$$

where $\omega$ is the angular frequency, and $Z'$ and $Z''$ are the real and imaginary parts of the complex resistivity. The loss tangent is obtained from the ratio of the real part of complex resistivity to the imaginary part of complex resistivity whiles the capacitance
$C(\omega)$ is related to the complex resistivity ($Z^*$) via the relation $C(\omega) = 1/[i\omega Z^*(\omega)]$ (Czichos et. al., 2006). The values of the electrical parameters obtained for the various samples were normalized by the highest measured value of that electrical parameter. Normalizing the measured electrical values keep them in the range of 0 and 1. This enables the electrical response of all the samples to be analyzed on the same plot, revealing their distinct relationships with the deformational parameters.

### 4.5.1 Influence of Effective Stress on Electrical Parameters

The effective stress condition of a soil medium is indicative of the magnitude of interparticle contact forces existing in the medium and therefore provides information on the strength of the soil (Mitchell and Soga, 2005). Changes in the effective stress condition of soils result in characteristic structural changes which reflect in measurable soil properties such as void ratio and dry density. When soil samples are saturated beyond its liquid limit there are virtually no grain to grain contacts. Loading such samples under undrained conditions therefore result in very low effective stress conditions within the sample. As the sample is allowed to drain, there is a gradual increase in effective stress due to reduction in pore water pressure and enhancement of soil particle contacts. This increasing effective stress changes the structural characteristics of the soil resulting in increased soil strength (Duncan and Wright, 2005).
The structural changes in soils due to changing effective stress conditions influence their electrical conduction by controlling the movement of ions through the fluid-filled pore space (electrolytic conduction) and the movement of surface charges at the interface between the soil particles and pore fluid (surface conduction). Thus, changes in the effective stress conditions of soils, resulting from its structural changes, give rise to distinctive electrical responses. Figure 4.1(a-d) shows the influence of changes in effective stress of soil samples with varying clay content on their electrical parameters. Resistivity amplitude is observed in Figure 4.1(a) to decrease with increasing clay content. Increasing the amount of clay decreases the resistivity because higher concentration of ions absorbed on surfaces of clay particles tends to increase the surface conductivity. Secondly, when clay is added to sand, ions from the clay may combine with ions from the mixing fluid (this was the case in this study) and this increases the pore fluid conductivity. Increasing the amount of clay therefore increases the conduction process leading to the observed lower resistivity response.

Resistivity amplitude values are also observed to generally increase with increasing effective stress with two recognizable trends for the samples containing some amount of clay. The different trends (sharp and gentle slopes) observed are indicative of the pore volume and water content changes in the soil medium. The first segment (open markers) of each variation corresponds to sample with water content beyond its liquid
limit whiles the second segment (dark markers) are for sample with water content below its liquid limit. The figure suggests that the transition occurs around the liquid limit of the samples. Resistivity amplitude is shown to be sensitive to this transition (suspension like to frame support) and could be useful in monitoring the strength of soils non-invasively. Wood and Wroth (1976) reported the development of small but definite shear strength of about 1.7 kN/m\(^2\) at the liquid limit of slow drying clay slurry.

The observed change in the sensitivity of resistivity with increasing effective stress at this transition is as a result of the change in electrical conduction process due to the structural changes in the soil. For the first phase (open markers), the increase in resistivity is mainly due to a decrease in the voids and the corresponding decrease in electrolytic conduction. As the voids decrease and the solid grains begin to have contacts surface conduction process as well as conduction through the soil matrix increases while the electrolytic conduction decreases. This change in conduction process changes the sensitivity of resistivity with effective stress which is observed in the second phase (dark markers).
Figure 4.1: Plot showing influence of effective stress changes of samples from high to low water contents on (a) Resistivity (b) Phase (c) Loss tangent (d) Capacitance. Open markers implies water content greater than liquid limit; Dark markers for water content less than liquid limit.

The influence of effective stress on the Phase [Figure 4.1(b)], Loss tangent [Figure 4.1(c)] and Capacitance [Figure 4.1(d)] are also examined. Clay minerals with an electrically negative charged surface, when in contact with ionic solutions attract excess cations forming an electric double layer (EDL). The double layer consists of a fixed positive charge immediately adjacent to the clay surface termed the Stern layer and a diffuse mobile layer. The EDL establishes an electric potential through the pores which blocks or impedes the passage of ions resulting in membrane polarization measured as the phase response. The phase values for clay free samples are observed to be relatively
small because of the dominance of free electrolytic paths. The presence of clay however creates ion selective paths which induces polarization and increases the phase response values. As the clay content increases and becomes spatially continuous, the surface area required for ion exchange diminishes leading to a decrease in phase response.

As shown in Figure 4.1(b), at lower effective stresses (open markers), when the water content is above the liquid limit, the phase values are generally not sensitive to increasing effective stress for the clay containing samples. The phase values however decrease with increasing effective stress at higher effective stress levels (dark markers). As mentioned earlier, negative charges on the surfaces of clay establish an electric potential that extends throughout the pore. The magnitude of this potential is greatest at the pore wall and decreases with distance from the wall. The phase values at lower effective stress (open markers) might be insensitive because the pore sizes might have dimensions which induce generally the same blockage or polarization effect. Boadu and Owusu-Nimo (2010) observed phase values to be relatively insensitive to increase in pore size beyond 0.03 mm in their study of natural soil samples. Further increase in effective stress, which decreases the pore size or water content considerably, limits the ions available for polarization process resulting in a decreased phase value. Scott and Barker (2003) reported a decrease in the phase magnitude with decreasing pore-throat size of sandstone samples.
The response of loss tangent to changing effective stress conditions presented in Figure 4.1(c) reveal similar relationships, albeit inversely, as the phase response. The loss tangent gives a measure in relative terms, of energy transferred to a sample from the electric field due to DC conduction and polarization processes and is proportional to the energy dissipation in a soil medium (Campbell, 1990). Decreasing conduction and polarization processes result in an increase in the loss tangent due to increase in energy dissipation.

The capacitive response of the soil samples to changing effective stress conditions, shown in Figure 4.1(d) is also analyzed. The capacitance account for the amount of charges accumulated or stored in the soil medium, and is observed to increase with increasing clay content. Increasing clay content increases the fluid conductivity due to leachate of ions from the clays to the pore fluid. As the fluid conductivity increases, the ion density increases near the pore surface resulting in a lower ionic mobility. This limitation in ion movement leads to an increase in capacitance. The capacitance values are also found to generally decrease with increasing effective stress for all samples with clay. As the void ratio and thus water content reduces due to increase in effective stress, there is a decreased availability as well as accessibility of the electrolyte ions to the surface of the porous system resulting in a decrease in capacitance values.
4.5.2 Analysis of the Structural Changes in Soil due to Changing Effective Stress

The structural changes in the soils as a result of changing effective stress is further explained by considering the intergranular void ratio ($e_g$) which have been reported to play an important role on the undrained shear strength of soils (Thavanayagam, 1998). It is considered to be an index of active coarser-granular frictional contacts that sustain the normal and shear forces. The relationship between $e_g$ and effective stress is given in Figure 4.2(a). For all clay containing samples, the $e_g$ is observed to decrease sharply with increasing effective stress till a transition point when there is a slow decrease, creating two different response zones. The rapid change in the $e_g$ at lower effective stresses (open markers) is due to the closure of pores (water loss) before the inception of grain contacts. A further increase in effective stress, results in particle rearrangement which decreases the $e_g$ but to a lesser extent. The two different zones observed can further be elucidated by analyzing the plot of $de/d\log \sigma$ (ratio of the change in void ratio to the change in logarithm of effective stress) versus $\sigma$ (effective stress) shown in Figure 4.2(b). It is observed that in the first zone (dotted lines), the variation of $de/d\log \sigma$ with effective stress depends on the amount of clay present and the initial void ratio. For samples with higher clay content (10%), the slope ($de/d\log \sigma$) is observed to increase with increasing effective stress and then decreases. Increasing the amount of clay in the sample increases the initial void ratio and thus water content. A
small application of stress therefore results in a higher change in the voids resulting in the initial increase in slope. The slope however decreases as the particles begin to have contacts, thereby decreasing the change in void ratio. Samples with low clay content (2%) on the other hand, have relatively low initial void ratio and thus a little application of stress results in particle contacts, thus limiting the reduction in voids. This shape of the slope in the first zone thus give an indication of particle to particle contacts in the soil medium, with decreasing slope indicating near particle to particle contact.

Figure 4.2: (a) Variation of intergranular void ratio with effective stress. (b) Plot of $\frac{d\rho}{d\log \sigma}$ against effective stress
Figure 4.3: Relationship between effective stress and (a) Strain (b) Resistivity.

The effect of structural changes due to effective stress on the electrical parameters, specifically resistivity amplitude, is investigated by considering the axial strains and the relative change in porosity. The relationship between strain and effective stress and resistivity and effective stress is given in Figure 4.3(a-b). Strains are observed to increase sharply (exponentially) with increasing effective stress till a transition point, after which the strains barely increase for all the samples. The increasing strain at the lower effective stress levels (< 100 kPa) is mainly due to closing down of pores. After the transition point, there is minimal pore closure since particles are in contact and thus the soil sample becomes less compressible. A similar trend is captured in the resistivity-effective stress relationship [Figure 4.3(b)], indicating that resistivity can be used to infer
the structural changes in the soil being manifested as strains. This demonstrates the possibility of using resistivity amplitudes in estimating the compressibility of soils.

The influence of structural changes in the soil medium on the electrical conduction process indicated in the measured resistivity is explained by fitting an exponential model of the form \( a \times \exp(-bx) + c \) to the data points, with \( x \) being effective stress. The model parameters \( a, b, \) and \( c \) and the coefficient of determination \( R^2 \) for the various samples are given in Table 4.1. The measured fluid resistivity of the samples is also given in the table.

**Table 4.1: Parameters of resistivity – effective stress model.**

<table>
<thead>
<tr>
<th>Clay Content</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
<th>( R^2 ) (%)</th>
<th>Fluid Resistivity (Ωm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2%</td>
<td>-9.68</td>
<td>0.02753</td>
<td>28.68</td>
<td>96</td>
<td>10.37</td>
</tr>
<tr>
<td>5%</td>
<td>-8.11</td>
<td>0.01324</td>
<td>19.26</td>
<td>99</td>
<td>7.61</td>
</tr>
<tr>
<td>10%</td>
<td>-5.83</td>
<td>0.01354</td>
<td>11.82</td>
<td>99</td>
<td>7.45</td>
</tr>
</tbody>
</table>

For very low clay content (2%), it is expected that at zero effective stress the resistivity of the sample will be that of the fluid and the soil grains. Since the soil grains generally have higher resistivity because of its low clay content, the overall resistivity will be higher than the fluid resistivity. However, for samples with higher clay content (10%) there is a higher electrical conduction through the soil matrix in addition to the
fluid conductivity and thus the overall resistivity may be smaller than the fluid resistivity at low effective stress levels. The model indicates that at higher effective stresses, there is a minimal increase in resistivity for all the soil samples.

Analysis of the correlation between relative change in resistivity and the relative change in porosity also provides interesting results. The relative change in resistivity ($\rho_r$) for each sample was obtained from:

$$\rho_r = \frac{\rho_{\text{max}} - \rho_i}{\rho_{\text{max}}}$$  \hspace{1cm} (4-5)

where $\rho_{\text{max}}$ is the resistivity amplitude at the maximum effective level for a particular sample and $\rho_i$ is the resistivity amplitude at an effective stress level $i$. The relative change in porosity ($\Phi_r$) was also obtained from:

$$\Phi_r = \frac{\Phi_i - \Phi_{\text{max}}}{\Phi_{\text{max}}}$$  \hspace{1cm} (4-6)

where $\Phi_i$ is the porosity at an effective stress level $i$ and $\Phi_{\text{max}}$ is the porosity at the maximum effective stress level for a particular sample. A bilogarithmic plot of relative resistivity change versus relative porosity change is given in Figure 4.4.
Figure 4.4: Plot of relative change in resistivity with relative change in porosity

The figure shows a first approximation to straight lines for each of the samples with coefficients of determination $R^2$ greater than 0.96. The proportionality of the relative change in resistivity to the relative change in porosity indicates how dependent resistivity changes is to porosity changes and thus to structural changes in the soil medium. The amount of clay (2%, 5%, and 10%) in the sample however affects this relationship as indicated by the different slopes (0.40, 0.51, and 0.71 respectively) and they play a vital role in the deformational process. Schön (2004) reported that the value of such slope (cementation exponent) is dependent on the deformational properties of geomaterials. It is observed in Figure 4.4 that the higher the clay content the steeper the slope.
4.5.3 Electrical Parameters Relationship with Soil Properties

The effect of deformational properties (strain and dry density) on the electrical parameters (resistivity amplitude and capacitance) as the samples are consolidated from higher water contents (> Liquid limit) to lower water content (< Liquid limits) are analyzed below.

The measured strains show the compressibility of the sample as it progresses from low to high effective stress conditions. Knowledge of the compressibility of soils is useful in the assessment of its settlement characteristics and in monitoring the densification of soils. It is observed in Figure 4.5(a-b) that the higher the amount of clay in the sample the larger the strains. Samples with higher clay content tend to have higher initial void ratio and hence larger strains after consolidation. The strains are observed in Figure 4.5(a) to increase sharply with increasing resistivity till a transition point when the increase becomes gradual. Before the transition point most of the change in sample length is due to closure of pores whiles the change observed after the transition is due to particle rearrangement. Samples with less clay contents are therefore least compressible after this transition point due to enhanced coarse grain contacts and increased frictional resistance.

Changes in strain values which results from changes in the void ratio and particle rearrangement influences the electrical conduction process. Resistivity increases
with increasing strains due to decrease in void ratio resulting in reduction in pore volume available for electrolytic conduction. For a given value of clay content, the capacitance values also decrease with an increase in effective stress [Figure 4.5(b)]. This is due to the reduction in pore volume and/or change in tortuosity (Garrouch and Sharma, 1994) and the attendant decrease in electrolytic conductivity (Campbell, 1990). The strain-electrical parameters relationships show the possibility of using electrical measurement in assessing the deformational characteristics of soils. The ability of the electrical parameters to predict or detect the transition in strains demonstrate the likelihood of it being use to predict preconsolidation stress. This is the maximum stress that a soil has previously being loaded which marks the start of high compressibility.

The relationship between dry density and the electrical parameters are given in Figure 4.5(c-d). Dry density is used to quantify soil compaction in engineered earth works. For a given soil, an enhanced particle – particle contact would increase the dry density and decrease the void space and hence increase resistivity as observed in Figure 4.5(c). Also, as the dry density of the samples decreases due to poor particle to particle contacts within the soil solids, the capacitance values are observed to increase [Figure 4.5(d)]. These relationships can thus be useful in controlling the quality of soil compaction in the field by utilizing electrical measurements.
4.6 Conclusions

Controlled laboratory experiments were performed to enhance our understanding of how changing state of soil and its deformational characteristics influence their complex resistivity responses. Relevant electrical parameters including resistivity amplitude, phase, capacitance, and loss tangent were extracted from the complex resistivity measurements conducted at various effective stress levels. The
electrical parameters are observed to be sensitive to the structural changes occurring in the soil during the consolidation process. The resistivity amplitude and capacitance was found to reveal a characteristic transition when the effective stress conditions of the soils progresses from low to high levels. This transition occurs around the liquid limits of the samples. The liquid limit has been reported in previous studies to indicate the water content at which slow drying clay slurry start to develop shear strength, and thus these relations could be useful in monitoring the strength of soils. Analysis of the plot of $\frac{de}{d\log \sigma}$ versus $\sigma$ revealed two different zones with the variation of the $\frac{de}{d\log \sigma}$ with effective stress in the first zone depending on the clay content and initial void ratio. The relationship between resistivity and effective stress is also found to follow the same trend as that of strain and effective stress indicating the possibility of using resistivity amplitudes in estimating the compressibility of soils.

Significant relations between the electrical parameters and soil properties such as strain and dry density were also found. The insights and understanding gained from this investigation will therefore be useful in achieving the ultimate goal of using non-invasive geophysical methods in the assessment and monitoring of potential instabilities in unconsolidated geomaterials.
5 Investigating the Role of Fractures in Groundwater Contamination using Azimuthal Resistivity Survey


5.1 Abstract

The role of fractures in nitrate contamination of fractured groundwater aquifers at farmlands within the Akuapem South municipality (Ghana) is investigated using azimuthal square-array resistivity measurements. The study covers seven farming communities where azimuthal resistivity surveys (ARS) are conducted at sites with exposed rocks (outcrops) to measure real and imaginary parts of the electrical conductivity of the rocks which are then used to provide estimates of anisotropic coefficients and fracture porosities. At each outcrop, fracture orientations, apertures and lengths are measured and are used directly to obtain the porosities and specific surface areas of the fractures. Linear regression models are then developed between the specific surface area of the fractures and the electrical parameters. At selected well locations, azimuthal resistivity surveys are performed and the developed regression models are used to estimate porosities and specific surface areas of the subsurface fractures. Groundwater samples are collected from the selected wells to determine the concentration levels of nitrates. The estimated porosities and specific surface areas of the
subsurface fractures correlate with concentration levels of nitrate in the groundwater. The investigations suggest that nitrate concentration levels in groundwater in the study area tend to be higher in wells where the specific surface area of the fracture system is lower. Also, wells with lower fracture porosities tend to have lower concentration levels of nitrates. The establishment of linkages between subsurface fracture parameters obtained noninvasively from surface geophysics and nitrate concentration levels is a useful result that can be utilized in environmental impact assessment in complex fractured terrain such as that of the study area.

5.2 Introduction

Non-invasive characterization of fractured rock mass in the shallow subsurface using geophysical methods has been of growing interest in recent times in the geophysics community. Fractures control the movement of contaminants in the earth’s subsurface and there is the need to develop methodologies to characterize or assess the role of these fractures using non-invasive geophysical methods. Such developments will be useful especially in environmental impact assessment in complex fractured terrain. Farming activities by inhabitants of Akuapem South municipality occur close to dwelling places and the impact of these activities on groundwater quality has been of particular concern. Most of the groundwater wells are shallow and in fractured rock aquifers, and the excessive application of fertilizers to boost production of pineapples
has resulted in nitrate pollution of the groundwater resources. High concentration of nitrates (NO$_3$-N) in drinking water can be detrimental to human health, and is known to cause methemoglobinemia or ‘blue baby’ disorder in infants and unborn babies and other forms of cancer (Leaf and Stevens, 1996). It is for this reason that the World Health Organization (WHO) has set the maximum permissible limit of NO$_3$-N to 8 mg/L.

The underlying rocks in the study area are fractured and provide the reservoir necessary for storage and transmission of groundwater for drinking and domestic use (Dapaah-Siakwan and Gyau-Boakye, 2000; WRRI, 1994). The amount of nitrates from fertilizer application that leaches into the groundwater depends on the type of soil, soil thickness and the climatic (rainfall) conditions. The soil cover over the fractured rocks in the study area is sandy and the thicknesses vary from 0.5 - 2.5 m. Subsurface fractures occur in most parts of the terrain where intense agricultural activities take place. These fractures provide the necessary porosity to function as a high-yield aquifer, and as well, the permeability to control the transport of contaminants in the subsurface. Thus, it is contemplated that the vulnerability of the groundwater to contamination can be reasonably assessed if valuable and characteristic information about the subsurface fractures is available. Aligned vertical fractures cause anisotropic behavior and inhomogeneities in fractured rockmass, and the observed changes in apparent resistivity with azimuth can be interpreted to indicate presence of fracture anisotropy. Azimuthal
resistivity surveys (ARS) employing different electrode configurations have been successfully used to characterize fractured rockmass (Taylor and Fleming, 1988; Ritzi and Andolsek, 1992; Lane *et al.*, 1995). In particular the square array electrode configuration has been shown to provide higher sensitivity to rock anisotropy detection and requires less surface area than the conventional collinear array (Lane *et al.*, 1995). The array has been recently employed in DC resistivity surveys to locate productive fractured zones in crystalline bedrock for groundwater exploitation (Sehli, 1990). Boadu *et al.*, (2005) performed field azimuthal resistivity surveys in some localities within the study area and demonstrated that the fracture strike obtained from the ARS were in good agreement with those obtained from geological mapping. Recently, Busby and Jackson (2006) used azimuthal resistivity measurements to predict failure of coastal cliffs.

In this paper, geophysical, geological and geochemical measurements were conducted in the study area to ascertain the role of subsurface fractures in groundwater contamination by nitrates. Azimuthal resistivity surveys are conducted at well locations where groundwater samples were obtained and analyzed for nitrate (NO$_3$-N) concentrations using the HACH DR 2500 Spectrophotometer. The objective of this study is to investigate the potential role that fractures play in the contamination of groundwater by nitrates. The study describes how field geophysical electrical surveys
can be used to accomplish this goal by first, establishing a regression model between the fracture and electrical parameters from ARS and second, correlating the analyzed nitrate concentrations at each well with the subsurface fracture parameters obtained from the azimuthal resistivity surveys.

5.3 Geology of Study Area

The study area is located approximately 35 km northwest of Accra, the capital of Ghana (Figure 5.1). The original underlying rocks in the area consisted of alternating arenaceous sediments that have been metamorphosed by intense pressure into phyllites, schists and quartzite and are termed the Togo series (Kesse, 1985). Fractures occur in the quartzite rocks and are mostly vertical to sub-vertical in inclination with water-bearing potential (Kesse, 1985). The weathered soil covers are mostly loamy sands which possess high porosity and permeability (Kesse, 1985) with thicknesses ranging from 0.5 to 2.5 m. The climate in the area is semi-equatorial with two seasons, wet (rainy) and dry seasons. The nitrate concentration levels are expected to vary in the two seasons. For example, minimum dilution of groundwater is expected in the dry season and hence likelihood of higher concentration levels in comparison to that of the wet season.
Figure 5.1: Map showing the location and partitioned subareas of the study area, Akuapem South municipality, Ghana. The subareas are partitioned with dash-dot lines (after Boadu et al., 2005).

5.4 Field Methods

5.4.1 Geological Mapping

The study area covers an area of roughly 6 km$^2$ and is divided into three subareas namely, Amanfrom, Kitase and Nsakye (Figure 5.1). Geological mapping of exposed rocks was undertaken in each subarea, which involved measurements of fracture characteristics such as fracture lengths, widths and spacings along scanlines. Most of the observed fractures are oriented vertically, and the relatively thin and fairly homogeneous soil covers (Boadu et al., 2005) allow for azimuthal electrical sensing of the
fractures. Histograms depicting the distribution of the measured fracture parameters for the entire area are shown in Figure 5.2. The fracture spacings exhibit a near-normal distribution in the range from 9 mm to 30 mm. The fracture lengths depict a near exponential distribution for lengths up to 1500 mm and near uniform distribution thereafter. Fracture apertures are irregularly distributed, having near exponential up to 4 mm with peaks in values of 5 mm, 7 mm and 10 mm. These fracture parameters are useful in providing the hydraulic properties of the fractured medium and are sensitive to the geophysical measurements.

Figure 5.2: Histograms illustrating the distribution of characteristic fracture parameters: aperture, length and spacing obtained from field geological mapping of the study area.
5.4.2 Azimuthal Resistivity Survey

Azimuthal resistivity surveys were carried out over outcrops and at sites adjacent to the groundwater wells at seven selected localities in the study area; Aburi, Nsakye, Pokrom, Amanfrom, Nkukrom, Kwesi-Den and Kokoben. The square array electrode configuration was employed to measure the variations of apparent resistivity with azimuth. In the setup, current was sent into the ground by two current electrodes on one side of the square and a potential difference was measured at two electrodes on the other side. The length of each side of the square is termed the A-spacing, and the effective depth of investigation is approximately equal to the A-spacing (Degnan et al., 2001). For measurements close to the wells, the criteria for choosing the A-spacing were based on accessibility, depth to the water table (< 10 m), and availability of drill log data. From drill log information, the soil covers at the selected sites vary from 0.5 - 2 m and the static groundwater levels vary from 4 - 5 m. A-spacings were selected such that the sensing depths were below the overburden and within the fractured reservoir. For measurements over the outcrops, the choice of the A-spacing was dictated by the minimum and maximum values of the fracture parameters obtained from the geological mapping.

The square array was expanded about a center point in increments of 1 m starting with an initial A-spacing of 4 m up to a value of 7 m. The electrode positions
were rotated in increments of 22.5° about a central point [Figure 5.3(a)] following the procedure of Boadu et al. (2005). At each measurement site (outcrop or well location), the real and imaginary parts of resistivity at 5 Hz were measured with respect to the North [Figure 5.3(a)].

Figure 5.3: Electrode arrangement for the square array azimuthal survey; A,B = current electrodes, M,N = potential electrodes. (b) A homogenous anisotropic half space showing the orientation (φ) of current (C) and potential (P) electrode positions with respect to the strike of the fractures; ρ_{l} is the apparent resistivity measured when the electrodes are aligned longitudinal (parallel) to the fracture strike and ρ_{t} for traverse alignment of electrodes with respect to fracture strike; α is the angle the fracture makes with the vertical (after Boadu et al., 2005).
5.4.3 Groundwater Analysis

Groundwater samples were collected primarily from the selected groundwater well locations where azimuthal resistivity surveys were performed. All the water samples were analyzed for nitrate concentration levels using the HACH DR 2500 spectrophotometer. The concentration of nitrate (expressed as nitrate-nitrogen (NO$_3$-N)) was determined by the cadmium – reduction method (HACH Company, 1995).

5.5 Relations Between Electrical and Fracture Parameters: Results and Analysis

For the square array electrode configuration, apparent resistivity ($\rho_a$) is determined using the equation (Habberjam, 1972):

$$\rho_a = \left(\frac{2\pi A}{2-\sqrt{2}}\right) \times \frac{\Delta V}{I} \quad (5-1)$$

where $A =$ length of the square array, in meters; $\Delta V =$ potential difference, in volts; and $I$ is the current magnitude in amperes. The first term in brackets is the geometric factor for the square array electrode configuration. Variation of apparent resistivity ($\rho_a$) with the square array orientation over a homogeneous anisotropic earth has been presented by (Habberjam, 1972; Lane et al., 1995) as:

$$\rho_a = \frac{\rho_m}{2-\sqrt{2}} \left(\frac{2}{(1+(N^2-1)\cos^2\theta)^{1/2}} - \frac{1}{(2+(N^2-1)(1+\sin 2\theta))^{1/2}} - \frac{1}{(2+(N^2-1)(1-\sin 2\theta))^{1/2}} \right) \quad (5-2)$$

where $\theta$ is measured from the azimuth of current electrodes to fracture strike, $N$ is the effective vertical anisotropy and is related to coefficient of anisotropy, $\lambda$, and the dip of
the bedding plane [Figure 5.3(b)] $\alpha$, as $N = (1 + (\lambda^2 - 1)\sin^2 \alpha)^{1/2}$; and $\rho_m$ is the mean resistivity of the fractured rock mass. The parameters $\lambda$ and $\rho_m$ are diagnostic of an anisotropic medium, and are defined as $\lambda = (\rho_t/\rho_l)^{1/2}$ and $\rho_m = (\rho_t\rho_l)^{1/2}$, where $\rho_t$ and $\rho_l$ are respectively, the apparent resistivity transverse and longitudinal to the direction of fracturing. For a homogeneous isotropic medium, $\lambda = 1$ and $\rho_m = \rho_t = \rho_l$. To estimate fracture strikes, Boadu et al. (2005) utilized a graphical procedure based on polar plots (Habberjam, 1972; Lane et al., 1995), whereby the measured apparent resistivity for the azimuthal square array is plotted against the azimuth. A distinct ellipsoidal shape of the polar plot is interpreted to indicate the presence of anisotropy due to the presence of aligned vertical or near vertical fractures. The minor axis of the ellipsoid coincides with the strike of the fractures when the square array electrode configuration is used (Habberjam, 1972; Lane et al., 1995). The presence of more than one fracture strike will be depicted by a multiple-peaked pattern in the polar plot. The dominant or principal fracture direction is interpreted to be perpendicular to the direction of maximum resistivity. It should be emphasized however, that azimuthal variations in apparent resistivity may also be produced by gradational lateral changes in resistivity and by the presence of dipping beds (Matias, 2002).

Fracture porosity ($\Phi_f$) usually develops during tectonic fracturing of rocks and serves as a measure of fluid storage potential of fractured rockmass. This porosity is
estimated by utilizing the expression relating fracture porosity and electrical parameters derived by Lane et al., (1995), and referred to as Model A here,

\[
\Phi_f = \frac{3.31 \times 10^4 (N - 1)(N^2 - 1)}{N^2 C (\rho_{\text{max}} - \rho_{\text{min}})}
\]

(5-3)

where \( \rho_{\text{max}} \) and \( \rho_{\text{min}} \) are respectively the maximum and minimum apparent resistivities, and \( C(\mu\text{S/cm}) \) is the specific conductance of the pore filling material (groundwater and/or clay). For the vertical and near vertical fractures encountered, the value of \( N \) is approximately equal to the anisotropic coefficient (\( \lambda \)). Fracture porosity also can be estimated from field measurements of fracture width (\( b \)) and length (\( l \)) along a scanline (Hossain, 1992; Boadu, 2000) and referred to as Model B here,

\[
\Phi = \frac{\sum_{i=1}^{M} L_i B_i}{L_d h}
\]

(5-4)

where \( L_d \) is the length of the scanline, \( M \) is the number of fractures and \( h \) defines the span of the maximum fracture length. Comparison of outputs of Model A (from field geophysical surveys) and Model B (from field geological mapping), and as shown in Table 5.1, indicates a good agreement between the two models with an average error of 6.5%. Representative azimuthal measurements, with plots of apparent resistivity versus azimuth are shown in Figure 5.4. The estimated values of the anisotropic coefficient are given in the figure caption.
Figure 5.4: Plot of apparent resistivity (Ω-m) versus azimuth (°) at (a) a location near Aburi Girls Secondary School, with estimated value of $\lambda=1.31$ (A=4m); and (b) at Aburi Township, with estimated value of $\lambda=1.34$ (A=5m); (c) at Amanfrom (Site 1) with estimated value of $\lambda=1.50$ (A=3m); (d) at Amanfrom (Site 2), with estimated value of $\lambda=1.43$ (A=6m). The numbers on the plot are the radial axis units (after Boadu et al., 2005).
Table 5.1: Comparison of fracture porosities estimated using Eq. 5-3 (Model A) and porosities estimated using Eq. 5-4 (Model B)

<table>
<thead>
<tr>
<th>Fracture Porosity ($\phi_f$)</th>
<th>Model A</th>
<th>Model B</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aburi Township</td>
<td>0.001</td>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>Kokonuru (Kitase LT1)</td>
<td>0.002</td>
<td>0.0025</td>
<td>25</td>
</tr>
<tr>
<td>Nkukrom</td>
<td>0.007</td>
<td>0.0068</td>
<td>2.8</td>
</tr>
<tr>
<td>Kokoben</td>
<td>0.005</td>
<td>0.0043</td>
<td>14</td>
</tr>
<tr>
<td>Yaw Duodo</td>
<td>0.0015</td>
<td>0.0013</td>
<td>13</td>
</tr>
</tbody>
</table>

An important parameter characterizing a fractured rockmass and which is related to its hydraulic properties is the surface-area-to-pore-volume ratio, $S_{AV}$. This parameter is also termed the specific surface area (inverse of a hydraulic radius) and is related to the permeability of the fractured porous media via the Kozeny-Carman relation (Wels and Smith, 1994). The lower the value of $S_{AV}$, the higher the fracture permeability and vice versa. The specific surface area has been found to bear a linear relationship with both the real and imaginary components of the complex interfacial conductivity of unconsolidated porous materials (Börner et al., 1996) as well as fractured media (Boadu et al., 2005). The interfacial conductivity is the component of the complex conductivity due to grain/crack surface effects. Injection of electric current into a fractured rockmass will result in a current pathway defined by a network of
hydraulically connected fractures. When the current interacts with the fracture walls (rock-matrix) possessing charged ions (e.g., clay minerals) due to, for example, weathering and leaching processes, it may induce surface conduction which can substantially contribute to the effective conductivity of the fractured rockmass. The real part of the complex conductivity is influenced by both volume (electrolytic) and interface properties, whilst the imaginary part is influenced solely by the interfacial properties (Schön, 1996). Thus, exploitation of such interface phenomena may be useful in characterizing the geometric and hence the hydraulic properties of fractured rock mass using electrical geophysical methods.

As previously mentioned, at each of the seven townships, azimuthal resistivity surveys and measurements of fracture lengths, spacings and apertures (fracture parameters) were carried out on exposed rocks and which are close to well sites (< 400 m). Relationships between $S_{AV} \, (\mu m)^{-1}$ estimated from the fracture parameters and the anisotropic coefficient, real and imaginary parts of the electrical conductivity measurements of the exposed fractured rock masses at the seven sites are shown in Figure 5.5. The values of $S_{AV}$ were estimated using the formulation below (Wels and Smith, 1994; Boadu et al., 2005):
where \( l_i \) and \( b_i \) are respectively the length and width (aperture) of the \( i \)th fracture within a fractured zone (along a scanline) containing \( M \) fractures. As shown in Figure 5.5, the electrical properties of the fractured rock masses are approximately linearly related to their specific surface areas \( (S_{AV}) \) and are described by the equations:

\[
S_{AV} = 2.11 - 0.89\lambda, \tag{5-6}
\]

\[
S_{AV} = 13740\sigma_{imag} + 0.82 \tag{5-7}
\]

and

\[
S_{AV} = 1649\sigma_{real} + 0.78 \tag{5-8}
\]

where \( \sigma_{imag} \) (S/m) and \( \sigma_{real} \) (S/m) are the respective imaginary and real parts of the measured electrical conductivity of the fractured rockmass (across strike), and \( \lambda \) is the anisotropic coefficient. All the three equations predict strong linear relations between the specific surface area of the fractures and their electrical properties. The study area is covered with the same rock type (Kesse, 1985), and these are empirical equations which hold only for the study area, but similar relations will likely hold for other areas with similar rock types and stress regimes. The coefficient of determination or square of the correlation coefficients \( (R^2) \) for the fitting equations 5-6, 5-7 and 5-8 are 0.91, 0.86 and 0.9 respectively. The corresponding estimates of error variances are: 0.0027 for equation 5-6, 0.0045 for equation 5-7 and 0.0031 for equation 5-8. For example, in the relation between \( S_{AV} \) and \( \sigma_{real} \), the \( R^2 \) value of 0.9 and the relatively low error variance of 0.0031 indicate
that the proposed model fits the data quite well, and that the regression equation accounts for 90% of the variability in $S_{AV}$ making it an accurate prediction equation.

![Graph](image)

**Figure 5.5:** Relationship between the specific surface area ($S_{AV}$) and (a) anisotropic coefficient (b) imaginary parts, and (c) real parts of the complex conductivity measured at sites within the study area with exposed fractured rockmass.

### 5.6 Discussions

Water samples were collected from water wells and two local streams at different towns in a period that covers the two climatic seasons in southeast Ghana. Analyses of the samples indicate that the nitrate ($NO_3-N$) concentration levels range from 1.1 mg/L to 39.1 mg/L. Figure 5.6(a) shows the $NO_3-N$ concentration levels at different locations in
July 2004, which indicates that the levels in the wells located at Kwesi-Den, Pokrom and Aburi exceed the permissible limit of 8 mg/L set by WHO (1996).

The levels at all the well locations are relatively low in November 2004 [Figure 5.6(b)], which is nearing the end of the rainy season. The levels are relatively high in April [Figure 5.6(c)], close to the end of the dry season when we expect minimal dilution of the nitrates by recharged water from rainfall, and relatively low again during the rainy season in June [Figure 5.6(d)]. Water samples obtained from the two narrow
streams at Pokrom and Nsakye however indicate consistently low levels over the seasons. These low levels could probably be the result of additional nitrate removal by plant uptake and/or immobilization by microorganisms or due to the mixing processes of the slow flowing streams.

Fracture systems control the movement of fluids, and hence contaminant, in the earth’s subsurface. In the study area, the fracture systems were characterized using both field geological and geophysical mapping methods. The primary objective was to investigate how the characteristics of the fracture systems influence the subsurface hydraulic properties and consequently affect ground water quality, that is, nitrate contamination. This aim was achieved primarily with the aid of azimuthal resistivity surveys. Seven producing ground water wells with known information on the depths to the fractured reservoir, water table and thicknesses of the soil cover from drilling logs were identified (WRRI, 1996). In May 2006, water samples were collected from each of the seven wells for analysis of nitrate concentration. At the same time, azimuthal resistivity surveys (ARS) were conducted at locations close to these wells (< 10 m) to measure the real and imaginary parts of the rock resistivity and to estimate the anisotropic coefficient. The electrodes spacing were chosen between 4 m and 7 m based on information from drilling logs so as to probe the electrical properties of the vertical fractures below the soil cover. At each measurement location, the average value of
specific surface area of the subsurface fractures was estimated using the developed regression equations. The procedure for estimating the fracture porosity from knowledge of the anisotropic coefficient is discussed above (equation 5-3).

Figure 5.7: Variation of nitrate contamination levels with specific surface area ($S_{AV}$) at selected wells in the study area. The horizontal line marks the permissible limit (8 ppm) of nitrate concentration set by WHO.

Figure 5.7 shows the nitrate concentration level (arranged in order of magnitude) at well locations in the seven towns with the predicted values of $S_{AV}$ superimposed on them. It can be inferred from the figure that higher nitrate concentration values in groundwater are associated with wells located within fractures that have relatively lower values of $S_{AV}$. Variation of nitrate concentration in groundwater at the same wells with superimposed values of fracture porosity of the underlying fractured reservoir is
shown in Figure 5.8. As observed in the figure, wells with relatively high nitrate concentrations are those with relatively high fracture porosity.

Figure 5.8: Variation of nitrate contamination levels with fracture porosity at selected wells in the study area. The horizontal line marks the permissible limit (8 ppm) of nitrate concentration set by WHO.

To make these indications clearer, cross plots of $S_{AV}$ and fracture porosity obtained from the geophysical measurements with nitrate concentration levels are provided in Figure 5.9. Nitrate ions move downward freely with drainage water and are thus readily leached from the soil (Brady and Weil, 2002). The relatively thin porous and permeable sandy soil covers associated at the sites will likely enhance leaching of nitrates into the groundwater with minimal runoff. Also, fractured rockmass with lower values of $S_{AV}$ will tend to have higher porosity and permeability (Schön, 1996; Wels and
Smith, 1994) and thus a higher potential to transmit and store nitrate leachate from the surface to the groundwater.

Figure 5.9: Crossplot of nitrate concentration levels with specific surface area and porosity of fractures.

This reasoning implies the likelihood of higher concentration of the nitrates in the groundwater in fractured aquifers with lower specific surface area and higher porosity. These results indicate that it is possible to develop a prediction model based on hydraulic properties of fractured media derived non-invasively from geophysical measurements that can be used to predict nitrate concentration levels. Such a model, which may be useful only in similar fractured rocks, can then be used to predict the
possibility of a well exceeding the WHO standards for nitrate contamination. However, for such a model to be conclusive and versatile, more data will be needed to help develop a more quantitative model based on regression equations. Also, it should be noted that the nitrate levels were analyzed from the groundwater samples taken at a specific time of the year (May 2006). However, the nitrate concentration levels will change seasonally as a reflection on the farming practices since farmers apply the fertilizers during the rainy season. Thus, it will be appropriate to find the average value over a couple of seasons and correlate them with the geophysical and/or rock parameters.

### 5.7 Conclusions

Field geophysical, geological and geochemical measurements were conducted in the Nsawam district to ascertain the role that subsurface fractures might play in the nitrate contamination of the groundwater resources. Application of fertilizers on the farms serves as the primary source of the nitrates, and the thin sandy soils overlying the vertically fractured aquifer rocks provide a direct link between the nitrate leachates from the earth’s surface and the subsurface groundwater. The subsurface fractures provide the conduits for transport of the nitrate leachate. Groundwater samples were obtained from wells at seven towns over a 12-month period and analyzed for nitrate (NO$_3$-N) concentration levels using the HACH DR 2500 Spectrophotometer. Azimuthal resistivity
surveys (ARS) were conducted at these well locations where anisotropic coefficient, and the real and imaginary parts of the conductivity were measured.

Regression models were developed using geophysical and geological measurements on outcrops and are used to estimate the specific surface area and porosity of the subsurface fractures at the well locations. In these specific well locations, the porosity and the specific surface area of the fractures correlated well with the nitrate concentration levels in the groundwater. Nitrate concentration levels tend to increase with decrease in specific surface area of the fractures, and increase with increase in the fracture porosity.

The study demonstrates how one can ascertain the role that fractures can play in assessing the magnitude of nitrate contamination in the groundwater wells. This role was examined using information about the hydraulic properties of the subsurface fractures obtained from non-invasive surface geophysics. Such information will be useful in future assessment of the environmental impact of agricultural practices in the Nsawam district, and perhaps in predicting the probability of a well meeting the WHO standards in terms of nitrate concentration levels. Further work in acquiring more data will be very useful in this regard. This will help to provide a comprehensive and versatile methodology to promote use of geophysics in environmental and groundwater quality monitoring.
6 Conclusions, Contributions and Future Work

The need to use non-invasive techniques to characterize the earth subsurface and predict its properties and engineering behavior cannot be overemphasized. This research work which involved the conduction of various laboratory and field studies is a contribution to this important need. The studies conducted includes (i) investigation of the interplay of clay content and effective stress on spectra electrical responses of soils (ii) investigation of the influence of textural properties of soils on its electrical responses (iii) investigation of the structural and deformational changes in soils using complex resistivity measurements and (iv) investigation of the role of fractures in groundwater contamination using field electrical survey.

In general, the undertaken research efforts improve our knowledge and understanding of how engineering properties, specifically those that affect the mechanical behavior of geomaterials, influence electrical response. The results will contribute towards the utilization of complex resistivity methods during large scale pre-investigation studies for engineering projects such as landfills, tunnels and dams. It can also help in mapping weak zones in the subsurface, as well as landslide and subsidence areas. Ground truth measurements will however be required to constrain the results.
obtained from the complex resistivity measurements. As such complex resistivity measurements can be effectively used as a complementary method.

The study will also contribute towards using geophysical methods to monitor the strength and stability conditions of the subsurface. For example, repeated complex resistivity measurements can be conducted over time at a single location to monitor changes in water content and effective stress levels, which influence the stability conditions of the subsurface. This will however be done with the assumption that certain properties of the subsurface such as its composition will remain the same over time.

The contributions of the various studies are presented in the sections below.

6.1 Conclusions from and Contributions of “Effect of Clay Content and Effective Stress on the Spectral Electrical Response of Sand-Clay Mixtures”

- The results presented in this study show that the spectra electrical responses of soils are sensitive to changes in effective stress and clay content of soils.

- The presence of clay in soils is found to result in a characteristic peak in the phase spectra. The peaks shift toward lower frequencies as the clay content increases. The magnitude of the phase is found to increase with increasing clay content until the clay becomes spatially continuous within the mixture, after which the phase values decrease.
• Cross-plots between geotechnical properties (dry density, elastic modulus, and void ratio) and the geoelectrical parameters (phase, amplitude, capacitance, and loss tangent) of the soil samples at varying effective stress levels are shown to possess significant correlations. It is concluded from this study that geoelectrical parameters can be used to estimate these geotechnical properties.

• The information obtained from this study will be useful in the interpretation of field electrical measurements and contribute towards the use of non-invasive techniques in engineering and environmental investigations.

6.2 Conclusions from and Contributions of “Relationships between Textural Properties of Unconsolidated Materials and their Complex Resistivity Parameters”

• The study shows the relationships between textural properties (fines content, pore size parameter, specific surface area, and fractal dimension) of soils and their electrical parameters (amplitude, phase, percent frequency effect, and loss tangent). Models developed from the observed relationships will enable these textural properties, known to affect the strength behavior of soils, to be predicted from the easily measurable electrical parameters.
• The normalized phase and resistivity amplitude was found to be very sensitive to changes in amount of fines with fines content value of 18% being the transition value for the conduction process.

• This study also provides a methodology by which the relative amounts of fines in soils can be assessed from electrical measurements. The crossplot of the real part of complex resistivity and the phase values is found to be effective in discriminating the high (> 18%) and low (< 18%) ranges of fines in soils.

• Characteristic or transitional values of fines content (18%) and pore size (0.03 mm) are found to exist, beyond which the phase and normalized phase values of electrical responses are insensitive to their respective increases.

6.3 Conclusions from and Contributions of “Investigating the Deformational and Structural Changes in Unconsolidated Earth Materials using Complex Resistivity Measurements”

• The resistivity amplitude and capacitance was found to reveal a characteristic transition when the effective stress conditions of soils progresses from low to high levels. The information could be useful in using complex resistivity measurements in monitoring the strength of soils.

• The relationship between strain and effective stress and that of resistivity and effective stress were found to be similar, demonstrating that resistivity can be used to infer the structural changes in the soil being manifested as strains.
• The plot of \( \frac{de}{d\log\sigma} \) (ratio of the change in void ratio to the change in logarithm of effective stress) versus \( \sigma \) (effective stress) revealed two different zones, with the variation (or shape) of the \( \frac{de}{d\log\sigma} \) with \( \sigma \) in the first zone dependent on the clay content and initial void ratio.

• This investigative effort will contribute towards using non-invasive electrical measurements to assess and monitor the strength and stability conditions of the earth subsurface.

6.4 Conclusions from and Contributions of “Investigating the Role of Fractures in Groundwater Contamination using Azimuthal Resistivity Survey”

• This study involves the use of a non-invasive geophysical methodology to predict subsurface fracture parameters and then correlating these fracture parameters with nitrate concentration in groundwater wells.

• Regression models are developed to enable specific surface area and porosity of subsurface fractures in the study area to be estimated from electrical parameters.

• The study contributes towards using non-invasive geophysical techniques to examine the role of subsurface fractures in nitrate contamination of groundwater wells in the study area.
6.5 Future Work

Additional studies need to be conducted using samples prepared with other clay minerals such as illites and kaolinites. The experimental setup will also need to be improved to enable the acquisition of geotechnical and electrical parameters of soils as a function of consolidation time. This will allow the electrical response of the soil resulting from micro-structural changes and effective stress evolution, to be monitored during the consolidation process. Also, a new experimental setup incorporating the electrical measurement system with the triaxial test cell will be very useful. It will allow the compression of soil specimen during triaxial test to be monitored using complex resistivity measurements and provide a way to relate the strength parameters (cohesion and angle of internal friction) to electrical parameters.

Further, more studies on natural soil samples are required to enable the establishment of reliable models representing the relationships between the electrical and engineering properties of soils. In establishing predictive models, multiple regression analysis and other predictive tools such as artificial neural network which has the ability to adapt and generalize need to be used. Because of the inherent complex and non-linear relationships that exist between the engineering and electrical properties, using only multiple regression analysis may not be enough to fully capture the existing nonlinear relationships. Utilizing the pattern recognition power of artificial neural
network will therefore be useful due to its ability to recognize highly non-linear complex patterns within available data. Sensitivity analysis will also be needed in order to determine which engineering properties affect the electrical parameters the most in a given condition.
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Biography

Frederick Owusu-Nimo was born and bred in Accra, the capital of Ghana in West Africa. He had his junior high school education at Hansen Road S.D.A. School Complex and continued to Adisadel College at Cape-Coast, Ghana, for his senior high school education. In the year 2000 he enrolled in the civil engineering program at Kwame Nkrumah University of Science and Technology in Kumasi, Ghana, where he obtained his Bachelor’s degree, with first class honors, after four years later of study. After graduating, he was retained by the university as a teaching and research assistant for a year. In 2005, he joined FAS Consult (an engineering consulting firm) as an Engineer and was involved in the feasibility studies, design and construction supervision of several engineering projects.

With his quest to further his education, he moved to Duke University, NC in 2006 for his graduate studies at the civil and environmental engineering department where he obtained his MS degree in 2009 and PhD degree in 2011, both at the same department. His research interests include the use of geophysical techniques, especially complex resistivity method, in geotechnical engineering investigations, ground water exploration and environmental applications.

A list of his publications and presentations are as follows.
Peer-Reviewed Journal Papers


Manuscript in Preparation


Peer-Reviewed Conference Proceedings and Presentations

- Owusu-Nimo F., and Boadu F. K., 2010, Relating engineering properties of unconsolidated geomaterials to electrical parameters: Laboratory measurements: at the National Society of Black Engineers Convention, 2010, Toronto, ON.