

Chapter 9 Summary and Conclusions

The primary objectives of this research include: (1) evaluation of the ability of electromagnetic waves to characterize the composition and structure of various soils; (2) estimation of the engineering properties of a soil based on information obtained from its responses to an electromagnetic field.

The specific targets of this research project include the following:

(1) obtain the electromagnetic spectrum of natural and artificial soils in the frequency range from 1MHz – 1GHz; (2) identify and evaluate the most suitable models for describing permittivity and conductivity; (3) evaluate how well the EM waves can be used to estimate such properties as the specific surface area, soil water content and pore fluid chemistry; (4) study the possibility of using electromagnetic property measurements for determination of such engineering properties as compressibility, hydraulic conductivity and strength of fine-grained soils.

9.1 Summary of Accomplished Tasks

In this study, such tasks have been accomplished:

(1) Development of a physically based model that provides a means of investigating the combined 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, water content, degree of flocculation and pore fluid chemistry; The theoretical model provides a logical and supportable basis for

using electromagnetic property measurements for soil composition and structure characterization.

- (2) Verification of the theoretical model by measuring the frequency-domain dielectric spectra of saturated silicon sand, kaolinite, bentonite and bentonite-silicon flour mixtures.
- (3) Proposal of a practically applicable method to determine the volumetric water content, specific surface area and pore fluid electrical conductivity of a soil simultaneously from its dielectric spectrum;
- (4) Verification of the proposed method by measuring the specific surface areas of eight soils using the ethylene glycol monoethyl ether (EGME) adsorption method.
- (5) Deduction of the wide-frequency electromagnetic properties of a soil by measuring its responses to a step pulse voltage using time domain reflectometry (TDR).
- (6) Establishment of the correlations between the specific surface area and residual friction angle, compressibility, coefficient of consolidation and hydraulic conductivity.

9.2 Conclusions

- (1) Interfacial polarization is the most important mechanism contributing to the dielectric dispersion behavior of fine-grained soils over the 1 MHz and 1 GHz frequency range. The magnitude of dielectric dispersion due to interfacial polarization is controlled by the difference in electrical conductivity between the bulk pore fluid and clay aggregates.

- (2) The electromagnetic properties of clay aggregates or particles are anisotropic: both the real permittivity and DC electrical conductivity are the highest in the direction tangential to the clay faces and the lowest in the direction normal to them. The maximum DC electrical conductivity of a clay particle or clay aggregate is determined by the total specific surface area and surface conductance of the clay mineral.
- (3) Bound water polarization is also strongly related to the total specific surface area but its contribution to the dielectric dispersion magnitude is relatively small as compared with that of interfacial polarization.
- (4) At frequencies less than 50 MHz, the real permittivity of a soil decreases with increasing pore fluid electrical conductivity; the influences of the pore fluid electrical conductivity on soil real permittivity become small at frequencies higher than 50 MHz.
- (5) The real permittivity at 1 GHz is primarily determined by the volumetric water content. For a specific soil, the higher the volumetric water content, the higher the real permittivity at 1 GHz.
- (6) The dielectric dispersion magnitude from 50 MHz to 1 GHz is primarily controlled by the clay mineralogy and clay percentage, which may be conclusively characterized by the total specific surface area. At the same porosity, a higher specific surface area leads to a higher dielectric dispersion magnitude over the 50 MHz to 1 GHz frequency range.

- (7) Time domain reflectometry is a practical method for soil electromagnetic measurements. The frequency domain dielectric spectrum of a soil can be reliably converted from the TDR time domain waveform if the TDR is correctly calibrated.
- (8) The specific surface area from the EGME adsorption method represents the total specific surface area, which is approximately three times that from the water vapor adsorption method and about nine times that from the BET-N₂ adsorption method. The specific surface area from the BET-N₂ adsorption method represents the external specific surface area of clay clusters.
- (9) Good linear relationships between the total specific surface area and the compression ratio and residual friction angle of natural soils are observed. With increase of total specific surface area, the compressibility of natural soils increases and the residual shear strength decreases.
- (10) The hydraulic conductivity of natural soils is more related to the external specific surface area of the clay clusters, which can be estimated from the total specific surface area or from the liquid limit. The Kozeny-Carman equation provides a fairly good estimation for the hydraulic conductivity of clayey soils when the external specific surface area is used in the calculation.

9.3 Recommendations for Future Research:

9.3.1 Applications of the EM measurements for studying soil behavior:

The theoretical model developed in this study provides a very useful tool to relate the structure and components of a soil to its components and structure. The model can not

only be used for soil-water mixtures but also mixtures of soils and other materials, such as landfill leachate, non-aqueous phase liquid (NAPL) pollutants and liquid gas. Several possible applications are:

- Study the effects of micro-organism on soil hydraulic conductivity and strength.

Some micro-organisms tend to facilitate the flocculation of clay particles without significantly changing the pore fluid electrical conductivity. This process can be studied by monitoring the EM properties of the bio-treated soils, through which how much and how fast the soil structure changes can be determined. By establishing the relationship between the changes in soil structure and the changes in hydraulic conductivity and strength. The optimal environment for the micro-organisms to make the fastest changes in soil property can be identified and the best method to use the micro-organisms for soil improvement can be developed.

- Study the electromagnetic properties of the mixtures of the NAPL pollutants and soils. The study will be helpful to understand the interactions between pollutants and soils and to detect the presence and trace the movements of the pollutants in the ground.

- Study the effect of temperature on soil micro-structures and surface conductance.

This study has shown that the theoretical model has the capability of investigating the effects of temperature on soil electromagnetic properties. More work needs to be done by measuring the electromagnetic properties of pure clay at different temperatures so that how the temperature changes the surface conductance, pore fluid salt concentration and soil structure can be learned.

- Study the effect of the wetting and drying on soil EM properties. Almost all work in this study is for fully saturated or nearly saturated soils. The degree of saturation has strong influences on both the EM properties and engineering properties of soils, which is worthy of further investigation. The theoretical model has the flexibility of simulating the wetting and drying process by substituting either the intra-aggregate or the inter-aggregate pore fluid with air.

9.3.2 From localized measurement to spatial measurements

- Application of the ground penetrating radar

This study focuses on understanding soil electromagnetic properties and establishing the relationships between electromagnetic properties and engineering properties.

Therefore, localized measurements by TDR and Impedance analyzer were performed. In the field, special variation of geomaterials is also important for the overall behavior of earth structures. Ground penetrating radar provides a convenient tool to determine the spatial variation and it is also based on the propagation of EM waves. By measuring the velocity and attenuation of EM waves using the ground penetrating radar at different frequencies, it is possible to construct 2D or 3D maps for the frequency-dependent electromagnetic property of the ground. Using the correlations between the EM properties and engineering properties established in study, the compressibility, hydraulic conductivity and strength of the entire constructional site can be calculated and the settlement and stability can be estimated.

- Development of an EM-CPT probe

Time domain reflectometry is a very convenient tool for soil electromagnetic measurements because of its small volume and low price. However, current configuration of time domain reflectometry can not penetrate through the ground. Therefore, it is important to incorporate time domain reflectometry into the CPT penetrometer. Although several types of TDR-CPT penetrometer have been developed, their capability to deduce the frequency domain dielectric spectrum of soils is unknown. A TDR-CPT that can reliably determine soil frequency-dependent electromagnetic properties will significantly enhance the usefulness of the CPT tests. From the electromagnetic measurements, such information can be obtained: (1) the type of soils being penetrated can be determined using the correlation developed in this study; (2) the water content at different depths can be determined; (3) thin sand layers can be detected, which is very useful for the liquefaction potential assessment and in-situ hydraulic conductivity estimation; (4) pore fluid salt concentration at different locations and depth can be determined, which is important for tracing the movement of pollutants in the ground; (5) the compressibility, hydraulic conductivity and residual shear strength of each layer can be estimated. Combining the above information with the CPT penetration resistance and sleeve friction, our capability of looking into soils will be greatly enhanced.