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MOISTURE AND UNIT WEIGHT READINGS FROM A COMPLEX IMPEDANCE MEASURING INSTRUMENT

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MOISTURE AND UNIT WEIGHT READINGS FROM A COMPLEX IMPEDANCE
MEASURING INSTRUMENT

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THESIS

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of
Science in Civil Engineering in the College of Engineering at the University of Kentucky

By

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Lexington, Kentucky

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ABSTRACT

MOISTURE AND UNIT WEIGHT READINGS FROM A COMPLEX IMPEDANCE
MEASURING INSTRUMENT

Complex Impedance Measuring Instruments (CIMI's) are non-nuclear devices that calculate the dry unit weight and moisture content of soil by means of electromagnetic wave propagation theory. Unlike nuclear based test devices, these devices do not require certification or elaborate maintenance to own and operate. CIMI operation requires a soil specific calibration process where soil moisture and unit weight are correlated to electrical parameters. A new, smaller acrylic mold was developed as an alternative calibration tool to the manufacturer's recommended mold. Calibrated soil models were generated using manufacturer recommended procedures as well as new procedures involving an acrylic mold. Models were then tested for accuracy. The new procedure outperformed the manufacturer's procedure.

Another small, acrylic mold was used to investigate the relationship between CIMI readings and soil parameters. Using several samples from four soils, the relationship between moisture, unit weight, and some electrical parameters was characterized. This characterization was then used to create a new, accurate calibration procedure.

KEYWORDS: Electromagnetic, Electrical Density Gauge, Nuclear Density Gauge, Quality Control, Complex Impedance Measuring Instrument.

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Chapter 1:   Introduction

Construction quality assurance (CQA) is an essential tool used by engineers to ensure that specified design parameters such as permeability and shear strength match the in-situ parameters. Currently, the most popular device is a nuclear-based testing device; however, due to regulative drawbacks, an alternative device with fewer restrictions is in demand.

Electromagnetic-based devices are a possible replacement for nuclear-based testing devices. Electromagnetic devices show promise; however, the application of this technology to CQA is still in its infancy. As such, research on improving the ease and accuracy of electromagnetic devices is ongoing.

There are several types of electromagnetic based CQA devices; however, this thesis focuses on the complex impedance measuring instrument (CIMI). CIMI's use measurements of impedance (Z), resistance (R), and capacitance (C) to interpolate values of unit weight and moisture content based on a soil model. This soil model is developed as a part of a calibration procedure. A typical soil model calibration procedure begins with taking several CIMI readings in a soil with a known moisture content and unit weight over a broad range of moisture contents and unit weights. Soil samples of known moisture content and unit weight can be tested in the field or in the laboratory. In the field, sand cone tests, drive cylinder tests, rubber balloon tests or some other reliable moisture/unit weight field test is taken alongside the CIMI readings. Soil samples of known moisture and unit weight can be developed in the laboratory using a mold.

1.1 Objectives of Research

Until a generalized electric soil model is developed, the most effective method of predicting soil moisture and unit weight values using CIMI technology is through calibration. For this reason, an efficient and accurate calibration process is essential for continued use of CIMI's. Therefore, it is the goal of this research to do the following:

- Analyze and assess current CIMI calibration technology

- Propose new calibration procedures

- Assess and analyze new calibration procedures

The ultimate goal is to provide the most efficient and accurate CIMI calibration procedure as possible.

1.2 Relevance of Research

As previously mentioned, CQA is vital in order to provide geotechnical engineering solutions. Although human judgment is a useful tool in geotechnical related CQA, an instrumented test is essential to provide consistent and reliable results.

Nuclear based test devices are reliable devices for CQA purposes; however, regulative restrictions have caused a demand for an alternative. A CIMI is a possible replacement for the nuclear based testing devices. An improvement to the calibration procedure for CIMI's would greatly increase the usability of similar devices. Therefore, this research is an important step towards providing an improved CQA tool.

1.3 Contents of Thesis

Chapter 2 examines a specific CIMI, the Electrical Density Gage (EDG) and the manufacturer suggested calibration procedures. Chapter 2 utilizes much of the data and

some of the text from Embry (2011). Although the EDG does allow for field calibration, an effective laboratory calibration is preferred due to safety, accuracy, cost and convenience concerns. The current manufacturer suggested laboratory calibration involves use of a large PVC proctor-type mold. The mold is very time and resource intensive to use and yields results not as accurate as the field calibration (Meehan and Hertz, 2013). Therefore, an alternative mold and calibration procedure was developed.

Calibrated soil models were developed for three clays and one sand using the manufacturer suggested method and the newly developed method. The accuracy of both calibrated models is examined by mimicking field conditions in a large test box. The testing and results are discussed further in Chapter 2. Work done under the current study and work done by Embry (2011) is clearly delineated in Chapter 2.

Chapter 3 makes use of an extensive set of laboratory data to examine the relationship between electrical readings taken from a CIMI and soil moisture and unit weight parameters. Over 100 soil samples from six different soils of varying moisture content and unit weight were prepared as a part of the analysis. Soil samples were prepared in a newly developed acrylic calibration mold similar to the mold used in Chapter 2.

Knowledge gained from this study was used to generate a new calibration procedure for CIMI's. A macro-enabled Excel workbook was developed, which automates the calibration process. The testing and results are discussed further in Chapter 3.

Chapter 4 presents the summary and conclusions of the research. Specifically, Chapter 4 presents the conclusions taken from Chapter 2 and 3.

Chapter 2:   Development of a New Calibration Procedure for a Non-Nuclear

Moisture-Unit Weight Device

2.1   Introduction

Quality control of subgrade materials used in civil infrastructure is an extremely important phase of construction.   A great deal of effort goes into ensuring that a foundation will provide adequate structural support.   Relating the dry unit weight and moisture content of the in-situ material to laboratory compaction tests is a common practice to assess the adequacy of subgrade materials.

The Nuclear Density Gauge (NDG) is the current state-of-the-art device used for quality assurance of compaction of in-situ subgrade materials. The NDG does have significant shortcomings, though. There is growing apprehension for using devices with a radioactive source. There are substantial financial costs associated with the ownership of nuclear compaction gauges including; training and certifications for technicians, semi-annual leak tests, yearly verifications, and bi-annual calibrations (USDA, 2013). There are also additional costs for storage, special handling, and shipping of hazardous material. Additionally, based on research from several sources, no clear consensus has emerged concerning the accuracy of nuclear based test devices (Isahai and Livneh, 1983; Gabr et al., 1995; Noorany et al., 2000) particularly when testing uncommon soil types such as coastal calcareous and volcanic soils (Brandes, et al. 2010).

These inadequacies have led to the demand for a non-nuclear device capable of providing quality assurance of subgrade materials, with electric based devices being one possible alternative. A fairly new addition to the list of electricity based methods and instruments used in soil moisture and unit weight determination is the complex-

impedance measuring instrument (CIMI). A CIMI utilizes soil measurements of resistance (R), complex-impedance (Z) and capacitance (C) in order to predict values of moisture content and dry unit weight. Complex impedance measurements have been shown to be comparable in accuracy to other electrical measurement methods, such as time domain reflectometry (Eller, 1996).

The Electrical Density Gauge (EDG) is a CIMI manufactured by Humboldt Manufacturing Company. The EDG uses electromagnetic (EM) wave propagation theory to relate electric readings of subgrade materials to physical properties of the materials in a manner benign to the user and environment.

Research has been performed on the EDG as a replacement for the NDG by various organizations (Adams et al., 2006; Brown, 2007). These case studies have shown that the EDG is suitable for use as a reference in CQA; however, there are concerns for the efficiency of the test methods of the EDG. The concerns pertain to the amount of material, time and labor required in the calibration process. The objectives for this study were to evaluate the EDG as a viable device to test for quality assurance of compacted subgrade materials using new and standard practices.

2.2 Theory and Operation of the Electrical Density Gauge

The Electrical Density Gauge (EDG) is a CIMI produced by Humboldt Manufacturing Company. The EDG has an operating frequency of 3 MHz, which is in the radio frequency range of the electromagnetic spectrum. The EDG and its components can be seen in Figure 2.1. The standard operating methodology for the EDG is formally presented in ASTM D7698 (ASTM D7698, 2011).

Figure 2.1: Components of the EDG

In general the device determines moisture and unit weight of soil a two-step process. First, a soil model is developed that relates electrical properties to the physical properties of the soil material. In this step, electrical measurements are collected by the instrument in the laboratory for samples that have varying measurable water contents and unit weights. These samples must be prepared such that they are in the range of anticipated moisture contents and unit weights that will be measured in the field. After collection of the electrical data from the lab samples, the physical data are measured and entered into the instrument. This combined data (electrical and physical) will be used to generate the correlating linear regression functions of the soil model. The second step involves determining field measures of weight and moisture content using the previously determined soil model linear correlating functions. The soil model can also be created from field measurements. In this approach, electrical measurements are collected at various locations and are correlated to measures of moisture content and unit weight determined by some reliable means of moisture content and unit weight measurement,

such as the sand cone density testing method (ASTM D-1556-07). A typical field setup

is shown in Figure 2.2
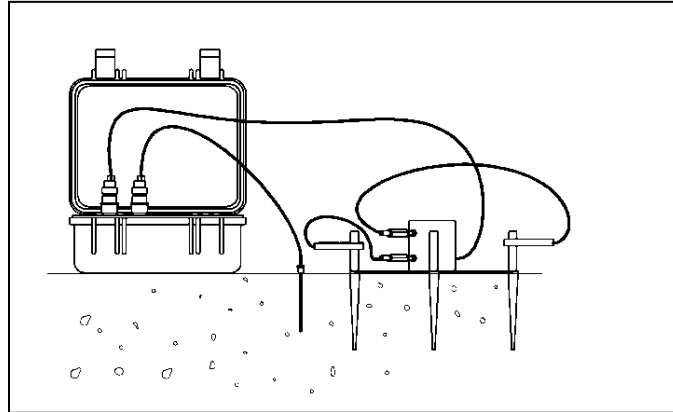
Figure 2.2: Typical field set up of EDG (ASTM D 7698-11)

2.3   Theoretical Basis of the EDG

The EDG measures current, voltage and phase and temperature. Resistance, capacitance and impedance are calculated by the EDG from these measurements. In the EDG's regression analysis, temperature corrected impedance (Z) is linearly correlated to wet unit weight and the temperature corrected ratio of capacitance to resistance (C/R) is linearly correlated to the weight of water per unit volume. Dry unit weight, moisture content and percent relative compaction are calculated and displayed by the EDG using these parameters.

Linear equation for the calculation of wet unit weight is given as:

$$\gamma_{wet} = A \times Z + B \qquad (1)$$

where γ_{wet} = wet unit weight in kN/m^3 or lbf/ft^3; A = soil model constant (established by the linear regression of data points from the soil model tests); Z = temperature corrected

impendence; B = a soil model constant (established by the linear regression of data points

from the soil model tests).

The linear equation for the calculation of the unit weight of water is given as:

$$W_w = D \times \left(\frac{C}{R}\right) + E \tag{2}$$

where W_w = weight of water, C/R = the temperature corrected ratio of capacitance to

resistance, D and E = a soil model constant (established by the linear regression of data

points from the soil model tests).

The dry unit weight, γ_{dry}, is calculated using the following equation:

$$\gamma_{dry} = \gamma_{wet} - W_w \tag{3}$$

The percent moisture content, ω, is calculated as follows:

$$\%\omega = \frac{W_w}{\gamma_{dry}} \times 100\% \tag{4}$$

The percent relative compaction, RC, is calculated as follows:

$$\% RC = \frac{\gamma_{dry}}{\gamma_{dry\,(max)}} \times 100\% \tag{5}$$

where $\gamma_{dry\,(max)}$ = maximum dry unit weight as determined by a standard proctor.

Currently, the manufacturer suggested laboratory calibration procedure involves

the use of a large PVC mold in which samples are compacted. This mold requires a large

amount of time and material in order to complete the calibration process. Field calibration

is another manufacturer suggested option; however, this is also often costly, time-

consuming and inefficient. An alternative laboratory procedure was created as a part of

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this study. In order to assess the manufacturer suggested procedure and compare it to the new one, several tests were performed. These tests are described below.

2.4   Materials and Methods

Four Kentucky soils were used for this research: a coarse grain, fast draining sand from Gallatin County, a lean, low plasticity clay from Lee County, a lean clay from Daviess County, and a fat, high plasticity clay Fayette County. This broad range in material type is beneficial, as it encompasses most Kentucky soils used for construction of subgrade materials. A material summary is shown in Table 2.1.

Table 2.1: Soil index and geotechnical properties of test soils

Soil	Specific Gravity	LL (%)	PI (%)	% Sand	% Silt	% Clay
Gallatin County sand	2.65	N/A	N/A	95.7	0.4	0
Lee County clay	2.76	34.4	7.6	20.5	48.9	21.2
Daviess County clay	2.72	23.3	3.9	4.4	75.3	20.3
Fayette County clay	2.86	64.3	29.3	13.2	12.0	74.8

LL=Liquid Limit, PI=Plasticity Index, % Sand = 4.75mm to 0.075 mm, % Silt = 0.075 m to 0.002 mm, % Clay = <0.002 mm

Two test boxes were constructed and used to represent field conditions. The first, a large polycarbonate box with length, width and height dimensions of 596 mm, 596 mm and 610 mm. The second was a smaller wooden box with length, width and height dimensions of 381 mm, 381 mm, and 356 mm. Prepared soil samples were compressed by a hydraulic load frame either four or five times for each moisture content. After each

compression the soil was allowed to rebound for a given amount of time, generally

around five minutes, and the EDG was then used to collect electrical measurements. A

sand cone reading was taken immediately after the electrical reading on the final

compression. Gallatin County sand, Fayette County clay, and Daviess County clay were

tested in the large test box. There was not sufficient Lee County clay to fill the larger

box; therefore, it was tested in the smaller wooden box.

2.5   Manufacturer Suggested Calibration Procedure

As previously stated, calibration of the EDG involves creating a soil model. For the

model, the manufacturer suggests using a six point matrix that consists of soils with three

moisture contents compacted at two unit weights. The moisture contents and unit weights

should be prepared such that they encompass the range of anticipated field moisture

contents and unit weights. The soil model points are illustrated in Figure 2.3. If a field

reading is taken outside the bounds of the soil model, the EDG will still calculate and

produce a reading; however, the soil model will have to be extrapolated and the reading is

more prone to error.
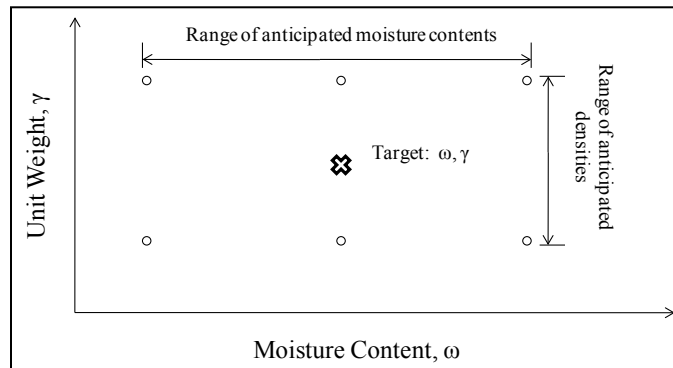
Figure 2.3: Soil model six point matrix

Currently, the manufacturer offers field and laboratory calibration procedures. Developing soil models in the field can lead to safety hazards and interfere with the contractor's project. For this reason, only offsite calibration methods were performed.

The manufacturer of the EDG supplied a calibration mold to create offsite soil models. The mold is a cylindrical PVC section with a diameter of 381 mm and a height of 254 mm. The soil is compacted into the mold using a plunger style hammer with a circular metal head with an inside diameter of 127 mm. The manufacturer suggests the soil to be compacted in three equal lifts; however, it does not suggest a methodology to ensure the desired unit weights are obtained.

Figure 2.4: Manufacturer suggested mold and hammer

As shown in Figure 2.3, three moisture contents are recommended compacted at two unit weights. The lower unit weight was achieved by using 15 blows with the plunger style hammer per lift for three lifts and the higher unit weight was achieved by using 30

blows per lift. For this study, a standard compaction test (ASTM 698) was performed on all soils to obtain an optimum moisture content, ω_{opt} and maximum dry unit weight, $\gamma_{dry(max)}$. These values were used as a reference to obtain the target moisture content and unit weight used to develop the soil models.

Unit weight of the soil compacted in the mold was calculated using weight of soil divided by volume of soil. The weight of soil was measured by weighing both the mold and soil, and subtracting the weight of the mold. The top soil layer was uneven, therefore using average measurements with just a ruler raised concern for erroneous soil volume readings, and therefore, another approach was developed and used. First, an impermeable layer covered the soil; in this case a black garbage bag was used. Water was poured on top of the soil and filled the rest of the mold. Then by dividing the weight of water added by the unit weight of water the volume of water could be calculated. Subtracting the volume of water from the total volume of the mold, the volume of soil can be accurately calculated, which also accounts for uneven soil layer height.

The current calibration procedure has concerns pertaining to the accuracy, efficiency and adequacy of the procedure. Using the plunger style hammer leads to varying compaction effort as there is no way to ensure consistent drop height and force. This leads to density variations within the soil sample. It was also found that achieving the maximum dry unit weight obtained from a standard compaction test was difficult to achieve in the EDG calibration mold.

Efficiency concerns for soil model development using the EDG mold stem from the amount of soil needed to create a model. Each one of the recommended six soil model points use approximately 0.356kN of soil. The resources and effort required to collect,

manage and store that amount of soil is significant. Preparation of each sample is labor intensive as well.

These concerns make use of the manufacturer-suggested calibration procedure less desirable. Therefore, a new calibration procedure is sought. The intent was to develop a calibration procedure that was less labor intensive, less time consuming, and required significantly less soil. The new procedure should also repeatedly perform at least as well as the current procedure.

2.6   Proposed Calibration Procedure

To address the major issues concerning the manufacturer's recommended calibration procedure and ensure an effective method, a prototype calibration apparatus was constructed to meet these criteria and is shown In Figure 2.5.
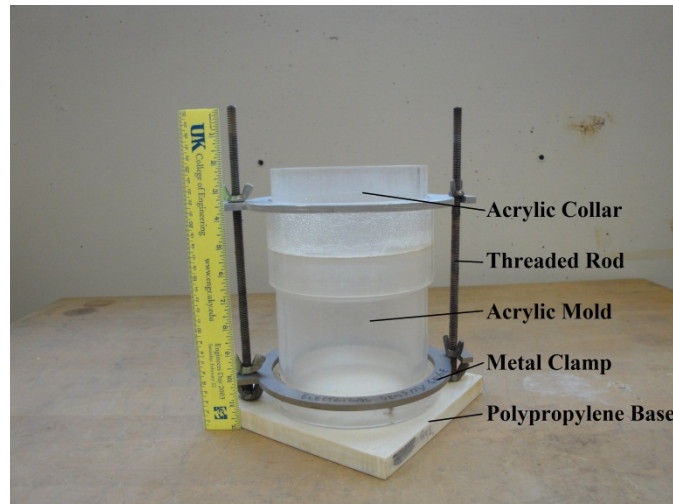
Figure 2.5: Proposed calibration apparatus

The proposed calibration mold is somewhat similar to the proposed mold used for a standard compaction test (ASTM D 698). The assembly consists of an acrylic mold,

acrylic collar, polypropylene base with threaded rods and metal clamps to secure the mold and collar to the base.

The acrylic mold was constructed out of two acrylic cylinders. The primary cylinder has inside and outside diameters of 127 mm and 152.4 mm, respectively, and a height of 152.4 mm. The second cylinder, located at the bottom of the mold, provides a platform on which a clamp sits to fasten the mold to the base, and serves the same purpose as the tabs on a metal proctor mold. The second cylinder was fabricated out of an acrylic cylinder, with inside and outside diameters of 152.4 mm and 177.8 mm respectively, with a height of 25.4 mm.

The collar was also constructed from two acrylic cylinders. The cylinders were machined to fit precisely together and joined with the Weld-On #16 Acrylic Solvent Cement. When assembled, the collar extends 76.2 mm above the acrylic mold.

The base of the proposed calibration apparatus was constructed from a sheet of polypropylene. It was fabricated to the length, width and height dimensions of 203.2 mm, 203.2 mm and 19.05 mm, respectively. A 3.18 mm circular indention was machined centered in the base to match the machined bottom of the acrylic mold. The two holes diagonal from one another are threaded so that the threaded rods can be securely fastened to the base. The threaded rods have a diameter of 12.7 mm and have a length of 304.8 mm.

To secure the mold and collar to the base, two metal clamps were used. The clamp on the left is used to secure the collar, and the clamp on the right is used to secure the acrylic mold to the base. The collar clamp differs from the acrylic mold clamp, by having an inside diameter 6.35 mm smaller than the inside diameter of the acrylic mold

clamp. This smaller inside diameter was necessary for the collar due to its' smaller diameter.

To develop a soil model point, soil is compacted into the acrylic mold in three equal lifts with a standard 2.45 x 10^{-2} kN proctor hammer. After the soil was compacted into the mold, the soil is struck off to ensure consistent sample volumes. The weight of the mold and soil is then taken and recorded in order to obtain a unit weight value. To take electrical readings, two metal rods, or "soil nails", are driven into the soil. The soil nails have a diameter of 3.18 mm and a length of 190.5 mm. The soil nails are driven into the sample the full length of the mold, 152.4 mm, the same penetration depth of the EDG soil darts. The electrical readings were taken at a nail spacing of 101.6 mm and 50.8 mm.

Since the soil was assumed to be homogeneous, only two soil nails are used, as opposed to four soil darts, as in the EDG specifications. The cross pattern was simulated by switching the electrode clamps on the nails to provide a complete the EDG reading. This proposed method is considered sufficient as each electrical reading consists of both nails acting as the source of the electromagnetic wave and both nails act as the receiver.

The proposed calibration procedure met all the desired objectives and considerations. The weight of the soil for one test never exceeded 4.45x10^{-2} kN. Therefore, for the recommended six point soil model, the total soil required would be less than one test with current calibration procedure in the 381 mm diameter PVC mold. This decrease in required soil significantly increases the efficiency of the proposed calibration procedure. Multiple soil samples can be prepared for the proposed calibration procedure in the amount of time it would take to prepare one sample of the current calibration procedure. Additionally, use of a proctor hammer in compaction, allows a more

controlled effort, more easily relatable to field effort. This also allows for the possibility of combining standard proctor test with the soil model development procedure.

2.7   Performance of Proposed Calibration Procedures

Soil models were created for each of the Kentucky soils using both the manufacturer's suggested procedure and the newly proposed procedure. Then, using the procedures outlined in Section 2.4, box samples intended to model field conditions were produced. EDG readings of the box samples were taken and used to assess the effectiveness of the new and old calibration and correlation procedures. As mentioned previously, the EDG currently utilizes the relationship of the ratio of capacitance to resistance versus the weight of water, and impedance versus wet unit weight. These relationships were also used in this study

Figure 2.6 shows the linear equations for the relationship between the ratio of capacitance to resistance and weight of water for all four soils used in this study.
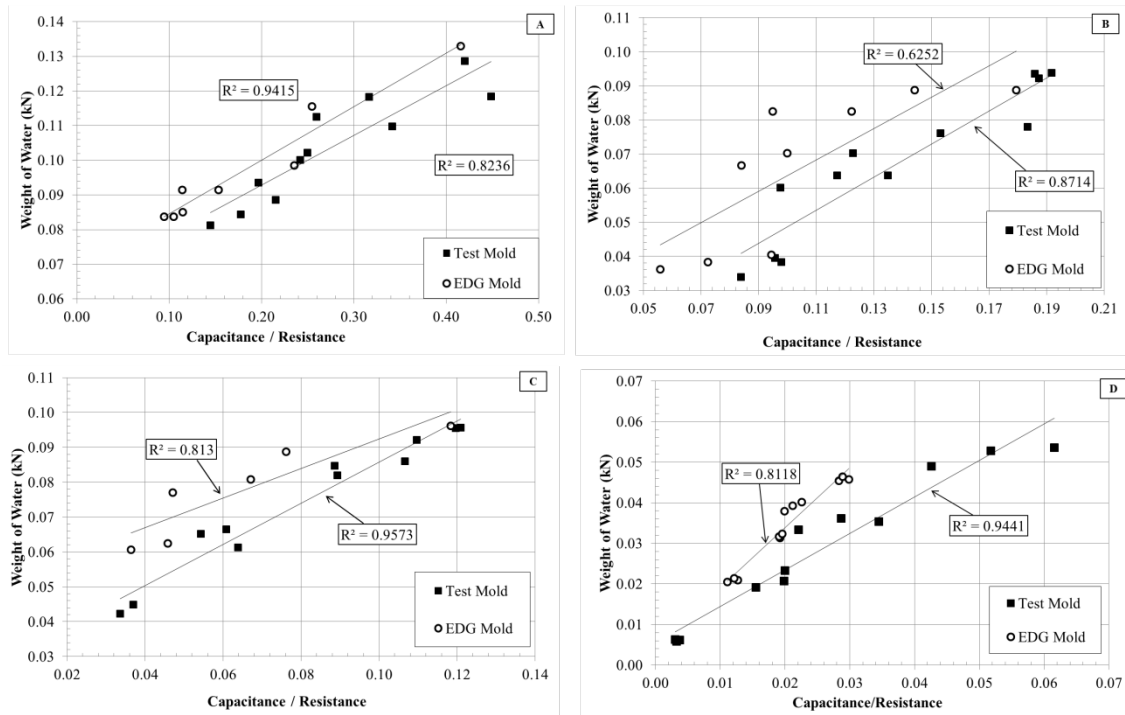
Figure 2.6: Weight of water as a function of Capacitance / Resistance for (A) Fayette County clay, (B) Daviess County clay, (C) Lee County Clay, and (D) Gallatin County sand

The "Proposed mold" points were the readings taken in the proposed calibration mold, and the "EDG mold" readings were taken in the current calibration mold. For the Fayette County clay, the EDG mold yielded slightly stronger correlations than the proposed mold for the weight of water linear equations. However, in every other case, the new proposed mold model had a higher R^2 value. The index properties of the Fayette County clay, specifically the specific gravity, liquid limit, plasticity index and percent clay, are significantly different than the other soils. This is a possible explanation for the difference in performance. The These high correlations are essential to justify the use of the new proposed mold.

Figure 2.7 shows the relationship between impedance and wet unit weight in the test soils.
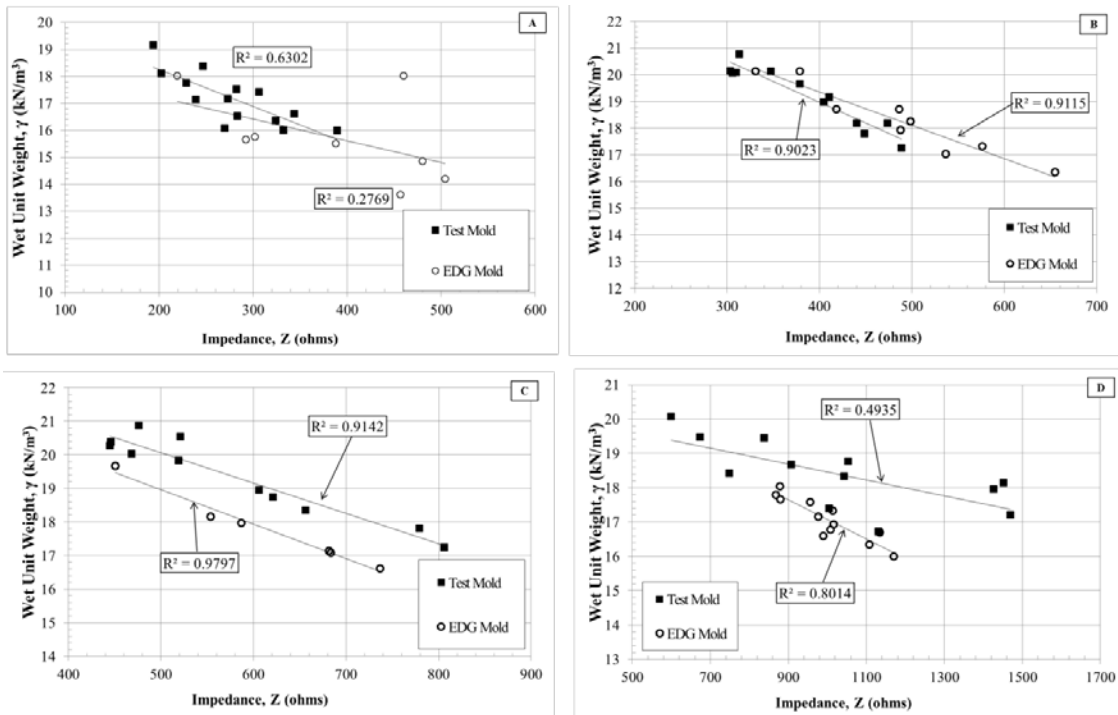
Figure 2.7: Wet unit weight as a function of impedance in (A) Fayette County clay, (B) Daviess County clay, (C) Lee County Clay, and (D) Gallatin County sand

The correlative results were more variable in the wet unit weight charts as opposed to the moisture charts for both molds. The new proposed mold yielded a stronger correlation than the current EDG mold only in the Fayette County clay; however, the correlation was not strong. In the Daviess and Lee County clay, the new mold did not correlate as well as the old; however, the new mold still yielded strong correlations. In the Gallatin County sand, neither mold provided especially strong correlations, with the new proposed mold providing results with the lower correlation. Lee County clay and Daviess County clay both share similar index properties, specifically specific gravity,

liquid limit, plasticity index, and percent clay. This may explain the difference in performance.

As can be seen, there is an offset between the Proposed mold and EDG mold points in both weight of water and wet unit weight graphs. It can be speculated that the electromagnetic field is constrained in both the proposed mold and EDG mold by the bottom and sides of the respective molds, affecting the electrical readings in the soil causing the offset. It is also possible that the aforementioned effect is enhanced or diluted due to certain soil index properties, which may explain the varying nature of the performance of the two molds.
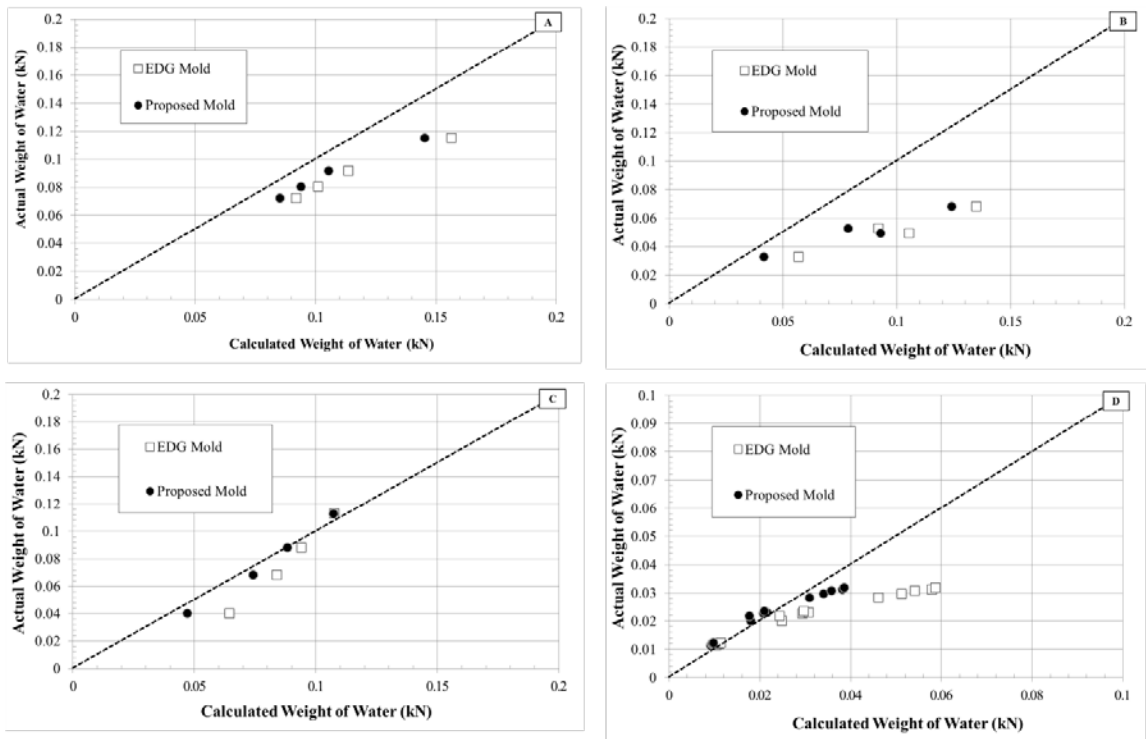
Figure 2.8: Weight of water performance results for (A) Fayette County clay, (B) Daviess County clay, (C) Lee County clay, and (D) Gallatin County sand

To assess the effectiveness of the proposed calibration procedure, soil models created with the proposed mold and soil models created with the EDG mold were both

used to predict moisture and unit weight in the soil test box. Figure 2.8 shows the performance of the calibration procedures on the four study soils tested. The dashed line represents a line of unity; ideally data points would plot along this line. "Actual" moisture contents and unit weights were determined using a sand cone density test (ASTM D1556-07). As previously mentioned, the Lee County soil was tested in the smaller wooden box. The other three soils were tested in the larger polycarbonate box. For every soil type, the new proposed mold soil model outperformed the old EDG mold soil model. This is a clear indication that soil models developed in the new test model yield more accurate measurements of soil water content.

Figure 2.9 shows similar model performance graphs for calculated wet unit weights.
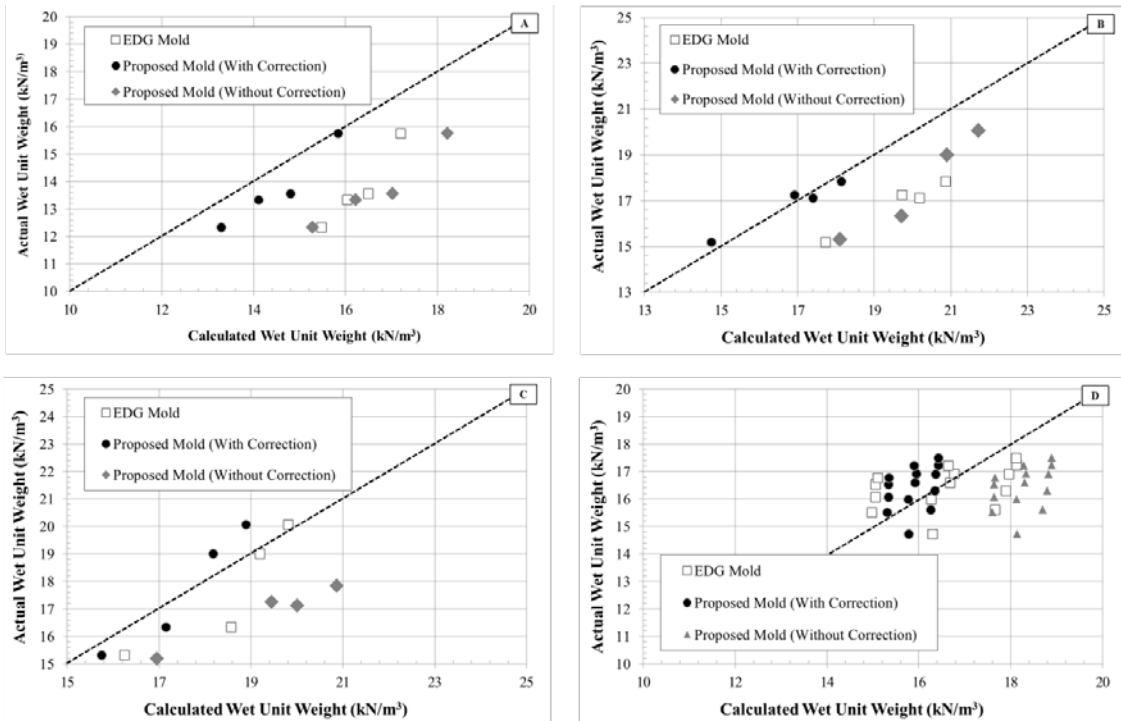
Figure 2.9: Wet unit weight model performance results for (A) Fayette County clay, (B) Daviess County clay, (C) Lee County clay, and (D) Gallatin County sand

Figure 2.9 was developed very similarly as Figure 2.8; however there is a slight difference in the calculation of the "Proposed Mold" points. Proposed Mold point with and without a correction are shown. The correction is explained below. The values generated from the proposed mold soil model consistently overestimated the actual value by approximately 15%. Therefore, for the development of the new proposed mold points, Equation 1 was amended as is shown in Equation 6. No adjustment was made for the EDG mold, as the skew of the data was not consistent. With this simple extra calibration step the proposed mold outperforms the old EDG mold in predicting wet unit weight.

$$\gamma_{wet} = \frac{(A \times Z + B)}{1.15} \qquad (6)$$

The summary of the results are presented in Table 2.2.

Table 2.2: Summary of percent error values from four Kentucky soils for both calibration methods

	Average Absolute % Error				
	Weight of Water		Wet Unit Weight		
	Proposed mold	EDG Mold	Proposed mold (with correction)	Proposed mold (without correction)	EDG Mold
Fayette County clay	27.93%	18.80%	5.84%	21.72%	19.17%
Daviess County clay	89.05%	60.94%	2.05%	14.58%	16.52%
Lee County clay	23.59%	7.76%	4.48%	14.33%	5.52%
Gallatin County sand	38.72%	15.62%	4.69%	11.54%	5.99%

Percent error was calculated as shown below.

$$Absolute\ \%\ Error = \left| \frac{Actual\ Value - Expected\ Value}{Actual\ Value} \right| \qquad (7)$$

As Table 2.2 illustrates, the new proposed mold outperforms the current standard EDG mold for every soil in both weight of water and wet unit weight calculations. The new mold performed especially well when calculating wet unit weight. The disproportionate amount of error in the Daviess County clay weight of water calculations is unexplained; however, it should be noted that the new proposed mold provided a percent error of nearly 30% less than the current EDG mold. The index property of Daviess County clay most different than other soils tested was percent silt. This could possibly explain the large error.

As previously mentioned, the large test box was compressed four to five times, with each moisture content and electrical reading being taken after each compression. After the last compression, a sand cone reading was taken to calculate actual moisture content and unit weight and a sample was collected for an oven moisture content. The initial and intermittent unit weights were calculated by dividing the weight of the soil by the measured volume of the soil. When plotting the relationship between the unit weights versus the electrical parameters, there was a very low correlation for the initial and intermittent unit weights, with R^2 values of approximately 0.35. When plotting only unit weights obtained by the sand cone, the trend scatter reduced significantly and R^2 values increased dramatically. Linear equations for all the clays were created by using the data obtained by the sand cone test.

There was a concern that a sand cone apparatus would not give valid readings in the Gallatin County sand, therefore all unit weights for the Gallatin County sand were calculated by dividing the weight of the soil by the measured volume of the soil.

Therefore, it is recommended that caution should be taken when evaluating the performance of the calibration methods in the Gallatin County sand.

2.8   Summary and Conclusions

As stated in the objectives, when developing the proposed calibration procedure, one main goal was for the proposed calibration procedure to perform as well as, or better than, the current calibration procedure. This was the case in every soil for both weight of water and wet unit weight. This result is a significant step forward for use of the EDG as a NDG replacement.

The new calibration apparatus and procedure is considerably more efficient and reliable than the current apparatus and procedure. The new method uses approximately an eighth of the soil as the current procedure. The new method can also easily be coupled with a standard proctor test to further conserve time, labor, soil, and money. Furthermore, use of the proctor hammer in compaction makes it easier to attain the desired unit weights in soil model development. In short, the new calibration mold and method is more efficient, more accurate, less expensive and less labor intensive.

It was acknowledged that the data presented does not cover a broad spectrum of soils. However, there is sufficient evidence to support the potential of the proposed calibration procedure. The efficiency gains of both time and effort would justify further research and development of the proposed calibration procedure in the proposed calibration apparatus.

Chapter 3: **A New Method for Obtaining Moisture and Unit Weight Parameters Using a Complex Impedance Measuring Instrument**

3.1 Introduction

It is often necessary to obtain the in-situ moisture content and dry unit weight of a soil. This is essential in order to ensure that the soil exhibits the desired shear strength, permeability or some other favorable engineering characteristic. Construction quality assurance (CQA) of soil is an essential tool for many civil infrastructure projects, including the construction of foundations, roadways, railways, landfills, embankments and dams.

There are several methods which can be used to determine the in-situ moisture content and unit weight of a soil. The sand cone (ASTM D1556), rubber balloon (ASTM D2167), and drive cylinder method (ASTM D2937) use actual measurements of weight and volume in order to obtain a moisture content and unit weight of a soil sample. Nuclear-based test devices (ASTM D6938) make use of a radioactive source which emits a constant amount of radiation. A measurement of the amount of radiation that arrives at the receiver located on the device at the ground surface is then correlated to moisture content and dry unit weight. A single manufacturer-provided correlative model can be applied to most soils.

Although nuclear-based test devices have achieved widespread acceptance for use in soil compaction CQA, there are several regulatory drawbacks associated with their use. Due to its radioactive source, users must undergo a specialized certification process.

Special accommodations must also be made for its storage, transportation and eventual disposal. Additionally, based on research from several sources, no clear consensus has emerged concerning the accuracy of nuclear based test devices (Isahai and Livneh, 1983; Gabr et al., 1995; Noorany et al., 2000) particularly when testing uncommon soil types such as coastal calcareous and volcanic soils (Brandes, et al. 2010).

3.2   Electrical Readings in Soil

Efforts have been made to create an electrical based device which can accurately determine moisture content and unit weight of a soil. Determination of unit weight and moisture content of materials through electrical measurements is not a recent innovation. Efforts were made as early as 1980 to gain moisture content readings using electrical measurements (Topp et al., 1980). Several researchers within the field of civil and agricultural engineering recognized the potential of electrical measurements for predicting moisture and unit weight and a steady stream of research has continued since (e.g. DeVoe et al., 1985; Powell et al., 1988; Eller and Denoth, 1996; Drnevich et al., 2001; Kelleners et al., 2005).

Several different methods have been employed to utilize electrical measurements to predict in-situ moisture content and unit weight. Methodologies include, but are not limited to, frequency and time domain reflectometry (Heimovaara, 1994; Drnevich et al., 2001; Umenyiora et al., 2012), capacitance and dielectric sensors (Eller and Denoth, 1996; Kelleners et al., 2005; Lee, 2005) and electrical impedance spectroscopy (Titta et al., 1999; Tetyuey et al., 2006; Chilcott et al., 2011).

Electrical readings in soils have proven to be a complex phenomenon, with several factors influencing the results. In addition to moisture content and dry unit weight, grain size, temperature, salinity and soil texture have also proven to have a significant effect on electrical readings (Lee, 2005; Oweiner et al., 2011). Some research suggests the impact of these parameters is relatively small compared to moisture content and unit weight (Eller and Denoth, 1996). However, other research suggests failure to account for variance in these parameters can result in percent errors up to 200 percent (Owenier et al., 2011). Furthermore, research has shown that loose soil follows a different electrical regime than compacted soil (Zainal et al., 2013). Due to this complex nature, it is often necessary to employ a soil-specific calibration in order to accurately correlate electrical readings with moisture content and dry unit weight.

3.3   Complex Impedance Measuring Instruments

A fairly new addition to the list of electricity based methods and instruments used in soil moisture and unit weight determination is the complex-impedance measuring instrument (CIMI). A CIMI utilizes soil measurements of resistance (R), complex-impedance (Z) and capacitance (C) in order to predict values of moisture content and dry unit weight. Complex impedance measurements have been shown to be comparable in accuracy to other electrical measurement methods, such as time domain reflectometry (Eller, 1996; Drnevich et al., 2001).

A CIMI generates an electromagnetic signal of known frequency and voltage that is transmitted to and from the soil using multiple embedded conductive darts or probes. Using onboard sensory equipment, measured values of R, Z and C can then be obtained

and correlated to moisture and unit weight. R, Z, and C values are related to moisture and unit weight values by way of a calibrated soil model.

ASTM D7698 explains the soil model calibration process in full; however, an overview of the process follows. In the field, CIMI tests are performed at several onsite locations. The tests are performed in locations such that they encompass the full range of moisture contents and unit weights expected to be encountered throughout the CQA process. Sand cone tests, drive cylinder tests, rubber balloon tests, nuclear-based tests or some other form of moisture and unit weight measurement are performed at the same location as each of the previously mentioned tests. At least 6 sample points are recommended by ASTM D7698. Next, the electrical readings are correlated to the measured moisture and unit weight values through linear regression analysis. Complex impedance is correlated to moist unit weight (γ_m) and the ratio of C to R is correlated to weight of water per unit weight (W_w). A mathematical formulation of the soil model is displayed in Equations 8 and 9.

$$\gamma_m = aZ + b \tag{8}$$

$$W_w = c\frac{C}{R} + d \tag{9}$$

where a, b, c and d are constants developed using a curve-fitting process.

Research has shown that using a CIMI in the manner described previously can generate readings that exhibit a significantly larger scatter (i.e. non-linearity) of values than a nuclear-based test device (Meehan and Hertz, 2013). In an effort to reduce the labor and increase the accuracy associated with the calibration of CIMI's, new laboratory based calibration procedures have recently been tested (Embry, 2011; Meehan and Hertz, 2013).

The first laboratory based calibration procedure, implemented by both Embry (2011) and Meehan and Hertz (2013), utilizes a large proctor type PVC mold. The mold has an inside diameter of 635 mm and a height of 254 mm. The mold has a removable, durable, plastic base. Similar to the field calibration procedure, several soil samples are prepared such that they encompass the necessary CQA range. Samples are compacted in the mold in several lifts using a hand-tamper. CIMI readings are taken in the mold for each sample. Measurements of moisture content and unit weight of the prepared sample are recorded. Then, using the same correlations as in the field calibration procedure, a soil model is developed. In both cases, results using this new laboratory calibration were undesirable. Additionally, the mold required a large amount of soil and effort to prepare sample points for soil model generation.

Embry (2011) developed a smaller, proctor type acrylic mold for use in CIMI calibration. The prototype mold was 127 mm in diameter and 152.4 mm tall with a removable polypropylene base. The smaller size of the mold allowed for more efficient creation of sample points for soil model generation. The calibration procedure was the same as the previously discussed procedure. Embry (2011) concluded that the new mold provided a much more useful soil model than the large PVC mold. The results still exhibited some variance from actual moisture and dry unit weight values, particularly concerning its use with sandy materials.

Despite much research in the field, there is room for improvement and innovation in the field of electrical based CQA. A major shortcoming of current CIMI calibration standards is their failure to account for the effect of moisture content on unit weight electrical readings and their failure to account for the effect of unit weight on moisture

content electrical readings. It is well documented that for a constant unit weight, electrical readings will vary with moisture content and that for a constant moisture content, electrical readings will vary with dry unit weight (DeVoe, D.R. et al., 1985; Ekwue and Bartholomew, 2011; Laloy, E. et al., 2011). This phenomena, so far, is not accounted for in current CIMI calibration procedures. This research aims to provide a deeper understanding of the relationship between moisture content, dry unit weight and electrical parameters. This new information will be used to generate a more accurate and efficient method for calibrating CIMI's.

3.4 Laboratory Testing Materials

Six Kentucky clays were as part of this research. The clays were chosen such that a broad range of specific gravity, liquid limit, plasticity index and clay fraction could be analyzed. Table 3.1 shows a summary of the index properties of the soils used.

Table 3.1: Index properties of test soils

Soil	Specific Gravity	LL (%)	PI (%)	% Sand	% Silt	% Clay
Warren County clay	2.75	42.8	18.3	13.1	19.5	68.5
Lee County clay	2.76	34.4	7.6	20.5	48.9	21.2
Daviess County clay	2.72	23.3	3.9	4.4	75.3	20.3
Fayette County clay	2.86	64.3	29.3	13.2	12.0	74.8
Lexington clay	N/A	55.7	26.1	N/A	N/A	N/A
Henderson County clay	2.69	28.2	8.5	0.6	79.4	20

LL=Liquid Limit, PI=Plasticity Index, % Sand = 4.75mm to 0.075 mm, % Silt = 0.075 m to 0.002 mm, % Clay = <0.002 mm

Organics, rocks, and other unwanted materials were removed from all soil prior to use. Large clumps were pulverized and the soil was then oven dried for approximately 12 hours. After drying, the soil was further ground using a mechanical crusher. Water was then added to the soil and it was then placed in a sealed container for at least 12 hours. Finally, the soil was hand-mixed prior to compaction.
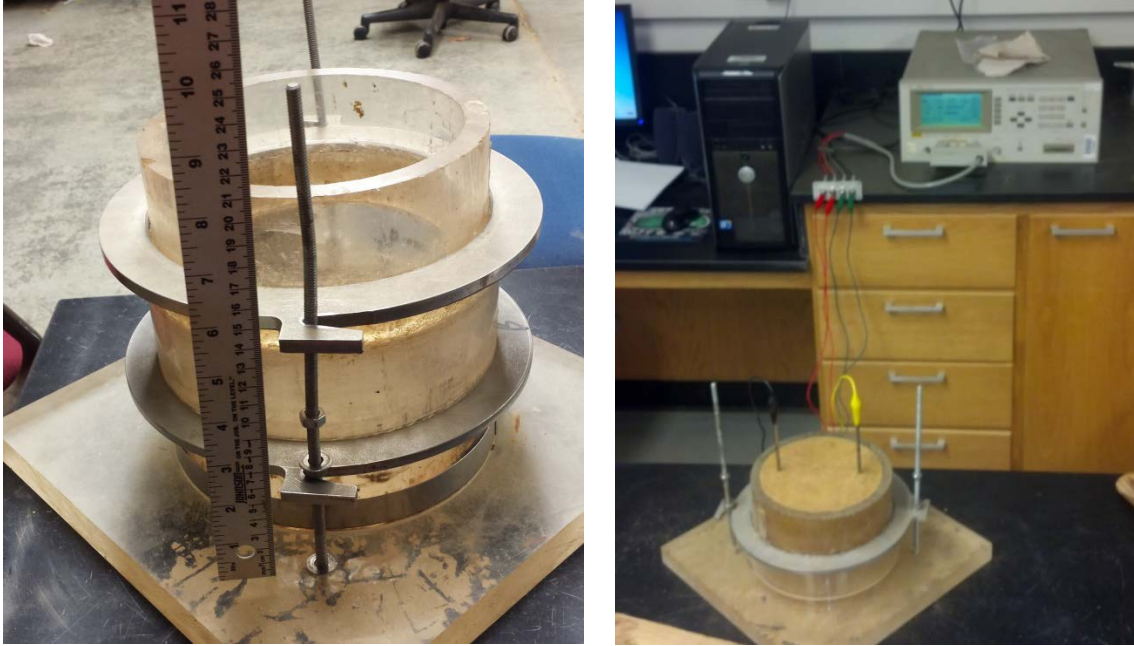
Figure 3.1: Prototype acrylic calibration mold (left) and prototype mold, soil nails, and LCR meter in use (right)

A new test apparatus was created for the purpose of this research. This apparatus is shown in Figure 3.1. The apparatus consists of an acrylic mold, an acrylic collar, an acrylic base, two threaded rods and two metal rings. The acrylic mold was constructed out of two acrylic cylinders. The inner cylinder of the mold has an inside diameter of 152.4 mm and an outside diameter of 177.8 mm. The outer cylinder of the mold has an inside diameter of 177.8 mm and an outside diameter of 190.5 mm. The height of both mold cylinders is 115.3 mm. The acrylic collar was also constructed out of two acrylic cylinders. The inner cylinder of the collar has an inside diameter of 152.4 mm and an outside diameter of 177.8 mm. The outer cylinder of the collar has an inside diameter of 177.8 mm and an inside diameter of 190.5 mm. The height of both collar cylinders is 76.2 mm. The metal rings rest atop the mold and collar and secure them both to the base. The

height and inner diameter of the mold is similar to the large 152.4 mm mold used for the modified proctor compaction test (ASTM D1557).

Once soil was compacted in the acrylic test apparatus, the collar was removed and the soil was struck off so that the surface is flush with the top of the mold. Using a wooden template to ensure consistent spacing and perpendicular entry, two metal rods, henceforth referred to as soil nails, were driven 114.3 mm into the sample. The nails are 3.175 mm in diameter and 190.5 mm long with one end tapering to a point. The nails were spaced 101.6 mm apart along the centerline of the mold. The soils nails were then connected to an Agilent 4285A Precision LCR Meter with alligator clamps. The LCR meter was then used to measure capacitance (C), resistance (R), and impedance (Z) of the soil. An input signal with a frequency of 3 MHz and an excitation voltage of 1 volt was used in all measurements.

3.5   Rigorous Model Development

For the Warren County clay, Lee County clay, Daviess County clay, and Fayette County clay, four batches of approximately 18 kg of dry soil were prepared as described in the "Laboratory Testing Materials" section. Differing amounts of water were added to each batch so that a range of gravimetric moisture contents could be tested. Soil from the batch was then compacted to the desired dry unit weight in the prototype acrylic test apparatus using a 101.6 mm hand compaction hammer. Each sample was compacted in five approximately equal lifts. Four samples were compacted at four differing dry unit weights from each batch. If possible, dry unit weights were selected such that the same four dry unit weights were compacted in all four batches for each soil. For the batches

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with higher moisture contents, it was not always possible or practical to compact the sample to the desired unit weight. After compaction, the collar was removed from the apparatus, the sample was stricken off, and the weight was recorded in order to obtain an exact unit weight.

Electrical measurements were taken on the sample in accordance with the procedure laid out in the "Laboratory Testing Materials" section. Once the electric readings had been taken, the mold was removed from the base, the soil sample was removed from the mold, and a portion of the sample was oven-dried in order to obtain an exact moisture content measurement.

After taking readings on the 64 samples (4 moisture contents compacted at 4 unit weights for 4 soils), the data was analyzed with the intention of finding a relationship between moisture, unit weight and electrical parameters. The data was sorted and grouped by moisture content and dry unit weight to aid in the model development. Obviously, it was not possible to obtain 4 samples with the exact same moisture content or dry unit weight; however, samples with similar moisture contents and dry unit weights were grouped together. Gravimetric water content (w), volumetric water content (θ), wet unit weight (γ), and dry unit weight (γ_d) were plotted versus several variations and combinations of electrical parameters, including C, R, Z, 1/R, C/R, R/Z, 1/Z, C/Z, $(C/R)^{0.5}$, $R^{-0.5}$, $C/R^{0.5}$, $C^{0.5}$, $C^{0.5}/R$, $(C/Z)^{0.5}$, $Z^{-0.5}$, $C/Z^{0.5}$, $C^{0.5}/Z$, $Z^{0.5}$, $R^{0.5}$. Although several electrical parameters correlated well with moisture content and unit weight, it was determined that γ_d versus $R^{-0.5}$ and w versus $Z^{-0.5}$ would be the most useful parameters for development of an electrical soil model.

In order to create more manageable values, several parameters in this study were normalized. Normalized dry density (γ_{dn}) values were generated as shown in Equation 10.

$$\gamma_{dn} = \frac{\gamma_d}{\gamma_w} \tag{10}$$

where γ_w is the density of water, 9.8 kN/m^3.

The prototype acrylic mold was filled with water and measurements of R and Z were taken in accordance with the procedure detailed in Section 3.4. Values of R$^{-0.5}$ and Z$^{-0.5}$ measured from soil samples were normalized to values of R$^{-0.5}$ and Z$^{-0.5}$ taken from the water-filled mold. These normalized values of R$^{-0.5}$ and Z$^{-0.5}$ will be referred to as resistance index (RI) and impedance index (ZI). Equations 11 and 12 show the calculation of RI and ZI.

$$RI = \frac{R^{-0.5}}{R_w^{-0.5}} \tag{11}$$

$$ZI = \frac{Z^{-0.5}}{Z_w^{-0.5}} \tag{12}$$

where $R_w^{-0.5}$ =0.05948 $\Omega^{-0.5}$, the R$^{-0.5}$ value of water in the prototype mold and

$Z_w^{-0.5}$ =0.05832 $\Omega^{-0.5}$, the Z$^{-0.5}$ value of water in the prototype mold.

Plots of these relationships are shown in Figure 3.2 and Figure 3.3. As mentioned before, sample points are grouped by moisture content and dry unit weight. The moisture content and normalized dry unit weight indicated in the legends of the following charts represent the average moisture content and normalized dry unit weight of the group.
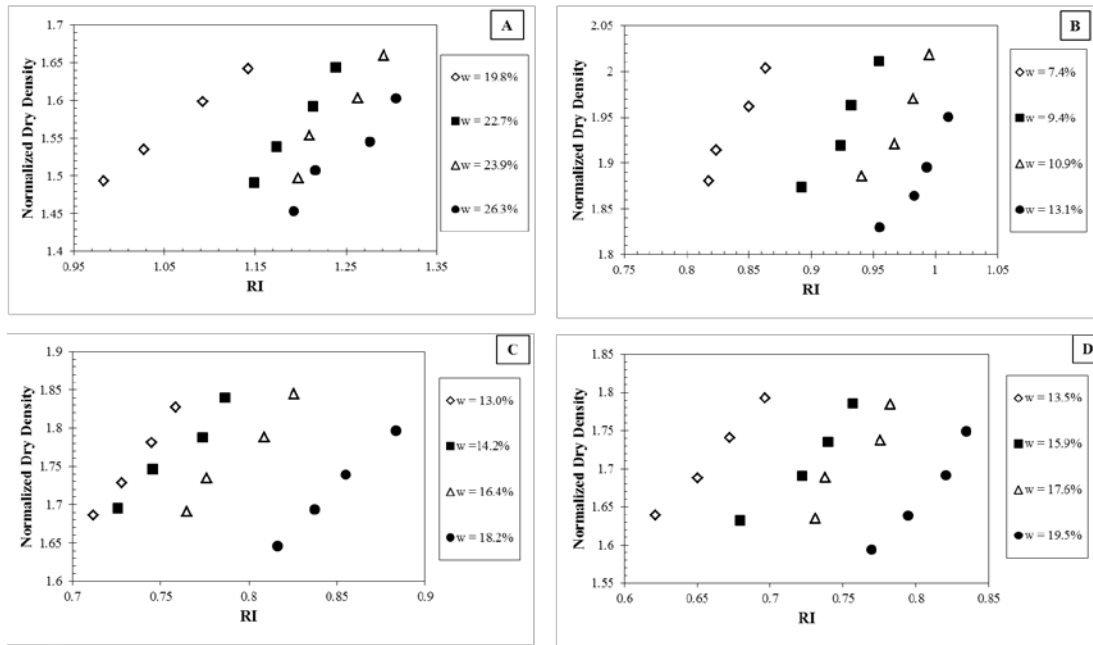
Figure 3.2: Normalized dry unit weight versus RI, grouped by average moisture content for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay

Figure 3.2 displays the relationship between RI and normalized dry unit weight and shows how that relationship varies as the moisture content of the sample varies. For a constant normalized dry unit weight, moisture content has a large effect on the RI value. For all soils tested, at a constant normalized dry unit weight, increasing moisture content resulted in an increased RI value. Similarly, for all soils tested, for a constant moisture content, increasing normalized dry unit weight resulted in an increased RI value. For a given normalized dry unit weight, the relationship between change in moisture content and change in RI does not appear to be proportional. However, for a constant moisture content, the relationship between change in normalized dry unit weight and change in RI does appear to be proportional. This proportionality appears as though it may be constant for all moisture contents for a given soil.

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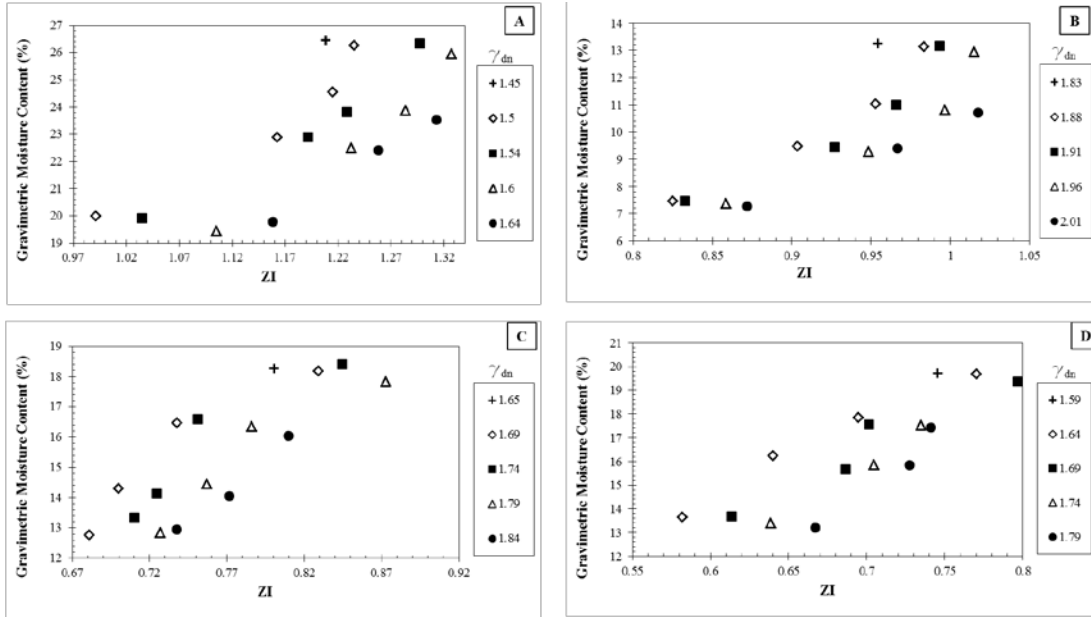
Figure 3.3: Gravimetric moisture content versus ZI, grouped by average moisture content for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay

Figure 3.3 illustrates the relationship between ZI and moisture content and how that relationship varies as the normalized dry unit weight of the sample varies. Although the relationship between moisture content and ZI does not appear to be as simple as the relationship between normalized dry density and RI, a correlation does exist. At a constant normalized dry density, the relationship between moisture content and ZI is non-linear. This non-linear relationship appears to be uniform for any dry density. However, the non-linear relationship does not appear to be similar between different soils. It does appear that the relationship between normalized dry unit weight and ZI is proportional for a constant moisture content. Although displayed in different ways, the relationship between moisture content, normalized dry unit weight and ZI shown in Figure 3.3 is

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similar to the relationship between moisture content, normalized dry unit weight and RI shown in Figure 3.2.

Patterns and relationships between moisture, normalized unit weight and electrical parameters have been noted and observed. However, in order to be useful, they must be quantified. Following are several steps which attempt to do so. The model generated using 16 sample points per soil (i.e. four moisture contents at four differing unit weights) will be referred to as the "rigorous model" from this point forward.

3.5.1 Determination of Normalized Dry Unit Weight

It was previously mentioned that for a constant moisture content, the relationship between change in dry unit weight and change in RI appears to be proportional and that this proportionality appears as though it is constant for all moisture contents for a given soil. Several steps were taken in an effort to confirm and quantify this observation. For each soil, the normalized dry unit weight versus RI data for each moisture content group was linearly curve fitted. For each soil, the mean of the four slopes from the curve fitting process was calculated in order to obtain an average slope of normalized dry unit weight versus RI at a constant moisture content. This average slope will be referred to as a_γ. For each soil, a new curve was linearly fit through each moisture content group, forcing a slope of a_γ. Intercept values, which will be referred to as $\gamma_{dn,int}$, were chosen such that the coefficient of determination (COD) value of the curve fit was as close to 1.0 as possible. Figure 3.4 illustrates the results of this process. COD values are displayed on the charts.
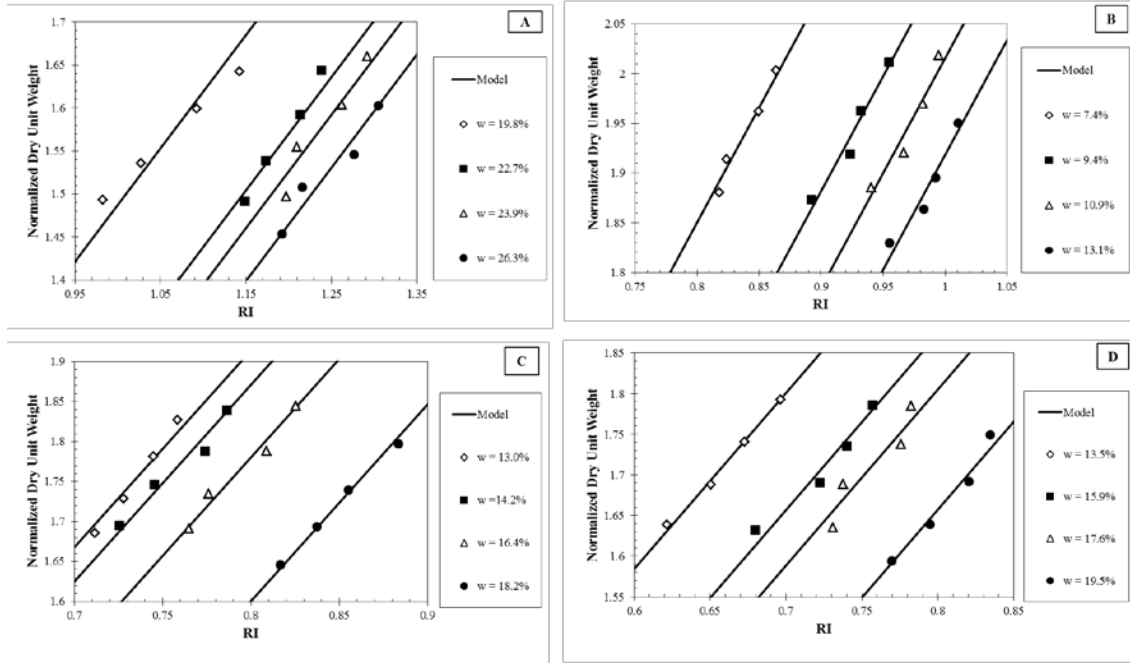
Figure 3.4: Normalized dry unit weight versus RI, grouped by average moisture content and fitted for a forced slope for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay.

As seen in Figure 3.4, the methodology of calculating and forcing a slope of a_γ yields very satisfactory results. With the exception of the $w = 19.8\%$ group from the Fayette County clay, all COD values were above 0.9. This implies that for a given moisture content, normalized dry unit weight will increase linearly with RI and that this proportionality is constant across all moisture contents. At this point, for a given moisture content, the relationship between normalized dry unit weight and RI can be described as shown in Equation 13.

$$\gamma_{dn} = a_\gamma RI + \gamma_{dn,\text{int}} \tag{13}$$

Table 3.2 tabulates a_γ, $\gamma_{dn,\text{int}}$, absolute percent errors and COD values for each of the moisture content groups of each soil. Absolute percent error is calculated as described

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in Equation 11. Note the extremely low average absolute percent error for every moisture content group.

$$Absolute \ \% \ Error = \left| \frac{Actual \ Value - Expected \ Value}{Actual \ Value} \right| \qquad (14)$$

Table 3.2: a_γ, $\gamma_{dn,int}$, COD, and average absolute percent error values for Fayette County Clay, Daviess County Clay, Lee County Clay and Warren County Clay.

Soil	a_γ	Average Group Moisture Content, w (%)	$\gamma_{dn,int}$	COD	Average Absolute Perecent Error (%)
Fayette County Clay	1.30	19.8	0.17	0.84	1.33
		22.7	-0.01	0.95	0.61
		23.9	-0.05	0.92	0.96
		26.3	-0.12	0.93	0.70
Daviess County Clay	2.30	7.4	0.01	0.97	0.39
		9.4	-0.18	0.95	0.38
		10.9	-0.28	0.94	0.57
		13.1	-0.38	0.93	0.59
Lee County Clay	2.50	13	-0.05	0.96	0.54
		14.2	-0.09	0.95	0.49
		16.4	-0.18	0.97	0.45
		18.2	-0.37	0.99	0.28
Warren County Clay	2.20	13.5	0.29	0.99	0.22
		15.9	0.14	0.95	0.70
		17.6	0.07	0.9	1.03
		19.5	-0.07	0.97	0.53

It is observed that $\gamma_{dn,int}$ is a function of moisture content; however, this relationship is highly non-linear. If a relationship between normalized dry unit weight, moisture content and RI is to be determined, the non-linearity of the relationship between

$\gamma_{dn,int}$ and moisture content must be quantified. Plots and curve-fits of $\gamma_{dn,int}$ versus moisture content are displayed in Figure 3.5.
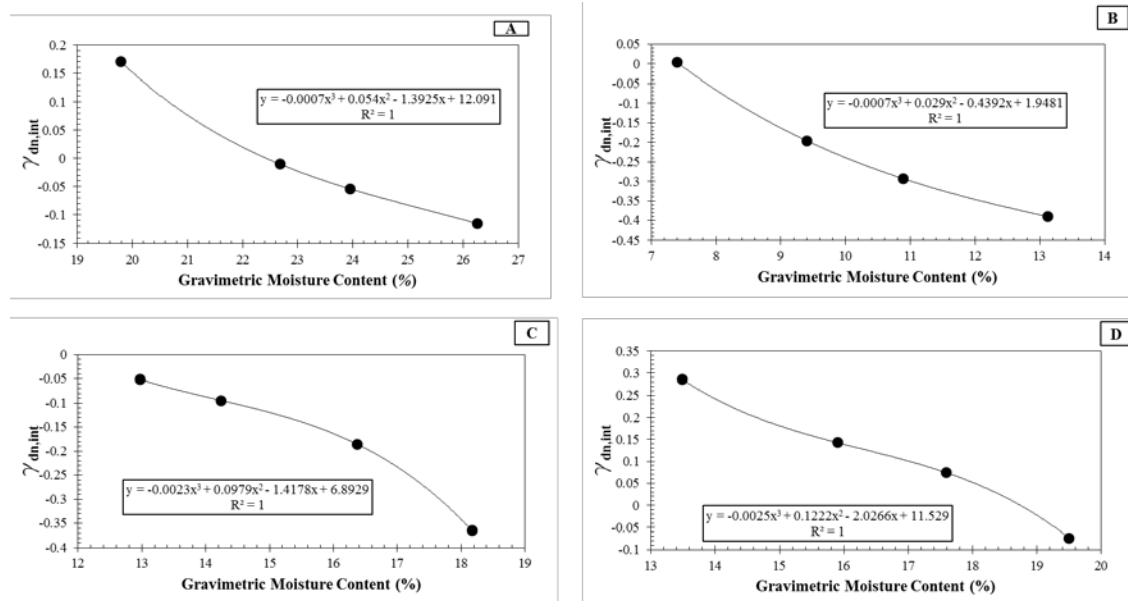
Figure 3.5: Plots of $\gamma_{dn,int}$ versus moisture content for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay.

A third order polynomial was chosen to describe the relationship over the range of moisture contents tested. Figure 3.5 illustrates the nonlinear relationship between $\gamma_{dn,int}$ and moisture content. Given the range of index properties encompassed by the four study soils, it is reasonable to assume that a polynomial function would apply to many clays.

It is acknowledged that because there are only four data points, the high COD values are meaningless. However, given the likelihood that the relationship between $\gamma_{dn,int}$ and moisture content exhibits two inflection points, it is important for future procedures to set the precedent of using a third-order polynomial to predict this relationship. A limitation of this methodology is that this relationship is likely highly variable outside of the range of tested data. Equation 15 shows the general form of the polynomial.

$$\gamma_{dn,int} = b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma \qquad (15)$$

Now that the variance of $\gamma_{dn,int}$ with respect to moisture content has been quantified, it is now possible to fully specify the relationship between normalized dry unit weight, moisture content and an electrical parameters. Equation 16 is created by combining Equations 13 and 15.

$$\gamma_{dn} = a_\gamma RI + b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma \qquad (16)$$

A summary of coefficients from the normalized dry unit weight formulation for each soil are summarized in Table 3.3.

Table 3.3: Coefficients for normalized dry unit weight formulation using rigorous model for Fayette County Clay, Daviess County Clay, Lee County Clay, and Warren County Clay.

Soil	a_γ	b_γ	c_γ	d_γ	e_γ
Fayette County Clay	1.32	-6.97E-03	0.05	-1.39	12.10
Daviess County Clay	2.31	-6.77E-03	0.03	-0.44	1.95
Lee County Clay	2.46	-2.26E-02	0.10	-1.42	6.89
Warren County Clay	2.16	-2.45E-02	0.12	-2.03	11.50

3.5.2 Determination of Gravimetric Water Content

Now a relationship must be found between moisture content, normalized dry unit weight and ZI. Figure 3.3 shows a plot of moisture content (w) versus ZI, with the data being grouped by average normalized dry unit weight. There are only four sample points within each normalized dry unit weight group, therefore it is not possible to obtain a

meaningful relationship between moisture content and ZI by curve fitting each normalized dry unit weight group due to the nonlinearity of the relationship and lack of data. Note, once again, that for a constant moisture content, dry unit weight appears to vary linearly with ZI. If this relationship can be confirmed and quantified, data from all 16 points for each soil can be collapsed to one common, arbitrary normalized dry unit weight. This data set can then be curve fitted and used to quantify the relationship between moisture content and ZI for a given normalized dry unit weight.

The same procedure was used to find the proportionality between normalized dry unit weight and ZI for a constant moisture content as was used to find the proportionality between normalized dry unit weight and ZI for a constant moisture content. For each soil, the normalized dry unit weight versus ZI data for each moisture content group was fitted using linear regression analysis. For each soil, the mean of the four slopes from the regression analysis was calculated in order to obtain an average slope of normalized dry unit weight versus ZI at a given moisture content. This average slope will be referred to as a_w. For each soil, a new curve was linearly fit through each moisture content group, forcing a slope of a_w. Intercept values, $\gamma_{dn,int}$, were chosen such that the coefficient of determination (COD) value of the curve fit was as close to 1.0 as possible.

Table 3.4 provides a summary of a_w, $\gamma_{dn,int}$, and COD values for each of the moisture content groups of each soil.

Table 3.4: a_w, $\gamma_{dn,int}$, and COD values for Fayette County Clay, Daviess County Clay, Lee County Clay and Warren County Clay.

Soil	a_w	Average Group Moisture Content, w (%)	$\gamma_{dn,int}$	COD
Fayette County Clay	1.26	19.8	0.22	0.83
		22.7	0.04	0.96
		23.9	-0.01	0.92
		26.3	-0.07	0.93
Daviess County Clay	2.14	7.4	0.13	0.97
		9.4	-0.06	0.99
		10.9	-0.15	0.99
		13.1	-0.22	0.95
Lee County Clay	2.11	13	0.25	0.93
		14.2	0.21	0.96
		16.4	0.14	0.98
		18.2	-0.05	0.99
Warren County Clay	2.16	13.5	0.36	0.96
		15.9	0.22	0.91
		17.6	0.16	0.88
		19.5	-0.01	0.92

As can be seen in Table 3.4, the methodology of calculating and forcing a slope of a_w yields very satisfactory results. With the exception of the $w = 19.8\%$ group from the Fayette County clay and the $w = 17.6\%$ group from Warren County clay, all COD values were above 0.9. This implies that for a given moisture content, normalized dry unit weight will increase linearly with ZI and that this proportionality is constant across all moisture contents.

Now that the relationship between ZI and normalized dry unit weight for a given moisture content has been determined, it is now possible to use this relationship to predict

the ZI value corresponding to some arbitrary, common dry unit weight for each sample point. In other words, since a reliable value of a_w has been determined, a theoretical ZI value which corresponds to any normalized dry density can be calculated for each sample point. The arbitrary normalized dry unit weight chosen was. Calculation of the aforementioned ZI value corresponding to this arbitrary normalized unit weight, which will be referred to as ZI_1, is shown in Equation 17.

$$ZI_1 = \frac{1 - \gamma_{dn}}{a_w} + ZI \tag{17}$$

where γ_d is the dry unit weight of a sample point in kN/m^3

Once ZI_1 has been calculated for each sample point, moisture content can be plotted versus ZI_1 and a curve fit can be used to more accurately quantify the relationship between moisture content and ZI for a given normalized dry unit weight. Plots of moisture content versus ZI_1 for each soil can be found in Figure 3.6.
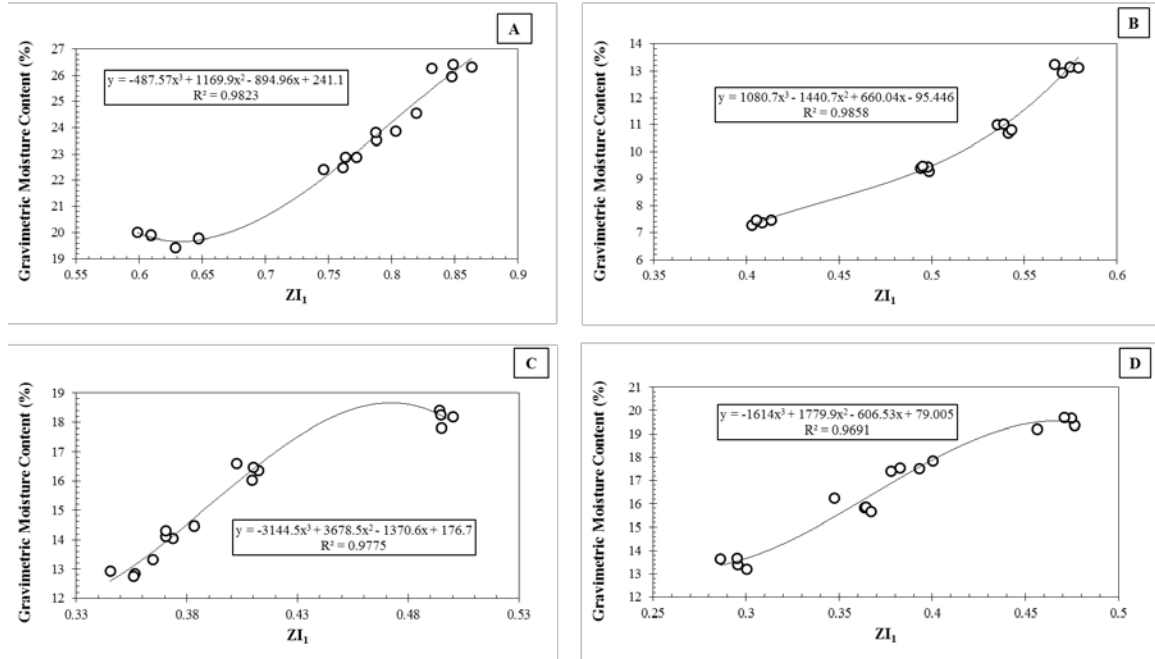
Figure 3.6: ZI_1 versus moisture content for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay.

Once again, a third order curve fit was used to estimate the relationship between gravimetric moisture content and ZI_1. This was done for the same reasons as presented during the generation of the relationship between $\gamma_{dn,int}$ and moisture content. Note the similarities between the curves in Figure 3.5 and Figure 3.6 for each soil. Moisture content can now be defined as:

$$w = b_w (ZI_1)^3 + c_w (ZI_1)^2 + d_w (ZI_1) + e_w \qquad (18)$$

where b_w, c_w, d_w, and e_w are constants from a curve fit as shown in Figure 3.7.

Now that a relationship between moisture content and ZI for a given normalized dry unit weight has been determined, it is possible to fully specify moisture content as a function of normalized dry unit weight and ZI. Combining Equations 17 and 18:

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$$w = b_w \left(\frac{1 - \gamma_{dn}}{a_w} + ZI \right)^3 + c_w \left(\frac{1 - \gamma_{dn}}{a_w} + ZI \right)^2 + \ldots \qquad (19)$$

$$d_w \left(\frac{1 - \gamma_{dn}}{a_w} + ZI \right) + e_w$$

Figure 3.7 plots both the predictive model (Equation 16) and sample data points alongside one another.
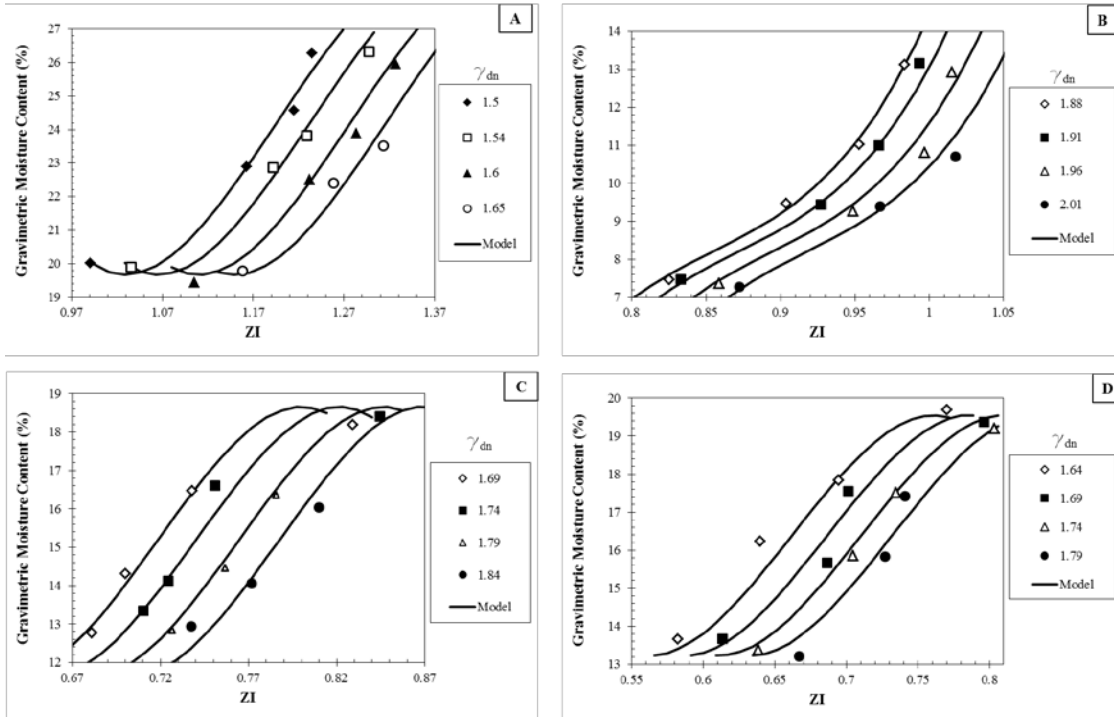
Figure 3.7: Gravimetric moisture content versus ZI, grouped normalized dry unit weight for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay.

As seen in Figure 3.7, the model appears to match very well the laboratory data. COD values are tabulated in Table 3.5 alongside average absolute percent errors for each dry unit weight group.

Table 3.5: COD and average absolute percent error for each normalized dry unit weight group for Fayette County clay, Daviess County clay, Lee County clay, and Warren County clay

Soil	Average Normalized Dry Unit Weight	COD	Average Absolute Perecent Error (%)
Fayette County Clay	1.50	0.96	1.40
	1.54	0.99	0.74
	1.60	0.99	1.02
	1.65	0.98	0.87
Daviess County Clay	1.88	0.99	1.47
	1.91	1.00	0.95
	1.96	0.99	1.57
	2.01	0.97	1.58
Lee County Clay	1.69	0.98	1.70
	1.74	0.97	2.01
	1.79	0.98	1.82
	1.84	0.95	1.77
Warren County Clay	1.64	0.96	2.09
	1.69	0.96	2.18
	1.74	0.99	1.25
	1.79	0.93	2.96

As was the case with the normalized dry unit weight formulation, the moisture content formulation process was very effective. All COD values of the predictive model were greater than 0.93. A more relevant statistic is likely the average absolute percent error for each normalized dry unit weight group, which was less than 3% in every case. A summary of coefficients for each soil from the gravimetric moisture content formulation are shown in Table 3.6.

Table 3.6: Coefficients for moisture content formulation using rigorous model for Fayette County Clay, Daviess County Clay, Lee County Clay, and Warren County Clay.

Soil	a_w	b_w	c_w	d_w	e_w
Fayette County Clay	1.26	-4.88E+02	1.17E+03	-8.95E+02	2.41E+02
Daviess County Clay	2.14	1.08E+03	-1.44E+03	6.60E+02	-9.54E+01
Lee County Clay	2.11	-3.14E+03	3.68E+03	-1.37E+03	1.77E+02
Warren County Clay	2.16	-1.61E+03	1.78E+03	-6.07E+02	7.90E+01

Normalized dry unit weight has now been defined as a function of moisture content and RI in Equation 16 and moisture content has been defined as a function of normalized dry unit weight and ZI in Equation 19.

3.6   Summary and Conclusions

RI and ZI can be easily determined with a CIMI. With RI and ZI known, there are two known relationships (Equations 16 and 19) and two unknown parameters, γ_{dn} and w. These two equations can be simultaneously solved in order to obtain a predictive normalized dry unit weight and moisture content value.

This methodology falls short in that it does not accurately predict moisture content and normalized dry unit weight outside the range of moisture contents and unit weights used to create the model. However, the same could be said for all CIMI calibration procedures. As with all calibration based electrical devices, it is imperative that the range of moistures and unit weights tested during the calibration process to match those expected to be measured in the field. It is possible, though, that with a larger range

of soil types, moisture contents and unit weights, a general model could be developed. A

summary of steps necessary for rigorous model development are shown in Figure 3.8 and

Figure 3.9

Measure R, Z, γ_d, and w for 16 soil samples in prototype mold (four moisture contents at four densities).

$\downarrow$

Plot normalized dry unit weight as a function of RI and group the data by moisture content. Perform a linear regression analysis for each moisture content group

$\downarrow$

Determine a_γ by calculating the average of the slopes found in the previous step

$\downarrow$

Determine $\gamma_{dn,int}$ for each moisture content group. For each moisture content group, perform a linear regression analysis forcing a slope of a_γ. $\gamma_{dn,int}$ is the intercept value from this linear regression analysis which yields a COD value closest to 1.0. Normalized dry unit weight can now be defined as follows:
$$\gamma_{dn} = a_\gamma RI + \gamma_{dn,int}$$

$\downarrow$

Perform a 3rd order polynomial curve-fit to estimate $\gamma_{dn,int}$ as a function of average group moisture content
$$\gamma_{dn,int} = b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma$$

$\downarrow$

Normalized Dry Density Formulation
$$\gamma_{dn} = a_\gamma RI + b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma$$

Figure 3.8: Summary of steps for rigorous model dry unit weight formulation
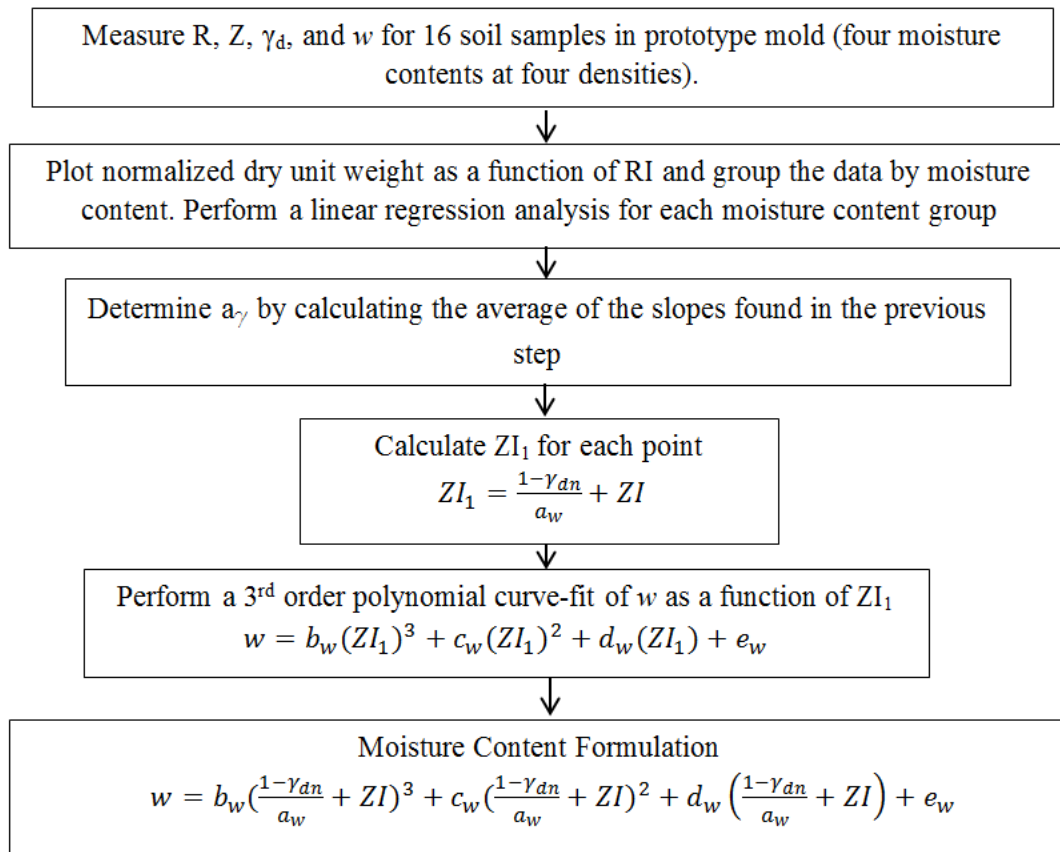
Figure 3.9: Summary of steps for rigorous model moisture content formulation

For a given moisture content, normalized dry unit weight will vary linearly with RI and ZI. This proportionality is consistent for all moisture contents tested for the given soils tested. For a given normalized dry unit weight, moisture content varies with RI and ZI in a highly nonlinear fashion. A curve which plots moisture content versus RI or ZI for a given normalized dry unit weight likely has two inflection points. Without further knowledge of this relationship, the best approximation is a third order polynomial curve fit.

Overall, the rigorous model performs exceptionally well, especially when compared to other lab-based calibration models. The high COD values and low absolute percent

error values are indicative of a model which is able to predict moisture and density with great accuracy. Due use of 3rd order polynomial regression analysis in the model development, the accuracy of the soil model is limited to the range of moisture content and dry unit weight values used in the generation of the model.

Chapter 4: Model for Obtaining Moisture and Unit Weight Using a CIMI

A properly calibrated CIMI can be a very powerful tool for CQA. A calibration procedure which generated a very accurate soil model was developed in the previous chapter. Although it proved to be very precise, development of the rigorous model required a large amount of data. Such an amount would not be desirable for practical application. Using the knowledge gained in the previous chapter about the relationship between dry unit weight, moisture content, and electrical parameters, a less rigorous methodology for model development has been established as a complimentary approach.

This less rigorous approach, which will be referred to as the "proctor model", only requires data from one 5-point proctor and one additional sample point. The additional sample point is chosen such that it shares a common moisture content with one of the proctor points but differs in unit weight. Since at least one proctor will certainly be performed for any construction quality assurance project, if the proctor is performed in the acrylic mold, this methodology will eliminate the large time and money expenditure typically associated with CIMI calibration. The proctor model development process is further explained in the subsequent sections.

Recall from the "Rigorous Model Development" chapter that for a constant moisture content, normalized dry unit weight varies linearly with both RI and ZI. This relationship was shown to be extremely reliable and consistent for 4 clays encompassing a wide range of index properties. Because this relationship is extremely consistent, if electrical readings are obtained from two points with common moisture contents and differing dry unit weights, a reliable value of a_γ and a_w can be calculated as shown in Equations 20 and 21.

$$a_\gamma = \frac{\gamma_{dn,a} - \gamma_{dn,b}}{RI_a - RI_b} \qquad (20)$$

$$a_w = \frac{\gamma_{dn,a} - \gamma_{dn,b}}{ZI_a - ZI_b} \qquad (21)$$

where subscripts a and b denote parameters corresponding to sample points a and b, which share a moisture content and differ in unit weight.

Recall that at this point in the "Rigorous Model Development" chapter, $\gamma_{dn,int}$ were determined for each moisture content group as a part of the normalized dry unit weight formulation and ZI_1 was calculated for each data point. For the proctor model development, $\gamma_{dn,int}$ and ZI_1 will be calculated for each point in accordance with Equations 22 and 23.

$$\gamma_{dn,int} = \gamma_{dn} - a_\gamma RI \qquad (22)$$

$$ZI_1 = \frac{1 - \gamma_{dn}}{a_w} + ZI \qquad (23)$$

As was the procedure for rigorous model development, curve fits of $\gamma_{dn,int}$ as a function of moisture content and moisture content as a function of ZI_1 must be developed. Once again, third order polynomial curve fits will be used. Because of this curve fitting process, it is very important that sample points encompass the range of moisture contents and dry unit weights expected to be encountered in the field. At least 6 sample points are required by this procedure. However, more sample points would yield even more reliable results. The spacing of moisture contents and dry unit weights should be kept as consistent as possible. Constants from the curve fitting process are displayed in Equations 24 and 25.

$$\gamma_{dn,int} = b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma \qquad (24)$$

$$w = b_w(ZI_1)^3 + c_w(ZI_1)^2 + d_w(ZI_1) + e_w \qquad (25)$$

At this point, moisture content can now be defined as a function of normalized dry unit weight and ZI and normalized dry unit weight can be defined as a function of moisture content and RI by the same relationships as those used in the rigorous model.

$$\gamma_{dn} = a_\gamma RI + b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma \qquad (26)$$

$$w = b_w(\frac{1-\gamma_{dn}}{a_w} + ZI)^3 + c_w(\frac{1-\gamma_{dn}}{a_w} + ZI)^2 + \ldots \qquad (27)$$
$$d_w(\frac{1-\gamma_{dn}}{a_w} + ZI) + e_w$$

This process is summarized in Figure 4.1 and Figure 4.2.

Measure R, Z, γ_d, and w for a 5 point proctor and for 1 additional point that shares a moisture content with one of the proctor points but differs in density

$\downarrow$

Calculate a_γ

$$a_\gamma = \frac{\gamma_{dn,a} - \gamma_{dn,b}}{RI_a - RI_b}$$

where subscripts a and b denote parameters corresponding to sample points a and b, which share a moisture content and differ in density

$\downarrow$

Calculate $\gamma_{dn,int}$ for each point

$$\gamma_{dn,int} = \gamma_{dn} - a_\gamma RI$$

$\downarrow$

Perform a 3rd order polynomial curve-fit to estimate $\gamma_{dn,int}$ as a function of w

$$\gamma_{dn,int} = b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma$$

$\downarrow$

Normalized Dry Density Formulation

$$\gamma_{dn} = a_\gamma RI + b_\gamma w^3 + c_\gamma w^2 + d_\gamma w + e_\gamma$$

Figure 4.1: Flow chart summarizing formulation of dry unit weight as a function of moisture content and R$^{-0.5}$

Measure R, Z, γ_d, and w for a 5 point proctor and for 1 additional point that shares a moisture content with one of the proctor points but differs in density

$\downarrow$

Calculate a_w

$$a_w = \frac{\gamma_{dn,a} - \gamma_{dn,b}}{ZI_a - ZI_b}$$

where subscripts a and b denote parameters corresponding to sample points a and b, which share a moisture content and differ in density

$\downarrow$

Calculate ZI_1 for each point

$$ZI_1 = \frac{1 - \gamma_{dn}}{a_w} + ZI$$

$\downarrow$

Perform a 3rd order polynomial curve-fit of w as a function of ZI_1

$$w = b_w(ZI_1)^3 + c_w(ZI_1)^2 + d_w(ZI_1) + e_w$$

$\downarrow$

Moisture Content Formulation

$$w = b_w(\frac{1 - \gamma_{dn}}{a_w} + ZI)^3 + c_w(\frac{1 - \gamma_{dn}}{a_w} + ZI)^2 + d_w\left(\frac{1 - \gamma_{dn}}{a_w} + ZI\right) + e_w$$

Figure 4.2: Flow chart summarizing formulation of moisture content as a function of dry unit weight and $Z^{-0.5}$

As Figure 4.1 and Figure 4.2 illustrate, what at first may have seemed like an extremely complex procedure requiring an impractical amount of data can be condensed into nine straightforward steps using only six sample points. In order to test the validity of this new modeling procedure, proctor models were developed for Fayette County clay, Daviess County clay, Lee County clay and Warren County clay.

A five point modified proctor test procedure (ASTM D698) was performed for each soil using the acrylic test apparatus. An additional sample was prepared with a

similar moisture content to one of the proctor points for each soil. Measurements of R and Z were recorded for each sample point. A proctor model was then developed for all four soils using the procedure previously described. A summary of coefficients developed in the process are displayed in Table 4.1 and Table 4.2.

Table 4.1: Coefficients for dry unit weight formulation using proctor model for Fayette County Clay, Daviess County Clay, Lee County Clay, and Warren County Clay.

Soil	a_γ	b_γ	c_γ	d_γ	e_γ
Fayette County Clay	1.46	-9.15E-04	0.07	-1.87	16.19
Daviess County Clay	3.34	-2.77E-03	0.11	-1.47	5.33
Lee County Clay	2.91	-8.16E-04	0.04	-0.55	2.54
Warren County Clay	3.10	-1.56E-03	0.08	-1.55	9.04

Table 4.2: Coefficients for moisture content formulation using proctor model for Fayette County Clay, Daviess County Clay, Lee County Clay, and Warren County Clay.

Soil	a_w	b_w	c_w	d_w	e_w
Fayette County Clay	1.54	2.45E+02	-4.63E+02	2.95E+02	-4.46E+01
Daviess County Clay	2.46	-1.56E+03	2.97E+03	-1.82E+03	3.73E+02
Lee County Clay	2.60	3.48E+02	-6.50E+02	4.29E+02	-7.81E+01
Warren County Clay	2.05	-1.87E+03	2.06E+03	-6.97E+02	8.76E+01

If the proctor model is to be useful, the validity of these models must be evaluated. In order for the proctor model to be validated, it must be proven that it is sufficiently similar to the more labor intensive rigorous model.

Table 4.3 compares a_γ and a_w from the proctor and rigorous models. Other coefficients from the soil model were not compared due to their highly empirical nature. Large differences between the other parameters could have little bearing over the range which the models are applicable.

Table 4.3: Comparison of a_γ and a_w from the proctor and rigorous models for Fayette County clay, Daviess County clay, Lee County clay, and Warren County clay.

Soil	a_γ			a_w		
	Rigorous Model	Proctor Model	Percent Difference (%)	Rigorous Model	Proctor Model	Percent Difference (%)
Fayette County Clay	1.32	1.46	10.1	1.26	1.54	20.0
Daviess County Clay	2.31	3.34	36.5	2.14	2.46	13.9
Lee County Clay	2.46	2.91	16.8	2.11	2.60	20.8
Warren County Clay	2.16	3.10	35.7	2.16	2.05	5.2

Overall, a_γ and a_w are fairly similar. The a_w parameters are more similar than the a_γ parameters, with the largest percent difference being 20.8 percent. Values of a_γ differ slightly more than a_w, particularly for the Daviess County clay and the Warren County clay, with percent differences approaching 37 percent. As several other parameters influence the model, it is difficult to assess the accuracy of the proctor model based solely on Table 4.3. As previously stated, numerical comparison of the other coefficients from the soil model would not be meaningful due to their highly empirical nature. For this reason, Figure 4.3 and Figure 4.4 provide visual comparisons of the two models.
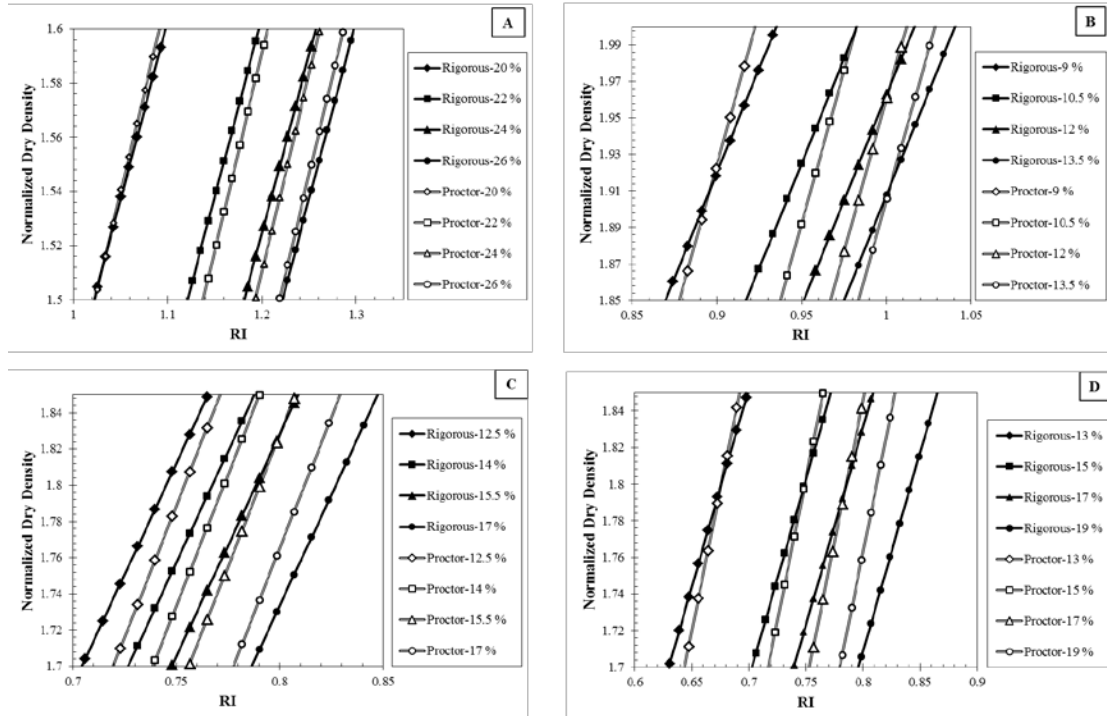
Figure 4.3: Comparison of rigorous model and proctor model for normalized dry unit weight formulation for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay

Figure 4.3 provides a visual representation of the normalized dry unit weight formulations for both the proctor model and rigorous model. For each soil, four moisture contents within the range of tested data were chosen for each soil to show the effect of moisture content on normalized dry unit weight values for each model. As the figure shows, the proctor model comes very close to the rigorous model for all four soils. Although the difference of a_γ values between the two models was the greatest for the Daviess County clay, it did not have a significant impact on the similarity of the two models. The largest difference between the two models occurs in the Warren County clay for the $w = 19\%$ moisture content group. A similar RI reading could result in a difference of approximately 0.6 kN/m^3 between the two models for this moisture content group.

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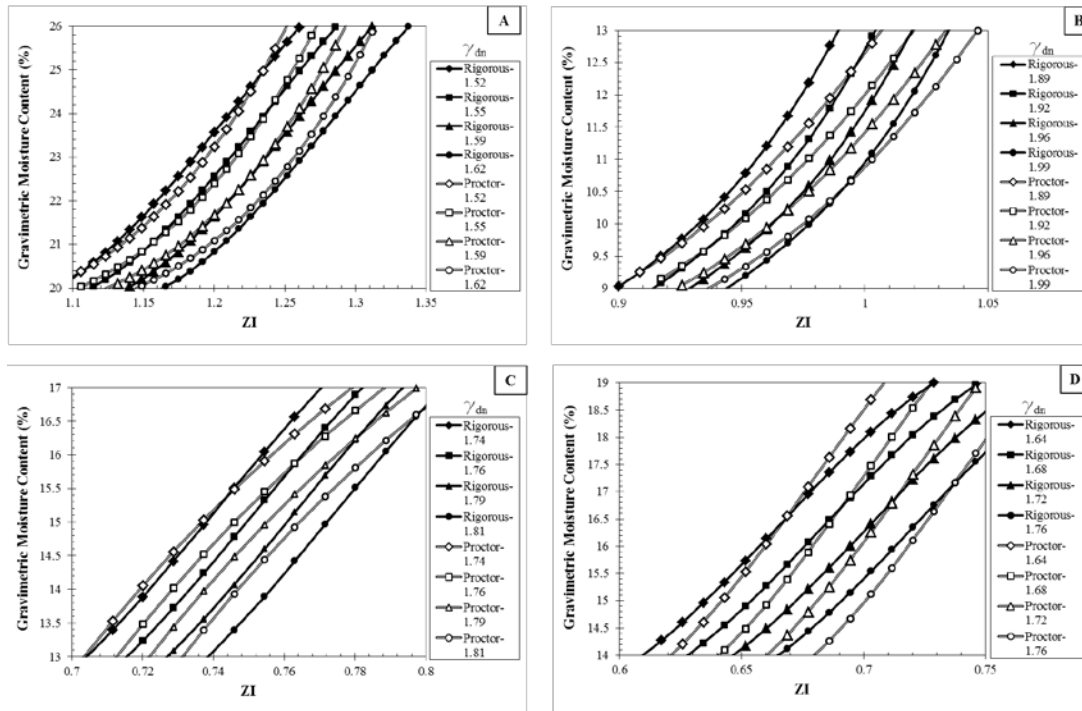
Figure 4.4: Comparison of rigorous model and proctor model for moisture content formulation for (A) Fayette County Clay, (B) Daviess County Clay, (C) Lee County Clay and (D) Warren County Clay

Figure 4.4 provides a visual representation of the moisture content formulations for both the proctor model and rigorous model. For each soil, four arbitrary normalized dry unit weights within the range of tested data were chosen for each soil to show the effect of normalized dry unit weight on moisture content values for each model. As the figure shows, the proctor model comes very close to the rigorous model for all four soils. The largest difference between the two models occurs in the Warren County clay for the $\gamma_{dn} = 1.64$ normalized dry unit weight group and the Daviess County clay for the $\gamma_{dn} = 1.89$ normalized dry unit weight group. A similar ZI reading could result in a difference in moisture content of approximately 0.75 percent between the two models for these two dry unit weight groups.

For both moisture content and dry unit weight formulation, the largest errors occur in dry unit weights and moisture contents near the limits of the range tested. This further reinforces the notion that range of moisture contents and dry unit weights used in model formation must be sufficiently broad.

4.1   Proctor Model Verification

The rigorous model has proven to accurately represent the relationship between moisture content, dry unit weight and electrical parameters. The proctor model has been demonstrated to be sufficiently similar to the rigorous model. In order to further solidify the proctor model as a useful soil model and CIMI calibration technique, it must be demonstrated that it is possible to generate an accurate soil model for additional soils that were not used in the conception of the proctor model procedure. Henderson County clay and Lexington clay were used for this purpose. The soils were chosen so that they would encompass a wide range of index properties. Index properties for these soils are listed in Table 3.1. To further justify use of the proctor model, a macro-enabled Microsoft Excel spreadsheet was developed that automates the process of proctor model generation. This spreadsheet is included with this thesis. Screenshots from the spreadsheet are supplied in Figure 4.5.

Enter the measured soil and electrical parameters in the field below

Soil ID	Mold Weight (kN)	Mold Weight + Soil (kN)	Mold Volume (cubic ft)	Tare (g)	Tare + Soil (g)	Tare + Oven Dry Soil (g)	Resistance, R (ohm)	Impedance, Z (ohm)	Moisture Content, w (%)	Normalized Dry Density, γ_{dn}	R1	Z1
h1	14.77	23.4	0.075	31.72	128.71	122.8	598.2	615.2	6.488802054	1.792190707	0.687388962	0.691298321
h2	14.77	23.71	0.075	31.56	131.73	124.5	446.7	456.3	7.779212395	1.772929062	0.795456653	0.802691269
h3	14.77	24.2	0.075	31.88	177.54	163	290.1	293.2	11.08907871	1.814383859	0.987076086	1.001363327
h4	14.77	24.18	0.075	32	150	135.2	254.2	258.1	14.34108527	1.759041799	1.05447865	1.097289175
h5	14.77	23.98	0.075	31.86	148.2	138.5	342.1	349.9	9.096024006	1.804427981	0.908966668	0.918646298
h6	14.77	23.41	0.075	31.78	152.2	140	330.2	337.4	11.2733321	1.659630835	0.925200717	0.933471636
			#N/A						#N/A	#N/A	#N/A	#N/A
			#N/A						#N/A	#N/A	#N/A	#N/A
			#N/A						#N/A	#N/A	#N/A	#N/A

Insert the Soil ID's corresponding to similar moisture contents compacted at differing densities.

Soil ID
h3
h6

Press this button to perform model development. Model coefficients and charts will be displayed below

Coefficient	Value
a_1	2.501044032
b_1	-0.001182584
c_1	0.047851857
d_1	-0.704318286
e_1	2.903729773
a_2	2.279410344
b_2	107.6338928
c_2	-135.8091114
d_2	69.53061245
e_2	-6.076603381

Normalized Moisture Content vs. ZI
Grouped by Normalized Dry Density

Normalized Dry Density vs. RI
Grouped by Moisture Content (w)

Figure 4.5: Screenshot from macro-enabled Microsoft Excel spreadsheet

A five point modified proctor test procedure (ASTM D698) was ran for the Henderson County clay and Lexington clay using the acrylic test apparatus. An additional sample was prepared with a similar moisture content to one of the proctor points for each soil. Readings of R and Z were recorded for each sample point. A proctor model was then developed for both soils using the macro-enabled Microsoft Excel workbook. A summary of coefficients developed in the process are displayed in Table 4.4 and Table 4.5.

Table 4.4: Coefficients for dry unit weight formulation using proctor model for Henderson County clay and Lexington clay

Soil	a_γ	b_γ	c_γ	d_γ	e_γ
Henderson County Clay	2.50	-1.19E-03	0.05	-0.70	2.90
Lexington Clay	1.60	-3.51E-04	0.02	-0.06	4.63

Table 4.5: Coefficients for moisture content formulation using proctor model for Henderson County clay and Lexington clay

Soil	a_w	b_w	c_w	d_w	e_w
Henderson County Clay	2.28	1.08E+02	-1.36E+02	69.60	-6.09
Lexington Clay	1.67	-1.44E+02	1.44E+02	-55.60	24.40

In order to test the accuracy of the predictive proctor model, four additional sample points were compacted in the acrylic apparatus. Measurements of R, Z, dry unit weight and moisture content were obtained for each sample. Using the R and Z measurements, predicted moisture content and normalized dry unit weight values were calculated. A sheet in the macro-enabled Microsoft Excel workbook can be used to solve the system of equations. Predicted values are compared to measured values in Figure 4.6.
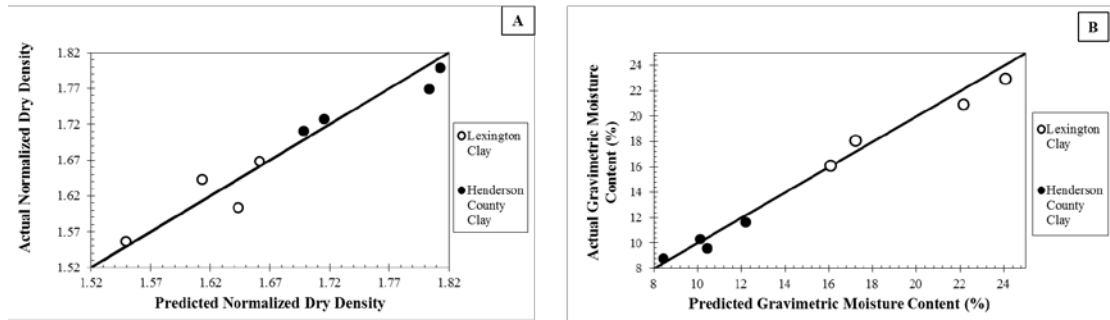
Figure 4.6: (A) Actual normalized dry unit weight for Henderson County clay and Lexington Clay and (B) moisture content values for Henderson County Clay and Lexington Clay versus values predicted by the corresponding proctor models. A line of unity is drawn through the data of each plot.

In Figure 4.6, the accuracy of the proctor model for Henderson County clay and Lexington clay are illustrated. Most points plot very near the line unity, which represents an accurate prediction. For the Henderson County clay, the maximum absolute percent error for normalized dry unit weight was 2.0 percent and the average absolute percent error for normalized dry unit weight was 1.0 percent. These errors are incredibly low and represent a very high degree of accuracy. For the Henderson County clay, the maximum absolute percent error for moisture content was 9.2 percent. The average absolute percent error for moisture content was 4.9 percent. Although higher than the percent error for dry unit weight, this is still a relatively low and encouraging value.

For the Lexington clay, the maximum absolute percent error for normalized dry unit weight was 2.4 percent. The average absolute percent error for normalized dry unit weight was 1.3 percent. As was the case with Henderson County clay, the dry unit weight formulation performed exceptionally well. For the Lexington clay, the maximum absolute percent error for moisture content was 5.8 percent. The average absolute percent error for

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moisture content was 4.0 percent. The moisture content formulation performance is adequate for the Lexington clay, which performed even better than the Henderson County clay.

4.2   Summary, Conclusions and Recommendations for Further Research

Dry unit weight can be accurately represented as a function of RI and gravimetric moisture content. Gravimetric moisture content can be accurately represented as a function of ZI and dry unit weight. This system of equations, along with measurements of R and Z can be used to create a soil model which can accurately predict unit weight and moisture content based on electrical readings, which is very useful for construction quality assurance.

It is possible to create this seemingly complex soil model based on six sample points, using a proctor-like acrylic testing apparatus. This proctor model can be generated with a relatively low amount of time and labor and can be very accurate.

There are some possible disadvantages of this model. Other CIMI calibration procedures allow for field calibration. It would be extremely difficult to perform a proctor model calibration procedure in the field. Another shortcoming is the variability of the model outside of the calibrated range of moisture contents and dry unit weights used in model generation. It should be noted that most CIMI calibration procedures highly recommend using the same range of moisture contents and dry unit weights in the calibration process as are expected to be seen in the field.

Chapter 5: Summary and Conclusions

As stated in the objectives of Chapter 2, when developing the proposed calibration procedure, one main goal was for the proposed calibration procedure to perform as well as, or better than, the current calibration procedure. This was the case in every soil for both weight of water and wet unit weight. This result is a significant step forward for use of the EDG as a NDG replacement.

The new calibration apparatus and procedure presented in Chapter 2 is considerably more efficient and reliable than the current apparatus and procedure. The new method uses approximately an eighth of the soil as the current procedure. The new method can also easily be coupled with a standard proctor test to further conserve time, labor, soil, and money. Furthermore, use of the proctor hammer in compaction makes it easier to attain the desired unit weights in soil model development. In short, the new calibration mold and method is more efficient, more accurate, less expensive and less labor intensive.

The data presented in Chapter 2 does not cover a broad enough spectrum of soils to warrant a recommendation to abandon the current calibration procedure; however; there is sufficient evidence to support the potential the proposed calibration procedure has. The efficiency gains of both time and effort would justify further research and development of the proposed calibration procedure in the proposed calibration apparatus. The research presented in Chapter 3 does just that.

From Chapter 2, it was gleaned that a small acrylic mold can be accurately used to predict field electric readings using a CIMI. As such, a similar, small acrylic mold was

used to investigate the nature of electric readings in soil. The following information was gained as a part of the research presented in Chapter 3.

For a given moisture content, normalized dry unit weight will vary linearly with RI and ZI. This proportionality is consistent for all moisture contents tested for the given soils tested. For a given normalized dry unit weight, moisture content varies with RI and ZI in a highly nonlinear fashion. A curve which plots moisture content versus RI or ZI for a given normalized dry unit weight likely has at least two inflection points. Without further knowledge of this relationship, the best approximation is a third order polynomial curve fit.

Normalized dry unit weight can be accurately represented as a function of RI and gravimetric moisture content. Gravimetric moisture content can be accurately represented as a function of ZI and normalized dry unit weight. This system of equations, along with measurements of R and Z can be used to create a soil model which can accurately predict unit weight and moisture content based on electrical readings, which is very useful for construction quality assurance.

It is possible to create this seemingly complex soil model based on six sample points, using a proctor-like acrylic testing apparatus. This proctor model can be generated with a relatively low amount of time and labor and can be very accurate.

There are some possible disadvantages of this model. Other CIMI calibration procedures allow for field calibration. It would be extremely difficult to perform a proctor model calibration procedure in the field. Another shortcoming is the variability of the model outside of the calibrated range of moisture contents and dry unit weights used in model generation. It should be noted that most CIMI calibration procedures highly

recommend using the same range of moisture contents and dry unit weights in the calibration process as are expected to be seen in the field.

Future research should be aimed at a more detailed understanding of the variance of electrical parameters with unit weight and moisture of a soil sample. In this research, dry unit weight has been shown to vary linearly with electrical parameters for a given moisture content; however, the ranges of dry unit weights and moisture contents in this research were limited. Similarly, the proposed relationship between moisture content and electrical parameters is based on this same limited range of sampled moisture contents and dry unit weights. If a much wider range moisture contents and dry unit weights were sampled and tested in a similar manner to this research, a more detailed understanding of soil moisture and soil unit weight's variance with electrical parameters could be obtained. Ultimately, this could lead to the generation of a generalized electrical soil model.

APPENDICES

Appendix A: Raw Data

Soil	Purpose	Test ID	Acrylic Mold Weight (lb)	Mold + Soil (lb)	Tare Weight (g)	Tare + Soil (g)	Tare + Soil - H20(g)	Moisture Content	Dry Density (pcf)	C (nF)	R (ohm)	Z (ohm)
Fayette	Rigorous	f-99-20	14.75	23.69	32.12	146.72	128.06	0.19449656	99.76604702	1.34	237	240.8
		f-102-20	14.74	23.95	18.17	129.61	111.2	0.197893153	102.4876883	1.67	216.7	219.1
		f-96-20	14.74	23.36	32.35	139.9	122.04	0.199130338	95.82327823	0.91	267.9	274.3
		f-93-20	14.74	23.13	32.52	134.18	117.23	0.20009444	93.1915825	0.848	292.7	299.4
		f-102-23	14.75	24.17	32.39	140.02	120.31	0.224181074	102.5735512	2.43	184.3	185.7
		f-99-23	14.76	23.89	18.19	121.8	102.77	0.224994088	99.34978556	2.11	191.9	193.6
		f-96-23	14.75	23.6	32.55	150.9	128.86	0.228844357	96.0117326	2.01	205.4	207.1
		f-93-23	14.75	23.33	33.14	118.73	102.78	0.229035037	93.05788405	1.42	214.2	217.5
		f-102-25	12.54	22.14	31.58	125.18	107.35	0.235317408	103.5911897	3.04	169.5	170.5
		f-96-25	14.72	23.73	32.15	138.1	117.72	0.238167582	97.00084361	2.23	193.3	194.8
		f-99-25	12.53	21.83	32.31	133.88	114.3	0.238809611	100.0710673	2.77	177.4	178.5
		f-93-25	14.72	23.45	32	126.13	107.57	0.24560106	93.42557009	1.89	197.2	199.2
		f-99-27	14.75	24.2	32.53	122.53	103.98	0.259622113	100.0049925	2.86	166	167
		f-93-27	14.74	23.65	18.16	124.32	102.23	0.262757226	94.05632179	2.17	191.1	192.75
		f-96-27	14.75	23.89	33.12	144.75	121.48	0.263354459	96.43865119	2.6	173.5	174.7
		f-90-27	14.75	23.35	32.35	122.39	103.56	0.264429153	90.66383807	1.73	198.9	201.26
	Proctor	f1	10.6	18.96	31.8	117.6	104.2	0.185082873	94.03460513	0.39	378.7	401.9
		f2	10.59	19.15	32.4	130.8	115.2	0.188405797	96.01501463	0.743	300.6	308.2
		f3	10.59	19.61	32.1	114.7	100.4	0.209370425	99.42082058	1.43	216.2	219.19
		f4	10.59	19.93	31.7	112.5	97.4	0.229832572	101.2350809	1.68	180.53	186.28
		f25	10.29	19.8	32.3	116.73	99.85	0.249888971	101.4236488	3.15	168.46	169.4
		F5	10.63	19.73	32.1	93.6	80	0.283924843	94.47827154	2.26	178.4	182.1
		Addtnl	12.64	20.86	32.2	108.2	94.1	0.227786753	89.24399921	1.48	225.4	229.5

Figure A.1: Raw Data from Fayette County clay

Soil	Purpose	Test ID	Acrylic Mold Weight (lb)	Mold + Soil (lb)	Tare Weight (g)	Tare + Soil (g)	Tare + Soil - H20 (g)	Moisture Content	Dry Density (pcf)	C (nF)	R (ohm)	Z (ohm)
Daviess	Rigorous	D-125-08	12.54	22.6	31.55	132.83	125.96	0.072767715	125.0035754	0.716	379.2	386.5
		D-122-08	12.54	22.4	31.78	129.67	122.95	0.073708457	122.411069	0.7	391.5	399
		D-119-08	12.54	22.17	31.97	128.11	121.42	0.074790386	119.4352887	0.693	416.8	423.9
		D-116-08	12.54	22	32.31	131.62	124.72	0.074667244	117.3403216	0.603	422.8	432
		d-122-10	12.55	22.59	31.97	145.21	135.59	0.09283922	122.46376	1.054	325.29	326.76
		d-125-10	12.55	22.85	32.31	145.11	135.42	0.093977306	125.5044316	1.11	310.17	314.475
		d-119-10	12.54	22.37	31.81	127.41	119.16	0.094447624	119.7260582	1.055	331.38	341.88
		d-116-10	12.54	22.14	31.59	118.72	111.18	0.09473552	116.8939874	0.9385	355.0365	360.045
		D-125-12	12.51	22.97	31.78	127.83	118.54	0.107076994	125.9458924	1.2	285.6	284
		D-122-12	12.54	22.76	32.34	107	99.71	0.108208401	122.9304884	1.185	293.15	296
		d-119-12	12.54	22.52	32.32	108	100.5	0.110002933	119.8495932	1.08	302.5	315
		D-116-12	12.54	22.34	31.59	150.89	139.04	0.110283853	117.6582003	1.05	319.7	323.8
		D-119-14	10.29	20.6	31.58	135.98	124.02	0.12938122	121.68814	1.115	276.9	285.4
		D-116-14	10.52	20.56	31.95	162.12	146.98	0.131617839	118.2671353	1.1	286.9	297.9
		D-113-14	12.55	22.42	32.29	157.63	143.08	0.131329542	116.2942318	1.101	292.5	304.1
		D-112-14	12.55	22.25	31.8	126.75	115.64	0.132514313	114.1716255	1.012	309.9	322.7
	Proctor	d1	10.27	20.05	31.7	117.5	110.7	0.086075949	120.0352517	0.781	367.1	372.4
		d2	10.27	20.59	31.8	119.8	111.2	0.108312343	124.1216891	1.08	290.6	294.6
		d3	10.26	20.67	32.4	118.3	109.4	0.115584416	124.3879872	1.14	279.59	283.34
		d4	10.6	20.73	32.4	106.2	97.8	0.128440367	119.6633016	1	284.6	290.5
		d5	10.26	20.05	31.8	123.4	110.9	0.158027813	112.6921984	0.919	277.4	283.7
		Addtnl	12.64	22.21	32.2	121.41	112	0.117919799	114.1120321	1.01	309.2	324.7

Figure A.2: Raw Data from Daviess County clay

Soil	Purpose	Test ID	Acrylic Mold Weight (lb)	Mold + Soil (lb)	Tare Weight (g)	Tare + Soil (g)	Tare + Soil - H20 (g)	Moisture Content	Dry Density (pcf)	C (nF)	R (ohm)	Z (ohm)
		L-114-13	14.76	24.42	22.08	178.46	160.54	0.12942366	114.0119554	0.238	491.7	540.5
		L111-13	14.77	24.18	31.44	138.43	126.25	0.128467461	111.1554425	0.237	509.6	556.4
		L-108-13	14.77	23.94	31.7	145.52	132.12	0.133439554	107.8452747	0.227	533.6	583.1
		L-105-13	14.77	23.67	31.82	168.16	152.72	0.12770885	105.2017992	0.176	558.2	633.9
		L-114-15	14.76	24.58	18.19	155.53	138.6	0.14060294	114.7643894	0.285	457	493.7
		L-111-15	14.76	24.34	32.53	138.07	124.73	0.144685466	111.5602528	0.263	472	513.2
		L-108-15	14.77	24.1	32.41	144.21	130.37	0.141282156	108.9729646	0.227	509	560.2
	Rigorous	L-105-15	14.77	23.84	33.13	155.72	140.37	0.143136889	105.7643237	0.198	537	600.2
		L-114-17	14.73	24.75	33.12	146.06	130.45	0.160382205	115.1056949	0.313	414.9	448.3
		L-111-17	14.75	24.49	18.16	121	106.54	0.163611677	111.5786328	0.267	432.3	475.9
Daviess		L-108-17	14.75	24.22	32.38	124.59	111.46	0.166034396	108.2601855	0.234	469.5	521.3
		L-105-17	14.76	23.98	32.54	133.5	119.22	0.164743886	105.5189914	0.22	483.3	540.3
		L-111-19	14.74	24.65	32.36	152	133.9	0.178254875	112.1152162	0.398	362.2	386
		L-108-19	14.74	24.38	33.13	136.05	120.05	0.184077312	108.5243325	0.373	386.6	412.1
		L-105-19	14.74	24.11	32.53	156.38	137.32	0.181887585	105.6801862	0.371	403.1	427.7
		L-102-19	14.74	23.85	18.16	129.6	112.39	0.182638226	102.6825426	0.304	424	458.6
		I10	10.29	19.25	31.8	166.79	154.15	0.103310176	108.2531482	0.1834	593.1	660.1
		I1	10.28	19.71	31.7	121.7	110.9	0.136363636	110.617672	0.1736	493.4	564.1
	Proctor	I15	10.29	20.14	31.84	152.76	136.2	0.158681487	113.31889	0.465	435	478.1
		I4	10.28	20.26	32.4	126.6	112.5	0.176029963	113.1207573	0.259	416.4	440.1
		I15	14.47	24.26	32.16	107.03	94.36	0.203697749	108.4165025	0.3049	362.1	370.1
		Addtnl	12.64	21.48	32.2	108.2	97.98	0.155366373	101.9911976	0.178	511.2	576.2

Figure A.3: Raw Data from Lee County clay

Soil	Purpose	Test ID	Acrylic Mold Weight (lb)	Mold + Soil (lb)	Tare Weight (g)	Tare + Soil (g)	Tare + Soil - H20 (g)	Moisture Content	Dry Density (pcf)	C (nF)	R (ohm)	Z (ohm)
Daviess		W-111-14	14.74	24.24	32.53	149.685	136.02	0.132041743	111.8642495	0.171	583	660.8
		W-108-14	14.74	23.98	32.39	152.6	138.4	0.133949627	108.6196397	0.147	625	721.4
		W-105-14	14.74	23.72	18.12	147.22	131.69	0.136743858	105.3037578	0.131	668.4	781.4
		W-102-14	14.74	23.46	33.1	121.7	111.05	0.136626042	102.2654731	0.113	731.8	868.2
		W-111-16	14.74	24.42	33.12	168.76	150.22	0.15832621	111.3972887	0.208	493.3	556
		W-108-16	14.74	24.15	18.16	157.59	138.5	0.158633871	108.2613785	0.183	516.2	592.4
	Rigorous	W-105-16	14.74	23.89	32.53	155.12	138.52	0.156618549	105.4535224	0.176	542.1	623.7
		W-102-16	14.74	23.62	32.34	142.4	127.02	0.16244191	101.8290884	0.142	612	718.3
		W-111-18	14.74	24.55	32.35	145.35	128.58	0.174269978	111.3605069	0.197	461.8	535.3
		W-108-18	14.74	24.3	33.12	148.95	131.68	0.175223214	108.4345497	0.194	470.1	545
		W-105-18	14.74	24.03	18.17	126.18	110.06	0.175427141	105.3537864	0.18	519.6	597.8
		W-102-18	14.74	23.76	32.51	127.18	112.84	0.178513631	102.0239366	0.175	529.3	609.9
		W-108-20	14.74	24.5	33.13	138.33	121.38	0.192067989	109.1387414	0.287	405.8	455.9
		W-105-20	14.74	24.19	18.15	145.69	125	0.193635938	105.5334344	0.27	420	463.7
		W-102-20	14.74	23.92	32.53	127.3	111.71	0.196893155	102.2392011	0.248	447.5	495.92
		W-99-20	14.74	23.67	32.36	129.44	113.45	0.197188309	99.43038959	0.232	477.1	529.2
		w1	10.6	18.95	31.7	111.6	102.4	0.130127298	98.48934731	0.0822	773.3	1007.9
		w2	10.28	19.19	31.8	115.5	104.8	0.146575342	103.587	0.14622	579.9	699.5
	Proctor	w4	10.28	19.41	32.1	123	110.9	0.153553299	105.502624	0.114	547.2	659.8
		w5	10.28	19.98	31.8	124.4	110.7	0.173637516	110.1711544	0.197	465.1	536.6
		w22-2	10.29	19.78	31.58	148.6	127.77	0.216550577	103.9839217	0.2441	413.3	440.1
		Addtnl	12.64	21.46	32.2	112.8	101	0.171511628	100.3580308	0.107	532.1	668.2

Figure A.4: Raw Data from Warren County clay

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Soil	Purpose	Test ID	Acrylic Mold Weight (lb)	Mold + Soil (lb)	Tare Weight (g)	Tare + Soil (g)	Tare + Soil - H20 (g)	Moisture Content	Dry Density (pcf)	C (nF)	R (ohm)	Z (ohm)
Henderson	Proctor	h1	14.77	23.4	31.72	128.71	122.8	0.064888011	108.0281672	0.373	598.2	615.2
		h2	14.77	23.71	31.56	131.73	124.5	0.077792124	110.5688169	0.592	446.7	456.3
		h3	14.77	24.2	31.88	177.54	163	0.110890787	113.1541475	1.26	290.1	293.2
		h4	14.77	24.18	32	150	135.2	0.143410853	109.7027369	1.32	254.2	258.1
		h5	14.77	23.98	31.86	148.2	138.5	0.09096024	112.5332487	0.998	342.1	349.9
		h6	14.77	23.41	31.78	152.2	140	0.112733321	103.5029668	1.04	330.2	337.4
	Confirmation	ah1	14.77	23.63	31.72	132.5	123.7	0.095672972	107.7911046	1.251	331.2	356.5
		ah2	14.77	23.71	31.56	148.7	136.5	0.116256909	106.7587569	1.05	298	313.3
		ah3	14.77	24.06	31.88	171.1	158.1	0.102994771	112.2722458	0.986	312.8	316.9
		ah4	14.77	23.78	32	121.3	114.1	0.087697929	110.4197193	0.845	381.1	385.6

Figure A.5: Raw Data from Henderson County clay

Soil	Purpose	Test ID	Acrylic Mold Weight (lb)	Mold + Soil (lb)	Tare Weight (g)	Tare + Soil (g)	Tare + Soil - H20(g)	Moisture Content	Dry Density (pcf)	C(nF)	R (ohm)	Z (ohm)
Lexington	Proctor	lex1	14.74096916	24.27885463	32.8	131.2	114.1	0.210332103	105.0455597	0.958	276.5	282
		lex2	14.74096916	24.07136564	32.6	165.6	139.8	0.240671642	100.2474634	0.81	281.9	289.3
		lex3	14.74096916	23.85814978	31.9	131	116.1	0.17695962	103.2592925	0.759	311	318.8
		lex4	14.74096916	23.1	32.8	115.8	105.1	0.147994467	97.06133976	0.459	492.4	499.7
		lex5	14.74096916	23.65	32.6	181.4	160.1	0.167058824	101.7578366	0.602	378.6	388.6
		lex6	14.74096916	23.41	31.9	146.2	126.5	0.208245243	95.6413292	0.649	336.4	339.2
	Confirmation	alex1	14.74	23.21	31.8	132.5	118.5	0.161476355	97.20826385	0.581	430.4	472.5
		alex2	14.74	23.61	32.8	154.9	136.2	0.180851064	100.1287153	0.664	341	346.1
		alex3	14.74	24.05	32.9	119.5	104.5	0.209497207	102.6065206	0.901	292.1	297.3
		alex4	14.74	24.35	32.6	121.5	104.9	0.229598893	104.1813722	0.961	264.1	277.8

Figure A.6: Raw Data from Lexington clay

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Appendix B: Operation of Macro-Enabled Excel Workbook

Enter the measured soil and electrical parameters in the field below

1

Soil ID	Mold Weight (kN)	Mold Weight + Soil (kN)	Mold Volume (cubic ft)	Tare (g)	Tare + Soil (g)	Tare + Oven Dry Soil (g)	Resistance, R (ohm)	Impedence, Z (ohm)	Moisture Content, w (%)	Dry Density, γ_d (kN/m³)	$\frac{1}{R}$ (ohm⁻²)	$\sqrt{\frac{1}{Z}}$ (ohm⁻²)
h1	14.77	23.4	0.075	31.72	128.71	122.8	598.2	615.2	6.488801054	16.97546893	0.040886204	0.040317337
h2	14.77	23.71	0.075	31.56	131.73	124.5	446.7	456.3	7.779212395	17.37470481	0.047314257	0.046813894
h3	14.77	24.2	0.075	31.88	177.54	163	290.1	293.2	11.0890787	17.78096182	0.0587119	0.058400695
h4	14.77	24.18	0.075	32	150	135.2	254.2	258.1	14.34108527	17.23860963	0.062720892	0.062245219
h5	14.77	23.98	0.075	31.86	148.2	138.5	342.1	349.9	9.096024006	17.68339422	0.054065903	0.055459886
h6	14.77	23.41	0.075	31.78	152.2	140	330.2	337.4	11.2733321	16.26438218	0.055031515	0.055441171
			#N/A						#N/A	#N/A	#N/A	#N/A
			#N/A						#N/A	#N/A	#N/A	#N/A
			#N/A						#N/A	#N/A	#N/A	#N/A

Insert the Soil ID's corresponding to similar moisture contents compacted at differing densities.

2

Soil ID
h3
h6

Figure B.1: 1st screenshot from workbook

In Figure B.1, two boxes are marked and numbered. Box 1 surrounds the first data entry field. For each soil enter a soil ID, weight of acrylic mold, weight of acrylic mold plus soil, tare weight, tare plus soil weight, oven dried tare plus soil weight, resistance reading and impedance reading. Blue colored boxes require user input. Orange boxes are automatically calculated; however, they can be changed by the user manually if they desire. At least two soils with similar moisture contents and differing dry unit weights are required for the proctor model. Indicate those soils in this box. Note that only two are required, but up to three can be entered.
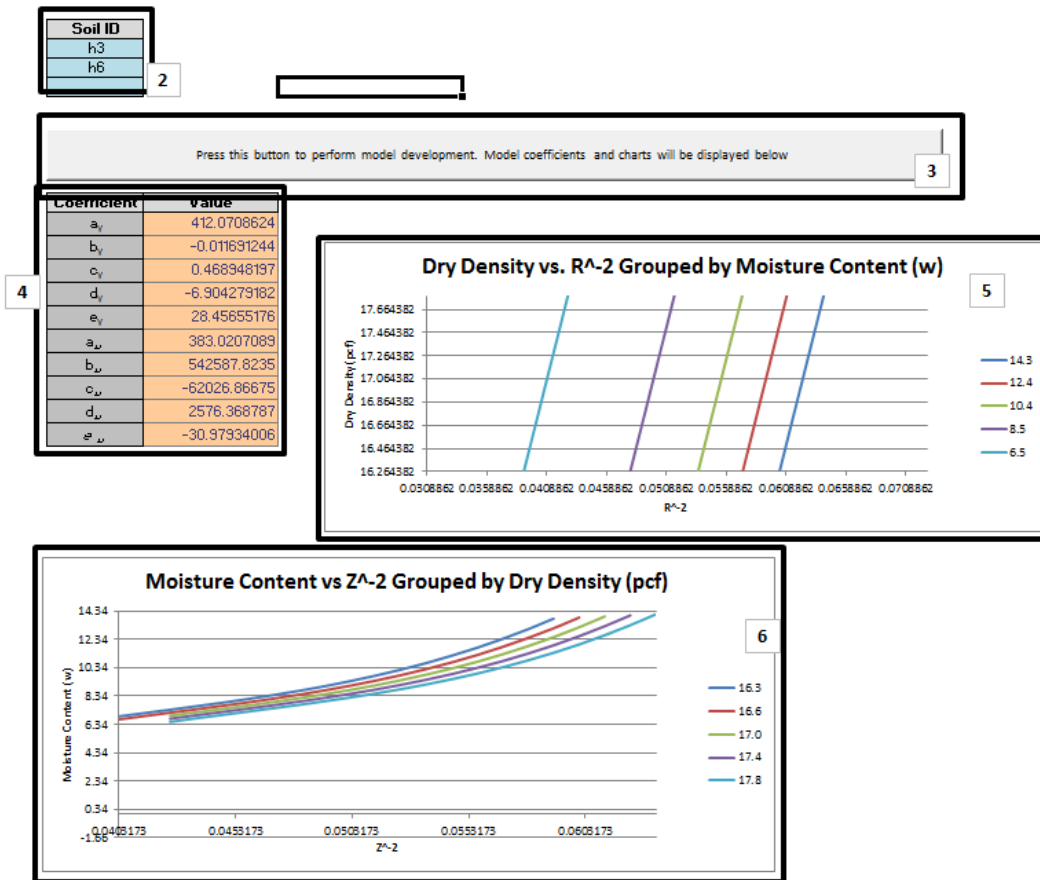
Figure B.2: 2nd screenshot from workbook

Once all the necessary information has been filled in boxes 1 and 2, box 3 should be

pressed. Once this box is pressed, a macro will run which adjusts chart axes and copies

and pastes the coefficients and graphs from a hidden "Calculations" sheet. It should be

noted that the points plotted in the charts are arbitrary and for illustrative purposes. The

macro code is as follows:

```
"Sub Macro10()
'
' Macro10 Macro
'

'
Application.ScreenUpdating7 = False
    Sheets("Calculations").Visible = True
    Sheets("Calculations").Select
```

```
Range("AA25:AD25").Select
Selection.Copy
Range("O34").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Range("AC27:AD27").Select
Application.CutCopyMode = False
Selection.Copy
Range("Q36").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=9
Range("AA47,AA67").Select
Range("AA67").Activate
Application.CutCopyMode = False
Selection.Copy
Range("Q38").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveSheet.ChartObjects("Chart 2").Activate
ActiveChart.Axes(xlCategory).Select
Range("Q38").Select
Application.CutCopyMode = False
ActiveCell.FormulaR1C1 = "0.0389219986834946"
ActiveSheet.ChartObjects("Chart 2").Activate
ActiveChart.Axes(xlCategory).Select
ActiveChart.Axes(xlCategory).MinimumScale = 0
ActiveChart.Axes(xlCategory).MinimumScale = ActiveSheet.Range("AA47").Value
Range("Q39").Select
ActiveCell.FormulaR1C1 = "0.0480629500065622"
ActiveSheet.ChartObjects("Chart 2").Activate
ActiveChart.Axes(xlCategory).Select
ActiveChart.Axes(xlCategory).MaximumScale = 4.89219986834946E-02
ActiveChart.Axes(xlCategory).MaximumScale = ActiveSheet.Range("AA67").Value
Range("P34").Select
ActiveCell.FormulaR1C1 = "0.103310175725378"
Range("P35").Select
ActiveSheet.ChartObjects("Chart 2").Activate
ActiveChart.Axes(xlValue).Select
ActiveChart.Axes(xlValue).MinimumScale = 0
ActiveChart.Axes(xlValue).MinimumScale = ActiveSheet.Range("AB25").Value
Range("O34").Select
ActiveCell.FormulaR1C1 = "0.203697749196142"
ActiveSheet.ChartObjects("Chart 2").Activate
ActiveChart.Axes(xlValue).Select
ActiveChart.Axes(xlValue).MaximumScale = 0.223310175725378
```

ActiveChart.Axes(xlValue).MaximumScale = ActiveSheet.Range("AA25").Value
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveChart.Axes(xlCategory).Select
Range("Q36").Select
ActiveCell.FormulaR1C1 = "0.0310616160700099"
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveChart.Axes(xlCategory).Select
ActiveChart.Axes(xlCategory).MinimumScale = 0
ActiveChart.Axes(xlCategory).MinimumScale = ActiveSheet.Range("AC27").Value
Range("R36").Select
ActiveCell.FormulaR1C1 = "0.0625515751191217"
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveChart.Axes(xlCategory).Select
ActiveChart.Axes(xlCategory).MaximumScale = 6.60616160700099E-02
ActiveChart.Axes(xlCategory).MaximumScale = ActiveSheet.Range("AD27").Value
Range("R34").Select
ActiveCell.FormulaR1C1 = "102.016701754386"
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveChart.Axes(xlValue).Select
ActiveChart.Axes(xlValue).MinimumScale = 0
ActiveChart.Axes(xlValue).MinimumScale = ActiveSheet.Range("AD25").Value
Range("Q34").Select
ActiveCell.FormulaR1C1 = "113.347226816628"
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveChart.Axes(xlValue).Select
ActiveChart.Axes(xlValue).MaximumScale = 182.016701754386
ActiveChart.Axes(xlValue).MaximumScale = ActiveSheet.Range("AC25").Value
ActiveWindow.SmallScroll Down:=-18
Range("P4:P26").Select
Selection.Copy
Sheets("Model Development").Select
Range("C32").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Sheets("Calculations").Select
ActiveSheet.ChartObjects("Chart 1").Activate
ActiveSheet.Shapes.Range(Array("Chart 1", "Chart 2")).Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Model Development").Select
ActiveWindow.SmallScroll Down:=6
Range("B57").Select
ActiveSheet.Paste

```
    ActiveWindow.SmallScroll Down:=27
    Sheets("Calculations").Select
    ActiveWindow.SelectedSheets.Visible = False
    ActiveWindow.SmallScroll Down:=-42
    Sheets("Model Development").Select
    ActiveWindow.SmallScroll Down:=-21
    Application.ScreenUpdating = True
End Sub"
```
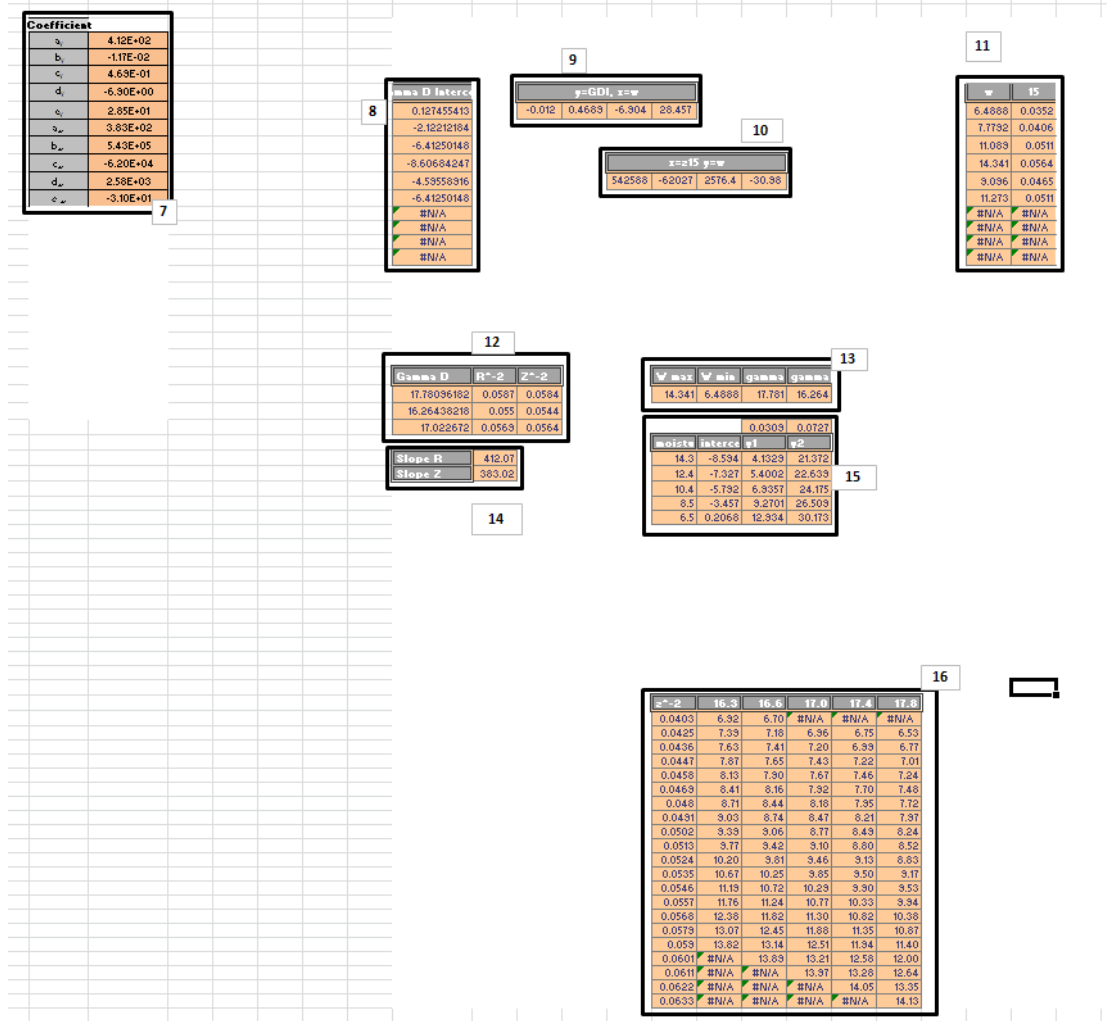
Coefficient

a_i	4.12E+02
b_i	-1.17E-02
c_i	4.63E-01
d_i	-6.90E+00
e_i	2.85E+01
a_w	3.83E+02
b_w	5.43E+05
c_w	-6.20E+04
d_w	2.58E+03
e_w	-3.10E+01

7

8 — mma D Interc

0.127455413
-2.12212164
-6.41250148
-8.60684247
-4.59558316
-6.41250148
#N/A
#N/A
#N/A
#N/A

9 — y=GDI, x=w

-0.012	0.4683	-6.904	28.457

10 — x=z15 y=w

542588	-62027	2576.4	-30.98

11

15

w	15
6.4888	0.0352
7.7792	0.0406
11.083	0.0511
14.341	0.0564
9.036	0.0465
11.273	0.0511
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A
#N/A	#N/A

12

Gamma D	R^-2	Z^-2
17.78036182	0.0587	0.0584
16.26438218	0.055	0.0544
17.022672	0.0569	0.0564

Slope R	412.07
Slope Z	383.02

13

W max	W min	gamma	gamma
14.341	6.4888	17.781	16.264

		0.0303	0.0727
moistu	interce	y1	y2
14.3	-8.594	4.1329	21.372
12.4	-7.327	5.4002	22.639
10.4	-5.792	6.3357	24.175
8.5	-3.457	3.2701	26.509
6.5	0.2068	12.334	30.173

14

15

16

z^-2	16.3	16.6	17.0	17.4	17.8
0.0403	6.92	6.70	#N/A	#N/A	#N/A
0.0425	7.33	7.18	6.36	6.75	6.53
0.0436	7.63	7.41	7.20	6.93	6.77
0.0447	7.87	7.65	7.43	7.22	7.01
0.0458	8.13	7.90	7.67	7.46	7.24
0.0463	8.41	8.16	7.92	7.70	7.48
0.048	8.71	8.44	8.18	7.95	7.72
0.0491	9.03	8.74	8.47	8.21	7.97
0.0502	9.39	9.06	8.77	8.43	8.24
0.0513	9.77	9.42	9.10	8.80	8.52
0.0524	10.20	9.81	9.46	9.13	8.83
0.0535	10.67	10.25	9.85	9.50	9.17
0.0546	11.19	10.72	10.29	9.90	9.53
0.0557	11.76	11.24	10.77	10.33	9.94
0.0568	12.38	11.82	11.30	10.82	10.38
0.0579	13.07	12.45	11.88	11.35	10.87
0.059	13.82	13.14	12.51	11.94	11.40
0.0601	#N/A	13.83	13.21	12.58	12.00
0.0611	#N/A	#N/A	13.37	13.28	12.64
0.0622	#N/A	#N/A	#N/A	14.05	13.35
0.0633	#N/A	#N/A	#N/A	#N/A	14.13

Figure B.3: 3rd screenshot from workbook

Box 6 shows the parameter table. Values are pulled from boxes 9, 10 and 14. Box 8 is where gamma d intercept is calculated in accordance with section 3.6. Box 9 is where gamma d intercept is curve fitted as a function of moisture content. Box 10 is where moisture content is curve fitted as a function of $z_{15}^{-0.5}$. Box 11 is where $z_{15}^{-0.5}$ is calculated

in accordance with section 3.6. Box 12 is used to look up dry unit weight, R, and Z values corresponding to samples A and B from section 3.6. Box 13 calculates max and min dry unit weight and moisture in order to properly set the axes. Box 14 is where a_{gamma} and a_w are calculated in accordance with section 3.6. Box 15 set ups the data to be plotted for dry unit weight. Box 16 sets up the data to be plotted for moisture content.

Insert the resistance (R) and impedence (Z) measurements in order to calculate moisture content and dry density

R [ohm]	330
Z [ohm]	337.4
R^2	0.055048
Z^2	0.054441

Press this button to perform calculation of moisture content and dry density.

Dry Density (pcf)	16.27103
Moisture Content (w)	11.12654

Guess
Dry Density	16.2643822
w	11.126549

Error
0.000408317	0.000409
4.345595E-07	

W max	W min	gamma d r	gamma d min
14.34108527	6.488801054	17.78096	16.26438

Dry Density (kN)	16.27102
Moisture Content (%)	11.12654

g	w	e	g	w
16.26438	6.488801054	0.004508	17.83264	9.513654
16.26438	8.451872108	0.000414	16.27349	11.1235
16.26438	10.41494316	0.001245	16.63535	10.69635
16.26438	12.37801422	0.000409	16.27103	11.12654
16.26438	14.34108527	0.000421	16.27664	11.11962
16.64353	6.488801054	0.004586	17.86251	9.487892
16.64353	8.451872108	0.001643	16.79131	10.52338
16.64353	10.41494316	0.000409	16.27123	11.12629
16.64353	12.37801422	0.000421	16.27664	11.11962
16.64353	14.34108527	0.004586	17.86251	9.487892
17.02267	6.488801054	0.004586	17.86251	9.487892
17.02267	8.451872108	0.002116	16.96839	10.33456
17.02267	10.41494316	0.000428	16.28009	11.11537
17.02267	12.37801422	0.000421	16.27664	11.11962
17.02267	14.34108527	0.004586	17.86251	9.487894
17.40182	6.488801054	0.004586	17.86251	9.487894
17.40182	8.451872108	0.002642	17.15811	10.14069
17.40182	10.41494316	0.000423	16.27807	11.11787
17.40182	12.37801422	0.000421	16.27664	11.11962
17.40182	14.34108527	0.004586	17.86251	9.487892
17.78096	6.488801054	0.004586	17.8625	9.487892
17.78096	8.451872108	0.003218	17.36248	9.940954
17.78096	10.41494316	0.000409	16.27102	11.12654
17.78096	12.37801422	0.000409	16.27103	11.12654
17.78096	14.34108527	0.000409	16.27103	11.12654

17
18
19
20
21
22
23
24
25

Figure B.4: 4th screenshot from workbook

Figure B.4 shows the Calculator sheet of the workbook. Note that boxes 18.19,21,21,23, and 24 are typically hidden. Box 17 is where the user inputs R and Z values. The inverse square roots are calculated but they can be entered manually. Box 18 contains initial guesses for the solver. Box 19 calculates the error of the solution generated by the solver. Box 20 calculates maximum and minimum values of moisture content and dry unit weight and confines the solution to this range. Box 21 calculates dry unit weight and moisture content using the initial guesses, soil model developed in the "Model Development" sheet and equations from section 3.6. Box 23 contains a range of initial guesses, solutions associated with each guess, and percent errors associated with each guess. Box 24 calculates the minimum error. Box 22 enables the macro which runs a solver that searches for a minimum percent error for each initial guess. Box 25 is where the macro pastes the solution with the lowest percent error.

The macro code is listed below:

```
"Sub sadavance()
'
' sadavance Macro
'

'
    Application.ScreenUpdating = False
 Range("B15:B16").Select
 Selection.ClearContents
 For ErrorRow = 11 To 35
   Range("N" & ErrorRow).Select
   Selection.Copy
   Range("E7").Select
   ActiveSheet.Paste
   Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
     :=False, Transpose:=False
   Range("O" & ErrorRow).Select
   Application.CutCopyMode = False
   Selection.Copy
   Range("E8").Select
```

```
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        SolverOK SetCell:="$H$7", MaxMinVal:=2, ValueOf:=0, ByChange:="$E$7:$E$8", _

            Engine:=1, EngineDesc:="GRG Nonlinear"
        SolverOK SetCell:="$H$7", MaxMinVal:=2, ValueOf:=0, ByChange:="$E$7:$E$8", _

            Engine:=1, EngineDesc:="GRG Nonlinear"
        SolverSolve True
        Range("H7").Select
        Selection.Copy
        Range("P" & ErrorRow).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Range("P6").Select
        Application.CutCopyMode = False
        Selection.Copy
        Range("Q" & ErrorRow).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Range("P7").Select
        Application.CutCopyMode = False
        Selection.Copy
        Range("R" & ErrorRow).Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=False
        Next ErrorRow
            Range("Q36:R36").Select
        Selection.Copy
        Range("B15").Select
        Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
            :=False, Transpose:=True
        '
    Application.ScreenUpdating = True
    End Sub"
```

Appendix C: Additional Embry Testing Information

Two test boxes were constructed and used to represent field conditions. The first was a large test box and can be seen in Figure C.. The box consisted of Lexan brand polycarbonate for the sides, fiberglass angles and shims for support, an acrylic base. The Lexan sides were 13 mm thick and the acrylic base was 25 mm thick. The box and angles were held together with Weld-On 45, a two-part methacrylate structural adhesive (Huff, 2010). The inside length, width and height dimensions are 596 mm, 596 mm and 610 mm respectively.

Figure C.1 Large test box (Huff, 2010).

The second test box was a small test box and can be seen in Figure C.. It was constructed out of nominal wooden boards, and fastened with wood screws. The crevasses between the boards were filled with a silicon base sealant. Asphalt sealer was applied to the inside of the box. Metal handles were applied to the outside for mobility. The inside length, width and height dimensions are 381 mm, 381 mm and 356 mm respectively.

Figure C.2 Small test box.

The soil in the large test box was compressed using a hydraulic load frame with a maximum loading capacity of approximately 890 kN. The test setup can be seen in Figure C.. Steel stiffening members were added to the box for lateral restraint. The stiffness members were HSS 38.5 x 38.5 x 6.35 mm members connected with 19.05 mm threaded rods. The load frame was equipped with a circular ball joint loading face to ensure a level loading platform. To distribute the load to the entire soil layer and prevent stress concentrations, a setup consisting of a round steel member (to match the load frame loading face), steel plate, six metal bars and a piece of plywood was used. A layer of pea

Figure C.3 Large box test setup (Huff, 2010).

gravel was added to the bottom of the box for drainage capabilities. A geosynthetic separation layer was used to separate the pea gravel and the soil to prevent soil migration into the pea gravel.

The prepared soil was compressed, by the load frame, four to five times each moisture content resulting in increasing densities. After each compression the soil was allowed to "rebound" for a given amount of time, generally around five minutes and the EDG was then used to collect electrical measurements. A sand cone reading was taken after the electrical readings on the final compression.

The soil was compressed in the small box using a hydraulic load frame with a maximum loading capacity of 534 kN. The load was distributed evenly to the entire soil layer which prevented stress concentrations by using a concrete cinder block, a steel plate, three HSS steel bars, and a sheet of plywood. Weight volume relationships were used to calculate the weight of soil and the load frame was used to compress the soil to the desired density. Electrical readings were taken with the EDG after the soil was allowed to rebound and a sand cone density was measured. Gallatin County sand, Fayette County clay, and Daviess County clay was tested in the large test box. There was not enough Lee County clay to fill the large test box, therefore, the Lee County clay was tested in the small box.

The following figures show research associated with the dielectric constant and imaginary dielectric constant.
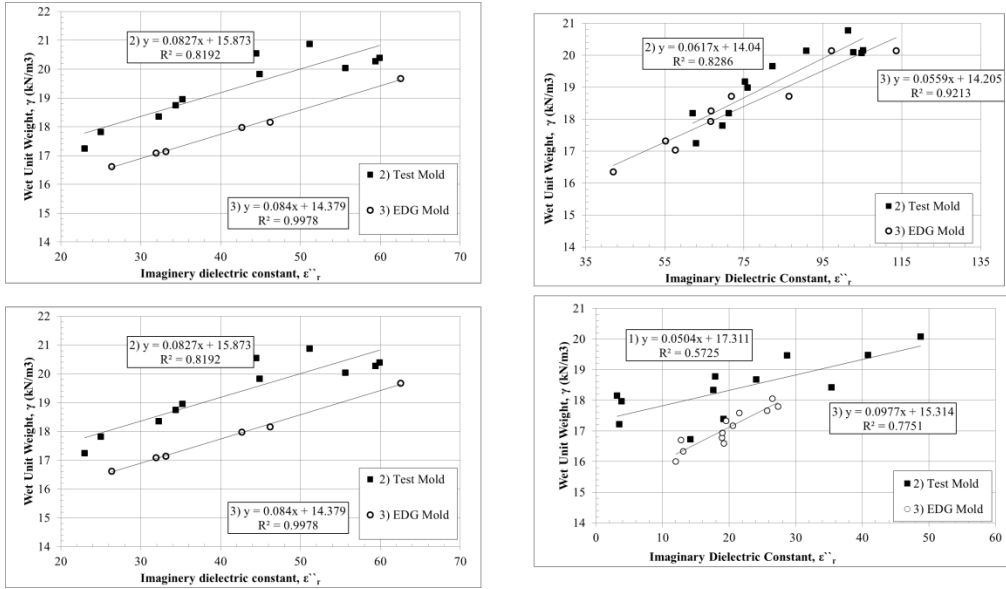
Figure C.4 wet unit weight as a function of imaginary dielectric constant for top left Fayette County clay, top right Daviess County clay, bottom left Lee County Clay, and bottom right Gallatin County sand
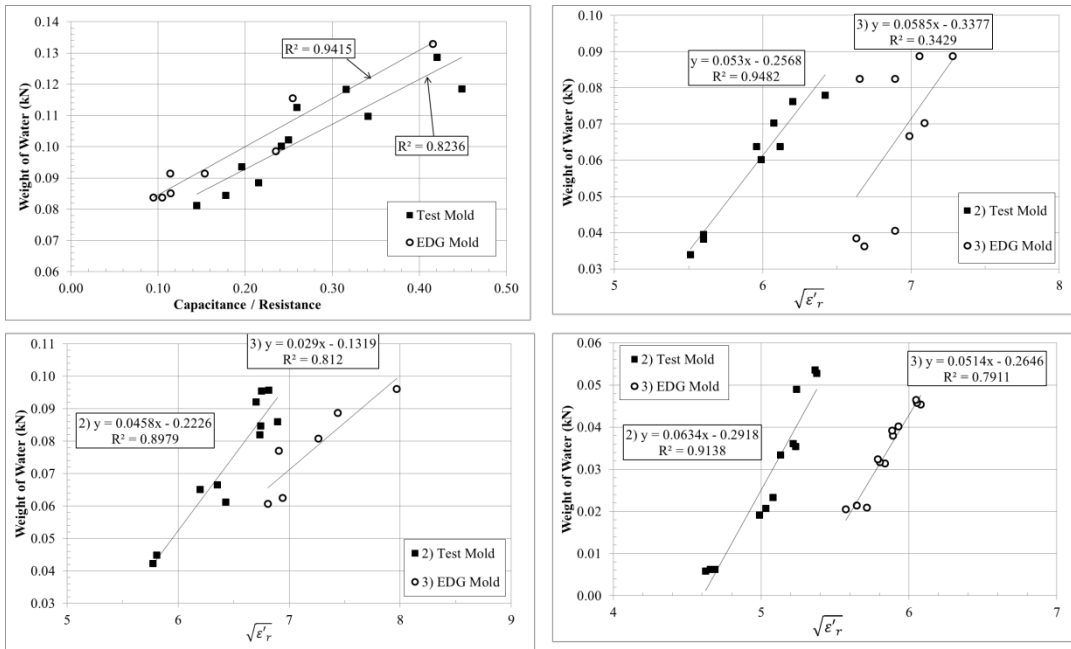
Figure C.5 weight of water as a function of dielectric constant for top left Fayette County clay, top right Daviess County clay, bottom left Lee County Clay, and bottom right Gallatin County sand

Figure C.6: predicted vs. actual wet unit weight as predicted by imaginary dielectric constant for top left Fayette County clay, top right Daviess County clay, bottom left Lee County Clay, and bottom right Gallatin County sand
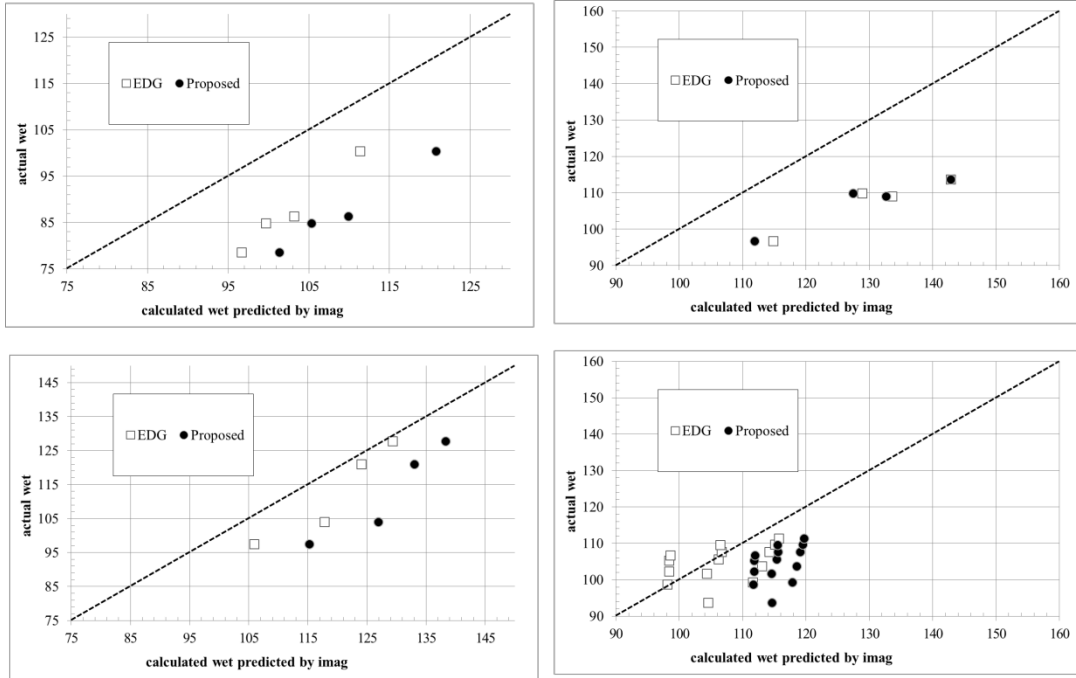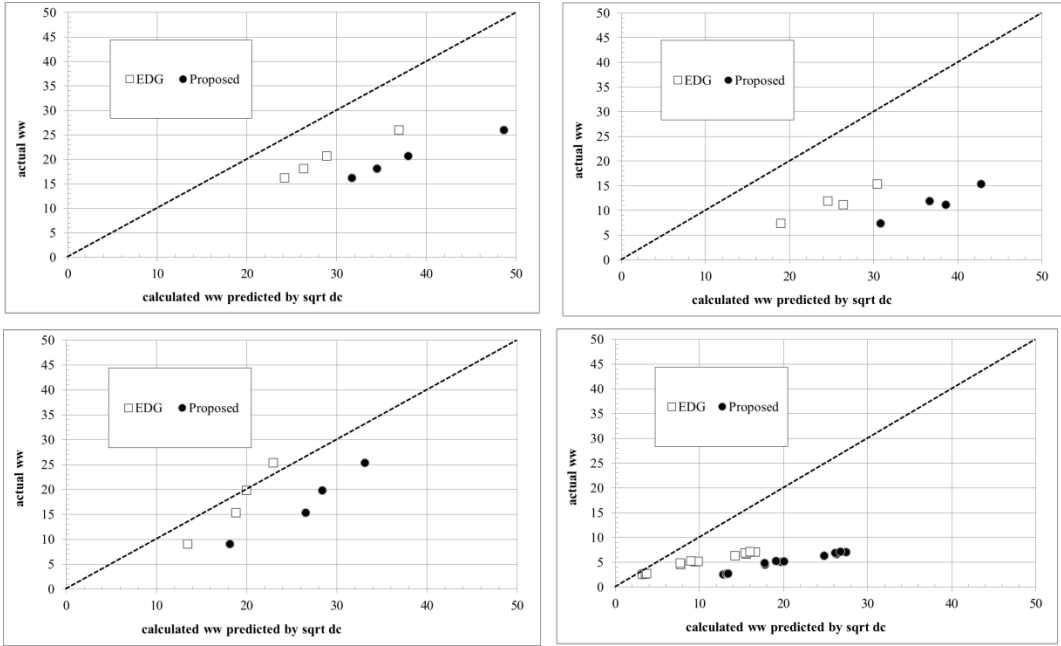
Figure C.7 predicted vs. actual weight of water as predicted by dielectric constant for top left Fayette County clay, top right Daviess County clay, bottom left Lee County Clay, and bottom right Gallatin County sand

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