Non-Destructive Impedance Spectroscopy Measurement for Soil Characteristics

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ABSTRACT: A non-nuclear, non-invasive instrument capable of measuring density and moisture content of soil using electromagnetic impedance spectroscopy (EIS) is currently being developed. During the development of the empirical soil model, it was found that the model was sensitive to the specific surface area of the material being measured. With the material's specific surface area being accounted for, in six test compactions a 119% increase in accuracy was seen by the soil density gauge's (SDG) wet density calculation when compared to the Nuclear Density Gauge's wet density calculation.

INTRODUCTION

Because of the growing effort to develop a non-nuclear alternative to the Nuclear Density Gauge (NDG), the investigators are currently working on the development of a non-nuclear, non-invasive instrument capable of measuring density and moisture content of soil during road and other civil infrastructure construction using electromagnetic impedance spectroscopy (EIS). Using EIS and a parametric approach, an empirical model was developed to calculate wet density and moisture of soil, specifically, a run-of-crusher poorly-graded gravel with silt and sand (ASTM USCS classification GP-GM), during a Department of Homeland Security (DHS) contract. The empirical model was then tested on four controlled gradations within the ASTM USCS classifications of 1) well-graded gravel with sand (GW), 2) well-graded sand (SW), 3) well-graded gravel with silt and sand (GW-GM), and 4) sandy silt (ML). The test compactions were completed with controlled moisture levels within a 36-inch by 36-inch by 15-inch wooden frame using an electric vibrator plate compactor, VIBCO/Heinrich Plate compactor Model TP-1830, which had an 18-inch by 18-inch plate area. Holding the moisture constant in four of the test samples and varying the gradation allowed for the investigation of the effect of changing gradations on the EIS frequency response, without the added complication of moisture influences. Next, moisture was varied to allow for a secondary test to be completed on the effect of gradation on the calculation of moisture.

A practical, real-world, real-time model to transform the impedance data into soil density and moisture does not exist for the sensor setup currently being using, i.e., a surface, non-invasive, concentric ring setup, shown in Figure 1. Therefore, experimental data was collected for the development of an empirical soil model to be used in the SDG via a parametric approach. The SDG's sensor operates by the transmission of a constant voltage from the center electrode to the receiving electrode, passing through the material under test (MUT) and utilizing 86 frequencies between 300kHz and 40MHz.

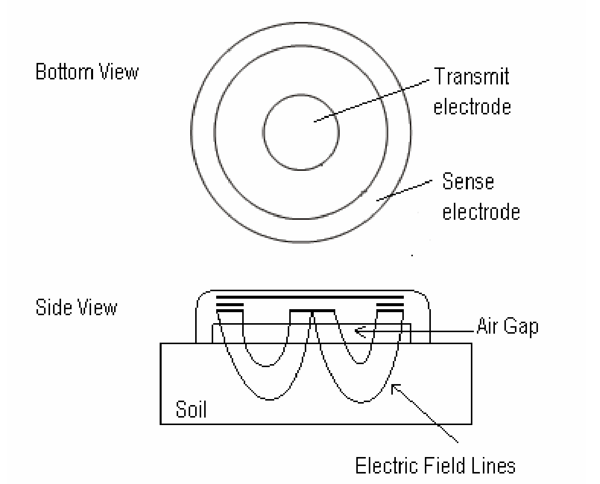

Figure 1. Surface, Non-Invasive Concentric Ring Sensor Setup

TECHNOLOGY BACKGROUND

EIS is the measurement of a material's dielectric properties (permittivity) based on the interaction of an external field with the electric dipole moment of the MUT, over a known frequency range. Typically, soil is a mixture of stone, water and air. Since the water molecule has a permanent dipole, its dielectric constant (approximately 80) is higher than that of dry soil, which is only polarizable by atomic and electronic polarization. Therefore, dry soil has a low dielectric constant (approximately 5). The dielectric constant of the soil matrix is not constant, but varies with frequency and 'depends on physical parameters such as soil texture, soil water content and type and concentration of ions in the soil solution' [1]. For these reasons, the investigators used both the real and imaginary parts of the measured permittivity. To take advantage of the fact that the permittivity of soil is dominated by the soil water content at low frequencies, an EIS measurement is taken from 300kHz to 40MHz.

The development of models to measure soil properties, like moisture and density, has been investigated and summarized by several researchers [1,5,6,7]. The use of dispersions seen in soil to develop these models is common. One such dispersion, commonly called the Maxwell-Wagner dispersion, is caused by the applied electric field on the bonds between the water and soil particles, which have different dielectric values [1,5,7]. Within the SDG's measurement frequency range, the investigators are able to make use of this information and the empirically derived soil dielectric mixing equation [1,8] to aid in the development of the empirical soil model. The investigators used second order parametric curve fitting and regression analysis on the frequency data to develop the empirical soil model. A second order curve was fitted to the frequency spectra (i.e., $y = Ax^2 + Bx + C$). Then, by completing a regression analysis on the second order fitted coefficients/parameters (i.e., *A*, *B* and *C*), a pattern was identified that was related to wet density and moisture content. Another benefit of using the curve fitting approach was the reduction in noise associated with the surface measurements and single point analysis. Using the spectra enabled the extraction of physical meaning from the fitted coefficients, thereby allowing the investigators to draw conclusions about the soil compaction data and enabling the development of an empirical linear inversion model for wet density and moisture. The empirical inversion model for the current sensor setup is proprietary information.

EXPERIMENTAL SETUP

Starting with a run-of-crusher GP-GM soil, the material was broken down for the gradation testing into twelve sieve sizes and reassembled into three predetermined gradation mixtures, GW, SW and GW-GM. The fourth gradation, ML, a sandy silt, was used as is from a quarry in New York State. Below, Tables 1 and 2, are the gradation breakdowns in terms of percent gravel, percent sand and percent fines as defined by ASTM D 2487 specification and Proctor test results as defined by ASTM D 698, respectively.

After each soil was assembled, GW, SW, GW-GM(1), GW-GM(2), and ML, de-ionized water was added to moisturize the soil to 7.09%, 7.14%, 7.30%, 5.61% and 8.25%, respectively. The GP-GM soil had a test moisture level of 7.12%. After the water was added, the soil was thoroughly mixed and allowed to sit covered overnight before testing began. The moisture levels were determined by pulling samples at the beginning and end of each compaction, as defined by ASTM D 2216.

The compaction of each material was completed in the wooden frame, using the VIBCO electric plate compactor. Data was collected with four SDGs and a NDG, a CPN MC3 Portaprobe with a 12-inch rod and with a current factory calibration, following the pattern shown in Figure 2, after one, two, four and eight compactor passes. In Figure 2, the four circles, labeled A, B, C and D, represent the centers of the SDG measurements and the three lines over the SDG circles represent the placement of the NDG for its three measurements. The SDG's measurement pattern is shown to the right as a clover-leaf pattern of five.

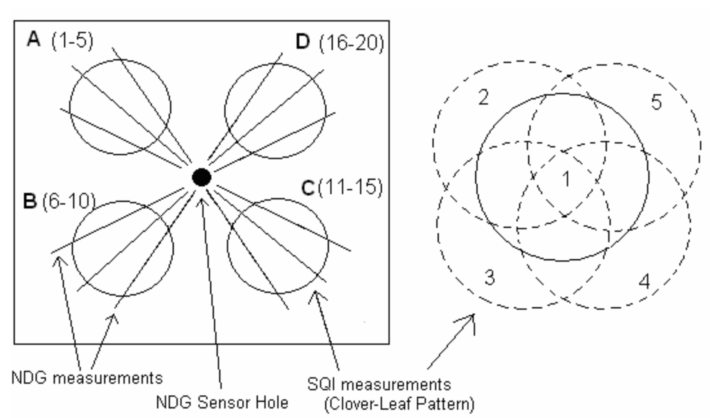

Figure 2. Data Collection Setup for SDG and NDG

Table 1. Tested Soil Gradation Summary

	GP-GM*	GW	SW	GW-GM(1)	GW-GM(2)	ML
% Gravel	48.21	65.04	10.03	53.63	40.77	2.90
% Sand	41.35	29.93	82.14	36.05	49.82	32.70
% Fine	10.44	5.03	7.83	10.32	9.41	64.40

Table 2. Tested Soil Proctor Information

	GP-GM*	GW	SW	GW-GM (1)	GW-GM (2)	ML
Proctor Peak (lb/ft^3)	137.27	136.65	135.22	141.5	141.5	125.02
Proctor Optimum Moisture (%)	8.50	9.50	8.13	7.63	7.63	10.13

* GP-GM soil was the material used for the break down and reassembly process.

EXPERIMENTAL RESULTS

Since the EIS response of soil using the SDG sensor could not be estimated in advance, several controlled compactions were completed, varying the moisture level, density level and gradation separately. Then, working with the soil responses of the collected compaction data, the form of the soil response was estimated with a second order equation. The equation's parameters that best fit the data were identified. Afterwards, the parameters were further interpreted such that statistically significant patterns were revealed expressing the soil's density and moisture properties. Using the identified patterns, a system model was developed to calculate the soil's wet density and moisture content. Applying this model to the gradation data, Figure 3, it can be seen that changing the soil type alters the response from the original model such that the original model for one soil type is not robust enough for all soil types in terms of wet density. In order to make the original model more robust, thus enabling use on handling several soil types, adjustment were made.

Model Enhancement

It was found that by using the MUT's specific surface area (SA), linear adjustments could be made to the soil model's calculation of wet density and moisture. Bulk SA adjustments were developed using the SA of idealized particles found in soil for gravel, sand and silt [2]. Other researchers have also found that their models are sensitive to the MUT's SA [3, 4]. Figure 4 shows the re-calculated wet density results using the model adjustments made by the MUT's SA. Table 3 shows the slopes of the wet density calculations without and with the SA adjustment. In five of the six tested materials, when the SA adjustment was applied, the slope of the SDG wet density calculation became closer to one. In addition, the average wet density error between the NDG and the SDG was reduced by 119% when the SA adjustments were applied to the model.

Table 3. SDG Slope without and with SA Adjustments

Material	Slope **without** SA Adjustment	Slope **with** SA Adjustment
GPGM	0.7059	0.9945
GW	0.3274	1.004
SW	0.8971	1.003
GWGM (7.30% M)	1.15	1.702
GWGM (5.61% M)	0.8173	1.113
ML	0.7812	0.8256

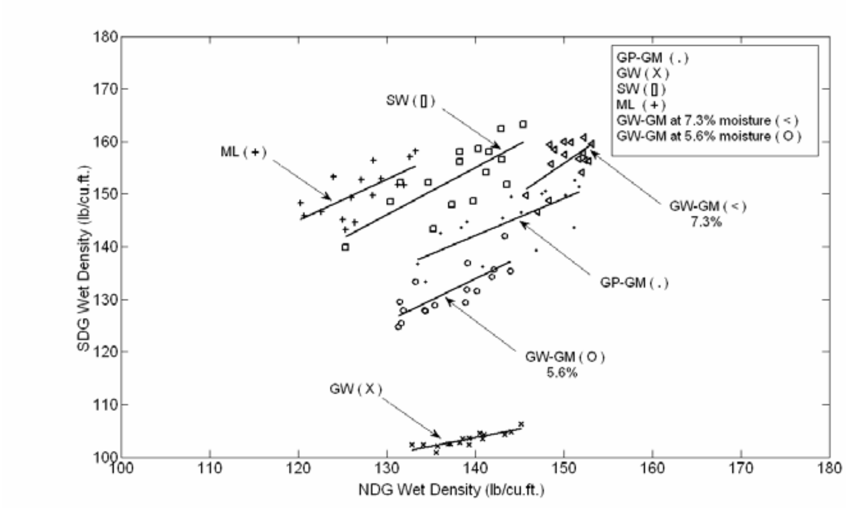

Figure 3. NDG Wet Density vs. SDG Wet Density without SA Adjustment

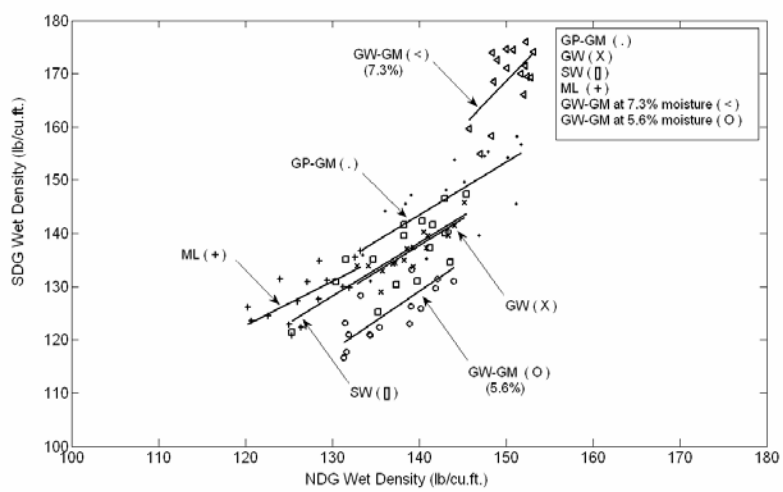

Figure 4. NDG Wet Density vs. SDG Wet Density with SA Adjustment

CONCLUSIONS

The investigators' testing and research demonstrated that soil gradation does affect the frequency response of the SDG/EIS instrument. Therefore, soil gradation affects the instrument's calculation of wet density. By using the gradation information of the tested materials, an adjustment was developed and applied to the empirical algorithm such that a variable was added to modify the slope and offset of the algorithm due to the soil's gradation, or more specifically, the specific surface area of the MUT. Currently the user enters the gradation of the MUT and the SDG instrument calculates the MUT's SA and adjusts the empirical inversion model accordingly. The specifics of the SA adjustment are proprietary information. The same method of SA adjustment is currently being applied to the measurement of moisture in soil. Initial results with the SA adjustment are encouraging and will be reported on at a later date. The SA of clay materials is significantly greater than that of the gravel, sand and fine materials that are typically used in road base and similar construction areas. As the empirical model continues to evolve, the use of the SDG on clay material will be possible.

Future applications of this technology include use as a quality control tool for concrete maturity, Cold in Place Recycled (CIPR) and Warm Mix Asphalt (WMA) road construction projects. This is made possible because of its ability to accurately measure the moisture content of these materials.

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