Chapter 1 Introduction

1.1 Statement of the Problem

Engineering properties of geomaterials are very important for civil engineers because almost everything we build - tunnels, bridges, dams and others – are in, on or with soils or rocks. For geotechnical engineers, the strength, the stress-deformation behavior and the fluid flow properties of earth materials are of primary concern and form the conventional framework of the geotechnical discipline (Mitchell 2004). Conventional techniques for the determination of these engineering properties can be generally divided into three categories – laboratory tests, in-situ tests and geophysical methods. Of these, geophysical methods have been least developed as regards to their suitability for specific quantification of soil properties. Laboratory tests have the advantages of directly measuring the specified engineering properties under controlled boundary conditions and different environmental conditions. However, soil samples are usually disturbed during the drilling and sampling processes, which may make the measured engineering properties deviate from their actual values. Moreover, it is costly to sample and run laboratory tests on soils. Thus, only a small volume of soils can be tested. In contrast, in-situ tests such as standard penetration tests (SPT) and cone penetration tests (CPT) are cheaper and can test a relatively large volume of soils. However, the determination of the parameters used for geotechnical design from the CPT penetration resistance, SPT blow counts, and other types of in situ tests is of high uncertainty. Therefore, better techniques that can quickly and reliably determine soil engineering properties in the field are desirable.

Low energy electromagnetic (EM) waves have the potential to be a very useful tool to characterize soils and sites because: (1) EM waves don't produce permanent residual effects or measurable perturbations on the tested materials, which is essential for soil structure measurements; (2) EM waves are suitable for the remote sensing of a site, which provides possibility for quicker and cheaper site characterizations; (3) EM waves can vary in a very broad frequency range, and the responses of a soil to EM fields at different frequencies can be a good indicator of its components and structure. EM waves may be useful for tracing the compositional and structural changes of geomaterials with time, which is essential to understand the behavior of geomaterials over the life of a project.

The electromagnetic properties of a soil refer to its responses in an electromagnetic field. Many investigations on soil electromagnetic properties have been made over the past several decades. These investigations showed that soil electrical conductivity, dielectric permittivity and their changes over the frequency range from 1MHz to 1 GHz are especially useful for deducing some important soil engineering properties because the electromagnetic properties over this frequency range are sensitive to soil compositions and structure.

Despite these extensive investigations, the relationships between the frequency dependent electromagnetic properties of fine-grained soils and their components and structure are still not well understood. This uncertainty has limited the application of electromagnetic property measurements for soil engineering property characterization. Hence, the estimation of soil engineering properties from electromagnetic measurements in a quantitative manner has not been achieved.

In addition, instruments that can be readily used in the field to measure soil electromagnetic properties over the 1 MHz to 1 GHz frequency range are still limited. It is desirable to develop instruments that can measure soil electromagnetic properties not only in the lab but also in the field.

1.2 Scope of Research

This study intends to better understand the relationships between the frequency-dependent electromagnetic properties of fine-grained soils and their components and structure, and to develop practically applicable methods for the determination of important soil compositional and structural parameters from electromagnetic measurements. The following tasks have been accomplished:

(1) Development of a physically based model that provides a means of investigating the coupled effects of important polarization mechanisms on soil electromagnetic properties, and a means of relating the electromagnetic properties of a soil to its fines content, clay mineralogy, anisotropy, state of flocculation and dispersion, temperature and pore fluid chemistry;

(2) Verification of the theoretical model by measuring the electromagnetic properties of sand, kaolinite, bentonite and mixtures of bentonite and silicon flour using a network analyzer;

(3) Deduction of the wide-frequency electromagnetic properties of a soil by measuring its responses to a step pulse voltage using time domain reflectometry (TDR);

(4) Proposal of a new method to determine the volumetric water content, specific surface area and pore fluid salt concentration of a soil simultaneously from its dielectric spectrum;

(5) Verification of the proposed method by measuring the specific surface area of eight soils using the ethylene glycol monoethyl ether (EGME) chemical adsorption method;

(6) Determination of the engineering properties of the tested soils, including residual friction angle, compression index, coefficient of consolidation and hydraulic conductivity;

(7) Establishment and interpretation of the relationships between soil engineering properties and soil compositional and environmental parameters that can be determined from electromagnetic measurements.

1.3 Arrangement of the Thesis

Chapter 2 includes two parts: (1) the definitions of electromagnetic properties, typical electromagnetic properties of different types of soils and important polarization mechanisms; (2) the applications of electromagnetic measurements in geotechnical engineering, including water content, dry density, void ratio, anisotropy, specific surface area, stiffness, liquefaction potential, strength, compressibility, swelling potential, hydraulic conductivity and time-dependent behavior of geomaterials.

Chapter 3 reviews the currently established theoretical and semi-theoretical models that relate the electromagnetic properties of soils to their components, examines the strengths and limitations of these models and develops a new physically-based model that

can analyze the electromagnetic properties of soils containing both sand and clay minerals. Based on the new model, the coupled effects of interfacial polarization and bound water polarization are analyzed.

Chapter 4 evaluates the influences of the porosity, clay percentage, clay mineralogy, anisotropy, pore fluid chemistry, dispersion and temperature on soil EM properties based on the theoretical model developed in Chapter 3. Methods to determine the volumetric water content, total specific surface area and pore fluid salt concentration from the electromagnetic measurements are proposed from the theoretical analysis. The application of these methods for pure clay and clay-sand mixtures is validated by measuring the electromagnetic properties of saturated Na-bentonite, kaolinite, and mixtures of bentonite and silicon flour.

Chapter 5 examines the currently available instruments that can measure soil electromagnetic properties. Two instruments used in this study – network analyzer and time domain reflectometry (TDR) – are emphasized. Some limitations of electromagnetic measurements are discussed.

Chapter 6 introduces the laboratory tests that have been performed to determine both the electromagnetic and engineering properties of soils. These properties include the electromagnetic properties from the TDR measurements, specific surface area from the ethylene glycol monoethyl ether (EGME) adsorption method, residual shear strength from the ring shear test and compressibility from the one-dimensional consolidation test.

Chapter 7 develops a method to determine the frequency-dependent soil dielectric spectrum from the TDR time-domain waveforms. The dielectric spectra of seven clays at different porosities were derived from their TDR waveforms. The reliability of the time-

domain to frequency-domain conversion was verified by performing electromagnetic measurements using a network analyzer immediately after the TDR measurements.

Chapter 8 is composed of two parts: (1) evaluation of the proposed methods for determining the volumetric water content, total specific surface area and pore fluid salt concentration of natural soils; (2) establishment of the relationships between engineering properties and total specific surface area.

Chapter 9 concludes this study and proposes new studies.