Using a Complex-Impedance Measuring Instrument to Determine In Situ Soil Unit Weight and Moisture Content

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Abstract: In situ measurements of soil unit weight and moisture content play a critical role in conventional compaction quality assurance and quality control procedures. Recently, there have been a number of attempts to develop alternative electrically-based test devices that can be used to measure the in situ unit weight and/or moisture content of a compacted soil; these devices are intended to serve as alternatives to more traditional tests such as sand cone, rubber balloon, drive cylinder, or nuclear density gauge tests. The study described in this paper focuses on the use of a relatively new electrically-based in situ soil test device that uses measurements of soil complex impedance, soil capacitance, and soil resistance to infer in situ soil unit weight and moisture content; this device is typically referred to as a complex-impedance measuring instrument (CIMI). This paper provides a detailed explanation of current CIMI operating principles and also describes the utilization of a CIMI for field- and laboratory-based testing. The CIMI used in this study was calibrated and assessed in two field compaction projects in which different silty sands were used for construction. A mold-based calibration approach was developed for building an electrically-based soil model using the CIMI; this approach provides an alternative to field calibration of the device. In order to perform a more complete assessment of the CIMI in a controlled environment, a series of CIMI tests were conducted in a large field box, and the resulting in situ measurements of soil unit weight and moisture content made using the CIMI are compared with the results from nuclear density gauge, sand cone, and drive cylinder tests. The advantages and disadvantages of field versus mold calibration of the CIMI are discussed, and side-by-side assessment of the CIMI relative to other conventionally used compaction control tests allows the reader to assess the accuracy of this device.

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1 Introduction

Mechanical compaction of a soil reduces the volume of air voids in the soil matrix, which compresses the soil skeleton and densifies the particle packing. Compaction-induced densification improves the strength and compressibility of a soil, and it is consequently common practice to utilize "end product"-based specifications to ensure that field soils are compacted to density levels that will ensure adequate engineering performance. The process of soil compaction in the field is typically monitored and controlled using quality assurance (QA) or quality control (QC) procedures that involve the use of periodic in situ measurements of soil density (or unit weight) and moisture content. In conventional practice, these measurements are made by a field technician using the sand cone method (ASTM D1556-07), the rubber balloon method (ASTM D2167-08), the drive cylinder test (ASTM D2937-10), or nuclear-based test devices (ASTM D6938-10).

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Nuclear-based test devices (which we refer to generically here as *nuclear density gauges*) are currently the most common tool in the United States for measuring in situ soil density (or unit weight) and moisture content. Unlike the drive cylinder, sand cone, or rubber balloon tests, which attempt to provide a *direct* measurement of soil unit weight and moisture content via weight and volume measurements, nuclear-based devices *infer* the unit weight and moisture content of a soil by measuring the amount of radiation that can be transmitted from a source to a receiver through a zone of compacted soil. (Typically, a gamma radiation source and receiver are used to infer unit weight, and a neutron radiation source and receiver are used to infer moisture content.) For a given nuclear density gauge (NDG) field test, manufacturer-provided calibration relationships are used to convert the measured gamma and neutron radiation counts to the in situ soil properties of interest. User-developed calibration relationships for a given soil are also sometimes used if the manufacturer-developed relationship yields unit weight or moisture content results that are believed to be inaccurate; typically, a series of sand cone tests are conducted when developing a soil-specific calibration.

Side-by-side comparisons of NDG test results with measurements of soil unit weight and moisture content made using sand cone or drive cylinder tests have been performed by a variety of researchers (e.g., Rosser and Webster 1969; Kaderabek and Ferris 1979; Ishai and Livneh 1983; Gabr et al. 1995; Noorany et al. 2000). These studies have yielded a range of results for tests conducted on different soils, with some researchers reporting that NDG unit weights are consistently less than (e.g., Kaderabek and Ferris 1979) or generally the same as those obtained via sand cone testing (e.g., Rosser and Webster 1969). Similar variability in agreement is also observed when comparing measured moisture content values. Some researchers feel that the repeatability of the NDG test is very high (e.g., Ishai and Livneh 1983), which makes it more useful for field control than the sand cone test; others feel that the opposite is true (e.g., Noorany et al. 2000). After a lengthy review of available literature in this area, perhaps the best overall conclusion that can be drawn is that the accuracy and repeatability of each type of QA/QC test may be dependent on the type of soil that is being tested. In the authors' opinion, additional research is needed in this area before more definitive conclusions can be drawn about the behavior of in situ QA/QC soil compaction tests by soil type. Overall, the geotechnical engineering profession appears to have widely accepted the NDG test as a substitute for the more traditional QA/QC tests, although some construction specifications still require that it be performed alongside other tests (e.g., the sand cone) to allow for soil-specific adjustments if needed.

In any case, like all in situ compaction QA/QC test approaches, the NDG test has some limitations with respect to the accuracy of its measurements, especially under certain field conditions (e.g., for NDG tests conducted in trenches, micaceous soils, large-particle soils, etc.). However, perhaps more significantly, the device also has a number of "logistical" issues that inhibit its widespread use as a total compaction QA/QC solution, which largely stem from the presence of the radioactive emission source in the device. In particular, there are numerous issues surrounding the handling, use, transport, and storage of the radioactive material that must be satisfied to ensure both personnel and public safety. There are also strict nuclear regulatory compliance requirements in the United States (which are overseen by the Nuclear Regulatory Commission), which are often prohibitively expensive for smaller firms or firms that maintain a large number of NDG devices; these requirements also restrict the sale of NDG devices on the international market.

In response to these issues, recently there have been a number of attempts to develop alternative *electrically-based* test devices that can be used to measure the in situ unit weight and/or moisture content of a compacted soil. These devices have used a variety of electrical approaches, including time domain reflectometry (e.g., Topp et al. 1980; Neiber and Baker 1989; Siddiqui and Drnevich 1995; Yu and Drnevich 2004), a series of capacitance sensors or dielectric sensors (e.g., Kelleners et al. 2004; Fares et al. 2007), or electrical impedance spectroscopy (e.g., Gamache et al. 2009). Because these types of devices are electrically-based, they do not burden the user with any significant nuclear regulatory compliance requirements. Further, in the long term, they also have the potential to be much smaller, lighter, and more cost effective than their nuclear-based counterparts.

The study described herein focused on the use of a relatively new electrically-based in situ soil test device that uses measurements of soil complex impedance, soil capacitance, and soil resistance to infer in situ soil unit weight and moisture content. In the remainder of this paper, we refer to this device generically as the *electrical density gauge* (EDG); this type of device is also commonly referred to as a complex-impedance measuring instrument (CIMI) (e.g., ASTM D7698-11). The EDG used in this study was calibrated and assessed in two field compaction projects in which different silty sands were used for construction. A mold-based calibration approach was also developed for building an electrically-based soil model using the EDG; this approach provides an alternative to field calibration of the device. In order to perform a more complete assessment of the EDG in a controlled environment, a series of EDG tests were conducted in a large "field box," and the resulting in situ measurements of soil unit weight and moisture content made using the EDG are compared with the results from NDG, sand cone, and drive cylinder tests. The advantages and disadvantages of field and mold calibration of the EDG are discussed, and a side-by-side assessment of the EDG relative to other conventionally used compaction control tests allows the reader to assess the accuracy of this device.

2 Operating Principles of the Electrical Density Gauge

The equipment necessary to perform an EDG test, as well as the associated test procedures that should be followed, are provided in detail in ASTM D7698-11, "Standard Test Method for In-Place Estimation of Density and Water Content of Soil and Aggregate by Correlation with Complex Impedance." A brief discussion of the basic equipment that is required and the associated test and calibration procedures that are commonly used is provided in the following sections.

2.1 *Equipment*

As shown in Fig. 1(a), the test volume of soil that is characterized during an EDG test is defined by the embedment of four tapered soil electrical probes of equal dimensions. Different probe embedment lengths are used to make electrical measurements for compacted soil layers of different thickness; embedment lengths ranging between 101.6 mm (4 in.) and 304.8 mm (12 in.) are consequently typical for use with the EDG. Typical probe diameters range between 6.4 mm (1/4 in.) and 12.7 mm (1/2 in.). The probes are also generally 76.2 mm (3 in.) longer than their embedment length, which allows a portion of the probe to be above the ground's surface during each test, to provide a location for connection with the soil sensor unit [Fig. 1(a)]; this additional length also makes it easier to drive and extract each probe. The conical shape of the probes below the ground's surface helps to ensure consistent and uniform surface contact with the soil media. The shape and other essential design characteristics of these probes are patented by the manufacturer (Lundstrom 2007).

A critical component of the EDG is the soil sensor unit, which combines a frequency source with three electrical measurement meters: an ampmeter, which measures the soil current; a voltmeter, which measures the probe-to-probe voltage; and a phase difference meter, which measures the phase difference between the probe-to-probe voltage and current. During each EDG test, a 3MHz radio frequency source current is generated in the soil sensor unit (from a battery power source) and then passes (1) through an electrical cable to one of the soil probes, (2) from one soil probe to a second soil probe a fixed distance away, through the soil test volume of interest, and (3) from the second soil probe back through an electrical cable to the three electrical measurement meters that are contained within the soil sensor unit [Fig. 1(a)]. The soil sensor unit also contains a test readout display console and an on-board computer that can be used to store soil model information and test readings when working in the field.

A thermistor temperature probe is also connected to the EDG, which allows for temperature readings in the soil near the test location during each test. These temperature readings are used to correct the measured electrical properties for the effect of temperature using proprietary temperature compensation algorithms.

2.2 *Test Procedure*

To begin an EDG test, a rubber mallet is used to gently drive the four electrical probes into the ground to the appropriate embedment depth; during this process, a circular plastic template is used to guide the placement of the probes in a square-shaped pattern [Fig. 1(b)]. The temperature probe is gently pushed by hand into the soil to the appropriate depth at a nearby location. Alligator clips are used to attach one pair of electrical probes that are opposite each other to the radio frequency source and electrical sensors in the soil sensor unit [e.g., the E-W soil probes shown in Fig. 1(b)]. The device is then activated, and simultaneous measurements of soil current, probe-to-probe voltage, and phase-difference are made between the soil probes in the E-W direction. While this is happening, the temperature is also simultaneously recorded at the thermistor probe location. During each activation, an electrical switch in the device allows for a set of readings to be made for current passing in the E-W direction and in the W-E direction (a reversal across the "soil circuit"). After a set of readings has been completed in the E-W and W-E directions, the alligator clips are switched to the open probes, and the device is reactivated to take readings in the N-S and S-N directions. The four resulting values of current, voltage, phase, and temperature for each of the test directions (E-W, W-E, N-S, and S-N) are then averaged to produce single representative values of soil current (I, in milliamps), probe-to-probe voltage (V, in volts), phase-difference angle (θ, in degrees), and temperature (T, in °C) for the soil at the test location.

From the measured and averaged electrical properties, representative values of soil resistance (R, in ohms) and soil capacitance (C, in picofarads) can be calculated using Eqs. 1 and 2 (be careful to include the appropriate unit conversion factors when performing these calculations). These values are determined by representing the soil test volume as a resistor and capacitor (respectively) in an equivalent parallel resistor-capacitor circuit. The complex impedance of the tested soil volume (Z, in ohms) is equal to the ratio of the measured probe-to-probe voltage to the measured soil current (Eq. 3). Alternatively, the soil complex impedance can be calculated using Eq. 4.

$$R = \frac{V}{I}\sqrt{1+\tan^2\theta} \tag{1}$$

$$C = -\frac{I}{\omega V}\left(\frac{\tan\theta}{\sqrt{1+\tan^2\theta}}\right) \tag{2}$$

$$Z = \frac{V}{I} \tag{3}$$

$$Z = \frac{R}{\sqrt{1+\omega^2 C^2 R^2}} \tag{4}$$

where ω is the natural frequency, which equals $2\pi f$, and the other variables are as previously defined. For the EDG,

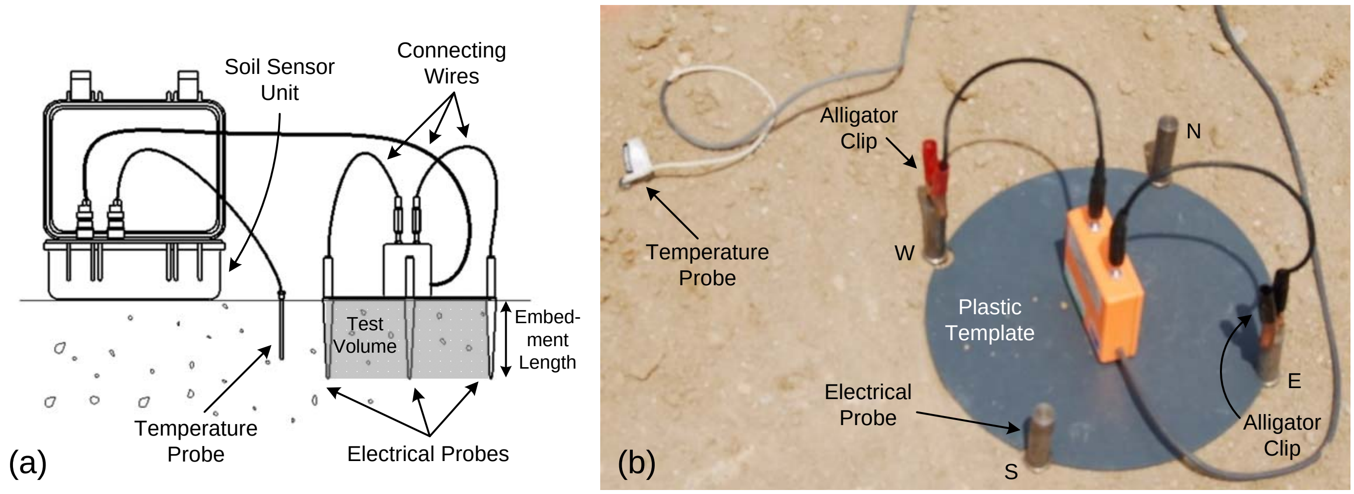

Fig. 1: Electrical density gauge: (a) diagram of an EDG in use (modified from ASTM D7698-11), and (b) typical EDG test setup.

the signal frequency (f) equals 3 mHz. During testing, values of R, C, and Z are calculated directly by the onboard computer in the EDG.

In electrical engineering, it is well understood that the electrical resistance in a circuit can be affected by the temperature of the circuit (e.g., Lundstrom et al. 2005). It follows that values of Z and C/R in a "soil circuit" (across the test volume) are also affected by temperature. ASTM D7698-11 consequently recommends the use of "temperature compensated" values of Z and C/R when building a "soil model" that relates electrical properties to in situ unit weight and moisture content values. In practice, the EDG uses an empirically determined temperature correction procedure to adjust the calculated electrical values (Z and C/R) to "constant temperature" values when building a soil model. This temperature compensation process is proprietary in nature and is built directly into the onboard computer in the soil sensor unit. In order for this process to work properly, the temperature probe must be used and the temperature correction mode must be turned on during an EDG test.

A "soil model" is built by correlating electrical values determined using the EDG to physical soil properties (e.g., unit weight, moisture content) that are obtained from NDG, sand cone, or other in situ compaction control tests. This process of building a soil model is sometimes referred to as "calibration" of the EDG. The following section describes the process for creating a soil model and the associated correlation relationships that are used to determine moist unit weight, dry unit weight, and moisture content from EDG-measured properties at a given test location.

2.3 *Field Calibration and Soil Model Development*

The field calibration process that is recommended for building a soil model with the EDG is described in detail in ASTM D7698-11. In general, for a given soil that is being compacted, this process consists of performing EDG tests at the same location as a series of in situ compaction QA/QC tests that are performed using currently accepted procedures (e.g., the sand cone test [ASTM D1556-07], the rubber balloon test [ASTM D2167-08], the drive cylinder test [ASTM D2937-10], or nuclear-based tests [ASTM D6938-10]). Typically, four to nine test points are recommended for building a soil model, and it is critical that they span the range of moisture contents and unit weights that could be recorded in a given project. A six-point model is recommended as a reasonably accurate compromise by ASTM. For example, for a soil that has a target relative compaction of 95% and an optimum moisture content of 7.5%, a typical six-point model might consist of calibration tests performed at the following field relative compactions and moisture contents: (1) 98% relative compaction at 5% moisture content, (2) 98% relative compaction at 7.5% moisture content, (3) 98% compaction at 10% moisture content, (4) 92% compaction at 5% moisture content, (5) 92% compaction at 7.5% moisture content, and (6) 92% compaction at 10% moisture content (i.e., a "moderately compacted" soil and a "well-compacted soil" at moisture contents that are "dry of optimum," "at optimum," and "wet of optimum"). Note that an upper and lower bound of the desired relative compaction in the field are represented here, as are moisture contents that are on the dry side of, directly at, and wet of optimum.

Upon completion of a given calibration test matrix (e.g., the hypothetical six-point matrix described in the preceding paragraph), moist unit weight values obtained from the traditional compaction QA/QC test (γ_m) are plotted versus temperature corrected impedance values (Z) from the EDG. Values of the weight of water per unit volume obtained from the traditional QA/QC test (W_w) are plotted versus temperature corrected values of the ratio of soil capacitance over soil resistance (C/R) from the EDG. Linear regression is then used to build linear calibration relationships of the following form:

$$\gamma_m = m_1 \times Z + b_1 \tag{5}$$

$$W_w = m_2 \times \frac{C}{R} + b_2 \tag{6}$$

where:

m = slope of the corresponding calibration equation, and

b = intercept of the corresponding calibration equation.

In general, the goal of the EDG calibration process is to determine the slopes and intercepts shown in Eqs. 5 and 6 for a specific soil. Once these values have been determined, the resulting soil models can be used to calculate the soil moist unit weight and weight of water per unit volume values for subsequent EDG electrical readings for tests conducted in the same type of soil. The corresponding values of dry unit weight (γ_d) and gravimetric moisture content (w), the parameters that are typically used to control the process of soil compaction, are determined from the values of γ_m and W_w using soil weight-volume relationships (note that throughout this entire calibration process, care must be taken to ensure that a consistent system of units is used):

$$\gamma_d = \gamma_m - W_w \tag{7}$$

$$w = \left(\frac{\gamma_m}{\gamma_d} - 1\right) \cdot 100\% \tag{8}$$

3 Assessing the Effectiveness of the Electrical Density Gauge Using a Field Calibration Procedure

ASTM D7698-11 describes a “field calibration” procedure in which EDG-measured properties are correlated to the results of in situ moisture and density tests that are performed using currently accepted field compaction control procedures (e.g., NDG, sand cone, rubber balloon, or drive cylinder tests). To assess the effectiveness of this calibration approach, an EDG was used alongside a NDG on two active construction projects in the state of Delaware: one located in Dover, DE, and the other located in Middletown, DE.

3.1 *Dover and Middletown Soils*

Field classification of soil samples at the Dover project site indicated that the soils that were placed and compacted were generally light gray to light brown silty clayey sands with trace amounts of fine gravel (ASTM D2488-09a). However, during the in situ testing process with the EDG and NDG, it was observed that the soils that were placed at each in situ test location were somewhat variable in nature. This observation was reinforced by visits to the soil borrow area, where distinct layers of silty sand and clayey silt were observed in the borrow pit (ASTM D2488-09a). The resulting soil that was placed on site consequently represents a somewhat variable mixture of these layered soil deposits.

Field classification of soil samples at the Middletown project site indicated that the soils that were placed and compacted were generally brown silty sands with trace amounts of fine gravel (ASTM D2488-09a). In contrast with the Dover site soils, these soils seemed much more uniform during their placement in the field, with a very similar visual-manual classification at each of the EDG and NDG in situ test locations. Field visits to the corresponding borrow area showed no evidence of significant layering or seaming in the borrow, as was observed for the Dover project site.

In an attempt to quantify the soil variability that was observed, sieve analysis tests were conducted in general accordance with ASTM D6913-04 on eight samples that were taken from EDG/NDG in situ test locations at the Dover site and on eight samples that were taken from EDG/NDG in situ test locations at the Middletown site (Fig. 2). The resulting grain size curves support the general observations that were made in the field with respect to soil variability for these two project sites.

As significant soil variability was observed at the Dover site, Atterberg limit tests (ASTM D4318-10) were not performed on these soils. However, based on the visual-manual classifications and grain size analyses that were conducted, it seems reasonable to assume that these soils had Unified Soil Classification System classifications (ASTM D2487-10) of either silty sand (SM) or silty clayey sand (SC-SM), based upon the relative proportions of sand and silt layers that were mixed from the borrow source during the soil excavation, transport, and placement process. For the Middletown site soils, a few Atterberg limit tests were conducted (ASTM D4318-10), which indicated that the finer portions of the soils that were tested were nonplastic in nature. Therefore, according to the Unified Soil Classification System (ASTM D2487-10), seven of the Middletown soil samples were classified as silty sands (SM), and one specimen was classified as a poorly graded sand with silt (SP-SM).

3.2 *Field Calibration Equations*

Field calibration of the EDG for the Dover and Middletown sites was performed using the calibration process described in ASTM D7698-11 and the “Field Calibration and Soil Model Development” section of this paper. For both projects, NDG and EDG tests were performed at the same in situ locations on previously compacted soil lifts. NDG tests were performed using a Troxler 3440 NDG in direct transmission mode, in general accordance with ASTM D6938-10. Three one-minute NDG “counts” were taken at each in situ test location (without moving the NDG source), in accordance with current Delaware Department of Transportation field procedures. The three count results were then averaged to produce one set of NDG readings that could be used for EDG calibration. A single EDG test utilizing 152.4 mm (6 in.) tapered electrical probes was

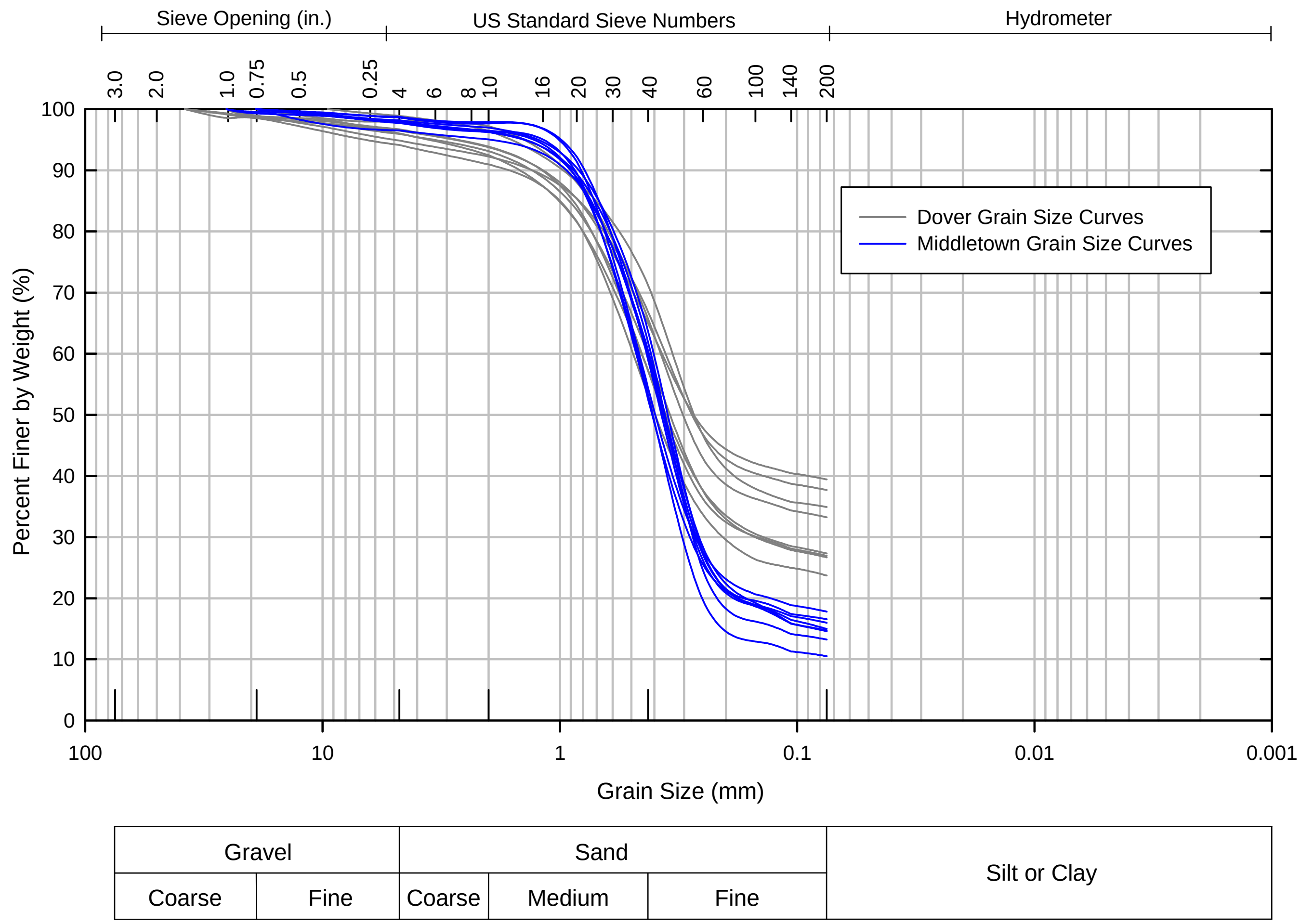

Fig. 2: Gradation distributions for soil samples from Dover and Middletown in situ test locations.

also performed at each test location, following the steps outlined in the "Test Procedure" section of this paper. A total of 20 EDG and NDG tests were conducted at the Dover site, and 29 EDG and NDG tests were conducted at the Middletown site. For both field projects, bag samples were also taken at a number of the in situ test locations for later soil classification testing.

In general, the ASTM recommends building a soil model using four to nine test points that span the range of moisture contents and densities that are expected to be encountered during field construction. In particular, soil conditions looser than 95% relative compaction and denser than 95% relative compaction are desirable (a few percentage points in either direction), and it is beneficial to have moisture contents that are dry of, at, and wet of optimum for the soil that is being compacted. Based upon our experience with this field study, we observed that it can be relatively difficult to precisely control field moisture contents and densities in order to build a calibration model. Consequently, it is often necessary to perform more than the specified number of calibration tests (e.g., four to nine) to achieve a well-populated calibration matrix that broadly represents the possible range of moisture contents and soil densities that might be encountered.

In order to achieve a higher quality calibration matrix, all of the measured field points were used to build soil models for the soils at the Dover and Middletown sites. The resulting moist unit weight versus impedance and weight of water per unit volume versus capacitance/resistance plots for the Dover and Middletown soils are shown in Fig. 3. For comparison purposes, data measured using the EDG are plotted in their originally recorded form, without any form of temperature correction applied (TC OFF), and after the EDG's proprietary on-board temperature correction had been applied (TC ON). The results from linear regression of the data are also presented on these figures, along with the associated coefficient of determination (R^2) values.

As shown in Fig. 3, the data used to build the calibration relationships are relatively scattered, with coefficients of determination from linear regression for the impedance equations ranging from 0.03 to 0.36, and for the capacitance/resistance equations ranging from 0.25 to 0.91. The relatively high value of R^2 for the Middletown data set is largely a function of the two separated data sets, which are both relatively scattered locally. In general, the C/R equations show better linear correlation than the Z equations. It can also be observed that the temperature cor-

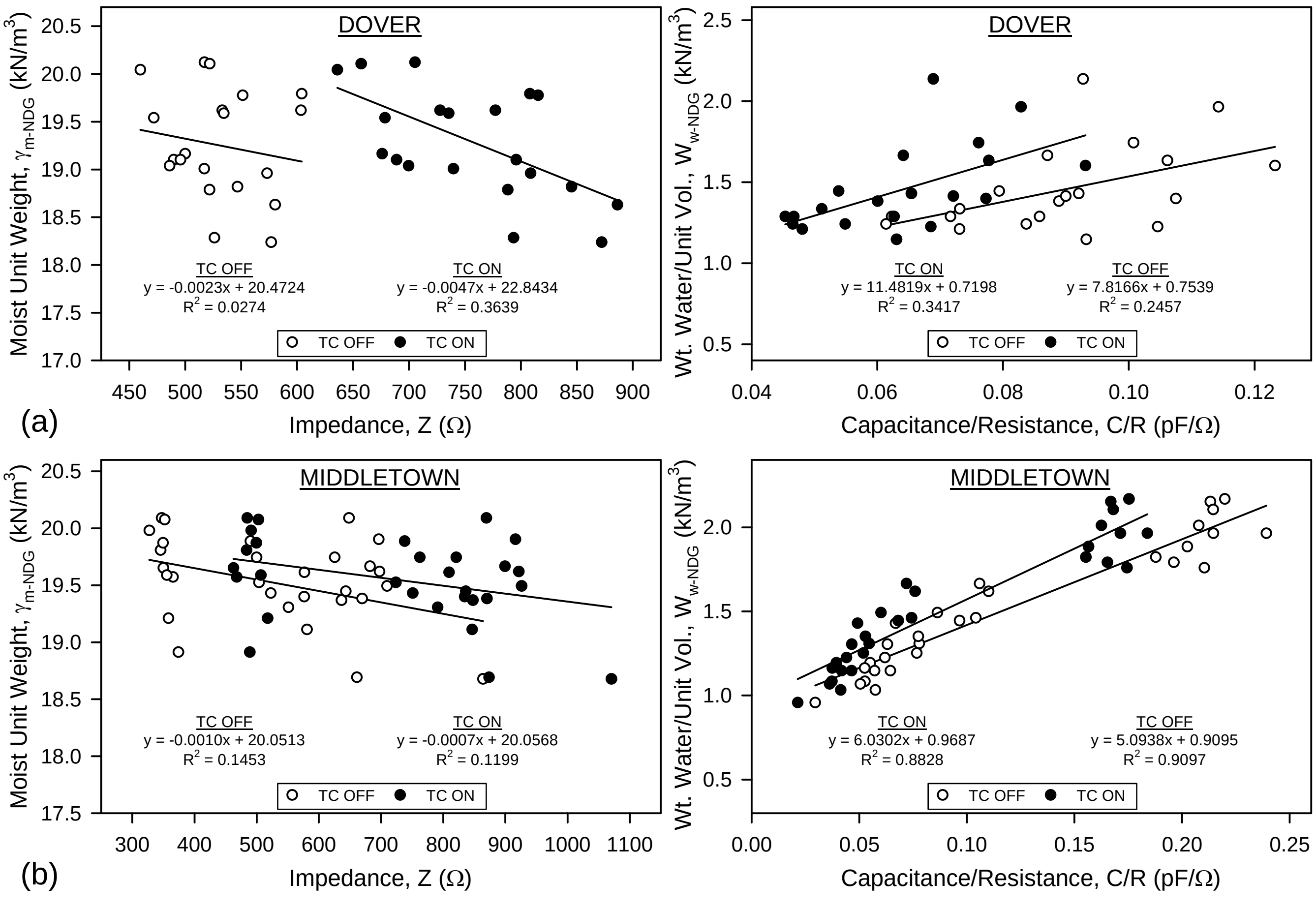

Fig. 3: EDG calibration for the (a) Dover soil and (b) Middletown soil (field calibration procedure).

rection that was used improves the quality of data fit for the Dover Z and C/R equations and makes things slightly worse for the Middletown Z and C/R equations.

3.3 *A Comparison of Nuclear Density Gauge and Electrical Density Gauge Results for the Dover and Middletown Soils*

Using the calibration equations shown in Fig. 3, it is possible to calculate soil unit weight and moisture content values from the recorded electrical properties for the 20 Dover EDG tests and the 29 Middletown EDG tests. Comparisons can then be made between the measured NDG in situ test values and the predicted EDG test values for each soil. A series of 1:1 plots that compare NDG measured values versus EDG predicted values for the Dover and Middletown soils are presented in Fig. 4; the in situ soil properties of interest that are shown in this figure are moist unit weight (γ_m), dry unit weight (γ_d), and moisture content (w).

Each of the plots shown in Fig. 4 also provides the root-mean-square error (RMSE) between the EDG and NDG data sets. The RMSE is a frequently used measure of the differences between values predicted by a model and the values actually observed for the variable that is being estimated; lower values of RMSE are consequently superior, as they indicate less error between predicted and observed values. RMSE is calculated by taking the square root of the mean square error; for an unbiased estimator, the RMSE is the square root of the variance:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (x_{1,i} - x_{2,i})^2}{n}} \tag{9}$$

From the results shown in Fig. 4, the following observations can be made:

1. In general, there was not strong agreement between the EDG and NDG test results, even when the entire NDG data set was used for EDG model calibration (Fig. 4). Also, the EDG results for the Middletown soil appeared to be relatively "binned" into two ranges of values, especially for the moisture content and dry unit weight. It should be noted that this lack of agreement can be reasonably attributed to the scatter in measurements that results from either test device, as both devices are reported by their manufacturers to have similar precision and bias.
2. The Middletown soil showed significantly less variability in the final results than the Dover soil; note that the RMSE values for Dover are all significantly greater than the RMSE values for Middletown. As there was

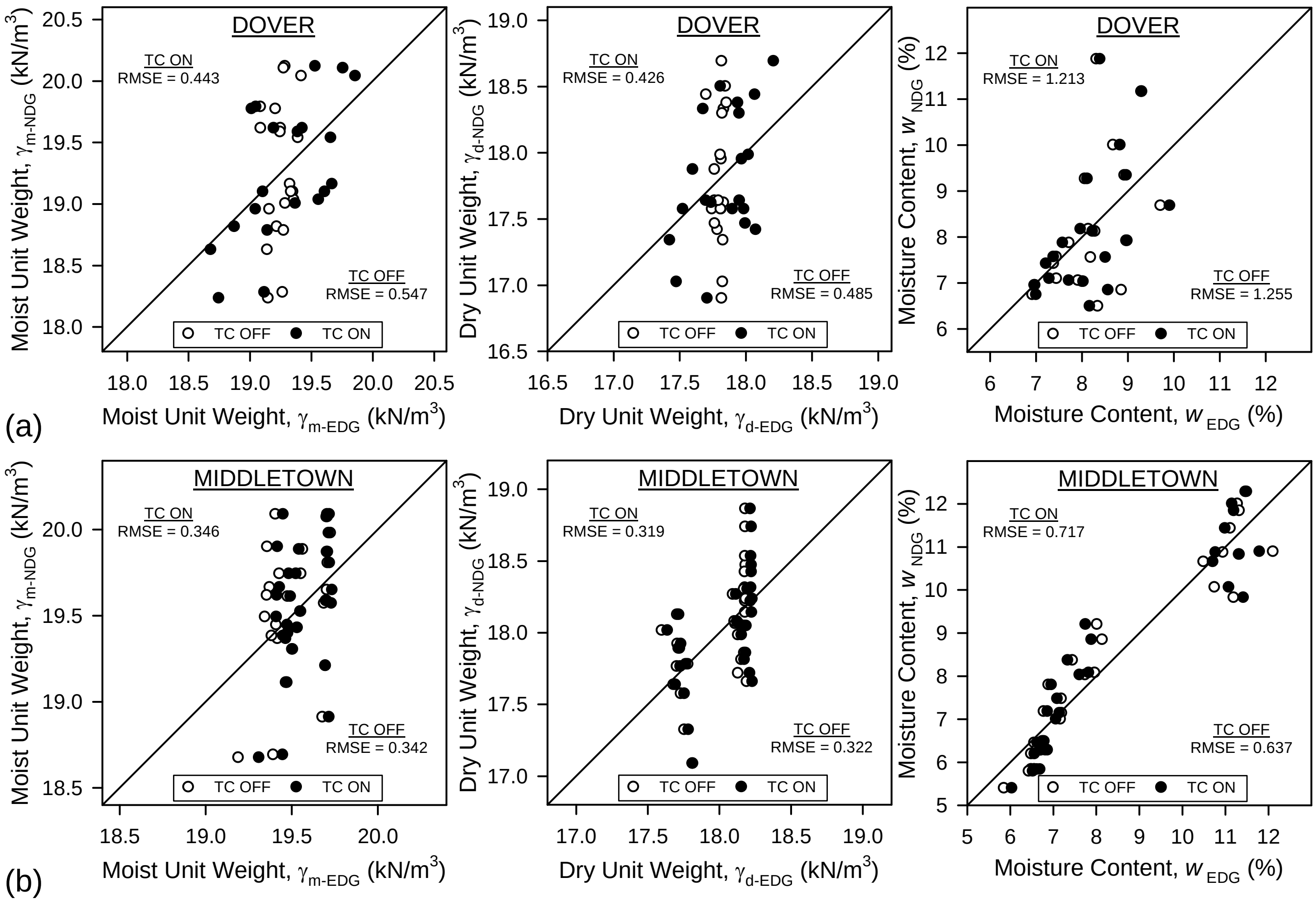

Fig. 4: A comparison of NDG- and EDG-measured moist unit weight, dry unit weight, and moisture content values for the (a) Dover soil and (b) Middletown soil (field calibration procedure).

greater variability in the borrow source for the Dover project than for Middletown, the final EDG results were consequently more variable for that soil. These results illustrate the potential sensitivity of the EDG to variations in the borrow source material, as different source materials can potentially require the use of different soil models.

3. For the Dover soil, the use of the proprietary EDG temperature correction improved the agreement between the EDG and NDG results for all of the properties of interest shown in Fig. 4. For the Middletown soil, the temperature correction had no significant effect on the moist unit weight and dry unit weight results, and it yielded only a slight decrease in agreement between the moisture content values. These observations are consistent with the trends that were observed with the calibration equations.

3.4 *Discussion of Results*

From the data that are presented in the preceding section, it is clear that there are some limitations to creating a soil model using the field calibration process. In particular, for the data that were recorded during these two field studies, relatively poor agreement was observed between the NDG and EDG predicted values. This lack of agreement occurred even when the "assessment" data set was the same as the "calibration" data set, which is a much less rigorous test than a truly "blind" assessment.

There are a number of possible causes for the general lack of agreement that was observed. Some of the more notable reasons that are believed to have been possible contributing factors in this field study include the following:

1. It is difficult to construct a soil model that is representative of the range of moisture contents and soil densities that will be encountered during the compaction process. In particular, on an active construction site, contractors try to maintain the same moisture content and reach the same density for the fill material they are compacting. This creates difficulty when trying to build a soil model that spans the range of densities and moisture contents that may be encountered in a fair and representative way. Getting the necessary field variability in moisture content can be particularly challenging under certain field conditions.
2. There are inherent uncertainties and sources of error in the tests that are used for the field calibration purposes themselves. In particular, the field calibration

process requires the use of an NDG or other standard in situ density test such as the sand cone or rubber balloon test. These tests have their own uncertainty and sources of error in measurement, and consequently this error has the potential to become compounded when building a soil model.

3. Soil variability exists on site. The EDG appears to be more sensitive than the NDG to variations in the soil borrow source. This effect is evident if the results from the Dover project are compared to those from the Middletown project. In particular, changes in the quantity or nature of the fines in a borrow soil are hypothesized to have a significant effect on measured EDG results. The authors believe that this might be because the electrical characteristics of a soil matrix are more affected by the characteristics of the finer particles in the matrix, because of their larger relative specific surface area, or perhaps because of their relative charge behavior and affinity for water (e.g., diffuse double-layer-type behavior).
4. Another observation captured by the field studies discussed in this paper is that although the proprietary EDG temperature correction algorithm did improve the data somewhat for the Dover soil, it did not exhibit a large enough improvement overall in the EDG-predicted results. Perhaps better improvement in the measured results is too much to expect of the temperature correction that is utilized, as it is hoped that the effect of temperature on measured electrical results has only a secondary effect. However, the authors believe that a "one size fits all" temperature correction is perhaps not the best approach for analyzing data from different soils, and that a different temperature correction might be warranted for different soils. An improved understanding of the effect of temperature on EDG results requires additional research.

Given the uncertainties involved with EDG calibration using current compaction control tests, as well as difficulties that can be encountered with soil variability on a field project site, the authors feel that it is worth exploring alternative approaches to field calibration in order to generate soil data that can be used to fairly assess the effectiveness of the EDG. One such alternative calibration approach that utilizes a Proctor-type compaction mold is described in more detail in the following section.

4 An Alternative Mold Calibration Procedure for the Electrical Density Gauge

An alternative to field calibration of the EDG using the procedure outlined in ASTM D7698-11 is to develop an approach that can be used for laboratory calibration in a controlled environment. Instead of gathering calibration test points in the field using traditional in situ compaction control tests (e.g., NDG, sand cone, drive cylinder, etc.), the authors attempted to develop a technique for gathering calibration test points by preparing compacted soil in the lab at various moisture contents and densities using a large "Proctor-type" mold (Fig. 5). Although this type of calibration approach seems reasonable, it should be noted that it is not specifically endorsed by either the EDG manufacturer or the existing ASTM procedure; the authors simply felt that it was worth exploring in the context of this study.

The mold shown in Fig. 5 was constructed from a 37.8 cm (14.9 in.) inside diameter and 38.9 cm (15.3 in.) outside diameter polyvinyl chloride (PVC) pipe. The mold was 25.4 cm (10 in.) deep and had a durable plastic base. The dimensions of this mold were selected such that it was large enough to allow an EDG test to be performed inside of it. Plastics are used for the mold construction because they are insulators (non-conductive) and consequently should cause less interference with the electrical measurements carried out by the EDG than a metal (conductive) mold might.

In order to create an EDG calibration point, a uniformly mixed soil is compacted into the mold using a consistent tamping procedure. The four EDG electrical probes are then driven into the mold using the plastic template for guidance [Fig. 5(b)], and an EDG test is performed in the same fashion as in the field. From this point, the "mold calibration" approach adheres to the same general principles that are used to create a soil model using field calibration (i.e., the same EDG data recording procedures, calibration relationships, and temperature corrections are used).

4.1 *Mold Calibration Test Procedure*

The following procedure was utilized when performing mold calibration tests for this research study:

1. Collect a sufficient volume of soil for calibration that is representative of the soil that is to be placed and compacted in the field. The more calibration points you want to have, the more soil you need. A minimum of four to nine mold calibration points are recommended, in accordance with ASTM D7698-11. Theoretically, the more calibration points that are generated, the better (more accurate) the soil model will be.
2. Mix the entire calibration soil volume thoroughly to ensure uniformity, and divide the mixture into separate volumes that are to be used for each calibration mold.
3. For the soil that is to be used in a given calibration mold, add water as necessary while mixing to adjust the moisture content of the soil to the desired range. Alternatively, lay out the soil to air dry. This process is essentially the same as that used for soil preparation for Standard Proctor (ASTM D698-07) or Modified Proctor (ASTM D1557-09) tests. After adjusting the soil mixture to the desired moisture content, seal the soil in a covered container and wait 24 h for the moisture in the bulk sample to come to equilibrium (this step helps to ensure moisture homogeneity). Large stand mixers or concrete mixers can be used to facilitate the mixing process if a large volume of soil is being prepared.
4. Measure and record the height and inside diameter of an empty plastic Proctor-type mold. Weigh the dry

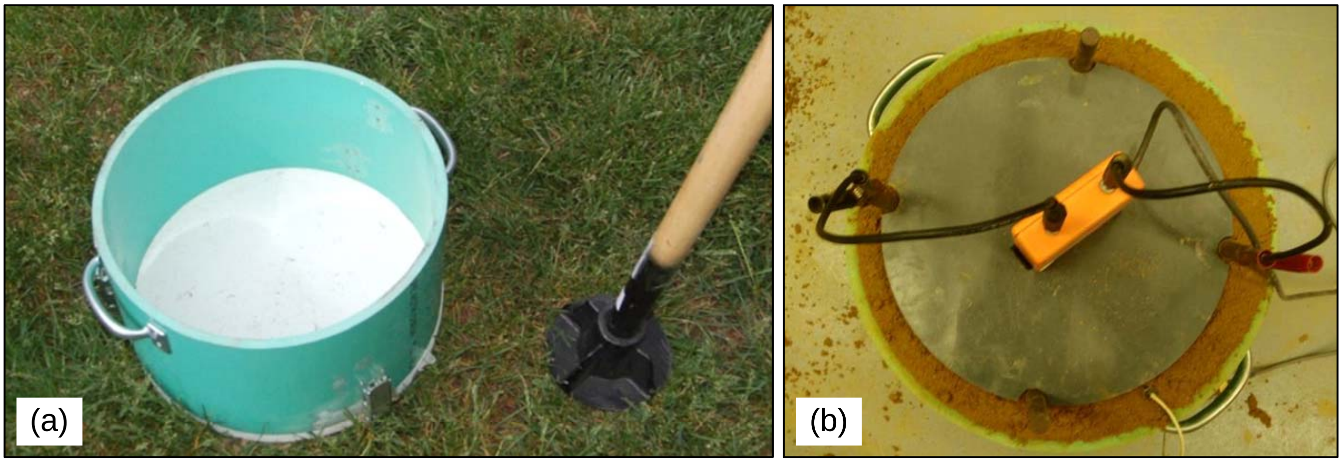

Fig. 5: Large "Proctor-type" mold calibration approach: (a) an empty plastic Proctor-type mold with a removable base and tamper; (b) a Proctor-type mold full of compacted soil that is being used for EDG calibration.

empty mold and base and record its mass.

5. Place the soil in a series of lifts in the mold, compacting the soil in each lift with a tamper that is dropped by hand from a height of 40.6 cm (16 in.) to 45.7 cm (18 in.). Soil is tamped into the mold at the desired moisture content, using a level of effort sufficient to achieve the desired soil unit weight. Remove the top collar (not shown in Fig. 5) and strike off the top of the mold as you would in a conventional Proctor compaction test.
6. Weigh the mold that is filled with the moist tamped soil and record its mass.
7. Set up the EDG and drive the EDG electrical probes and temperature probe into the soil in the mold [Fig. 5(b)] (152.4 mm (6 in.) tapered electrical probes were used for the mold calibration procedure).
8. Take electrical measurements with the EDG that can be used for the "soil model" calibration process.
9. Oven dry the mold soil to determine its moisture content and the dry unit weight of soil in the mold. One approach here is to simply dry all of the soil in the mold to get a good measure of the average moisture content. A second (and probably better) approach is to take local moisture content samples in the large mold that can be used to check for moisture variability throughout the test volume. If a good mixing process is used, these values typically will exhibit little variation (as was observed in this study).

4.2 *Mold Soils*

The soil used for the mold calibration tests was part of a large bulk sample taken from a relatively uniform borrow pit in Delaware. This large bulk sample was delivered by a dump truck to the field box testing location (the field box testing program is described in a later section) and mixed thoroughly, and a representative portion of the large bulk sample was set aside for the mold calibration tests. Visual-manual classification of the soil in the bulk sample from the borrow pit indicated that this soil was generally a brown silty sand (SM) with trace amounts of fine gravel (ASTM D2488-09a).

Sieve analysis and hydrometer tests were conducted in general accordance with ASTM D6913-04 and ASTM D422-63 on samples from all 12 of the mold tests that were conducted (Fig. 6). Atterberg limit tests (ASTM D4318-10) indicated that the fines in this soil were non-plastic. From these tests, 10 of the soil samples were classified as silty sand (SM), and 2 samples were classified as poorly-graded sand with silt (SP-SM), according to the Unified Soil Classification System (ASTM D2487-10). As shown, the mixing procedure that was utilized yielded relatively uniform soils in each of the mold calibration tests.

4.3 *Mold Calibration Equations*

Twelve mold calibration tests were conducted to build a soil model for the material being tested. In order to achieve a wide range of densities, various numbers of lifts and blows per lift were performed during the mold compaction process. Table 1 summarizes the number of lifts and blows per lift and the resulting physical data that were used for correlation with the electrical measurements taken by the EDG to build a soil model. Table 2 shows the corresponding EDG test results that were recorded in each of the calibration molds. Figure 7 shows the associated soil models that were developed using the EDG calibration process (using the data shown in Tables 1 and 2), with and without the proprietary EDG temperature correction applied.

4.4 *A Comparison of Mold and Electrical Density Gauge Results*

Following the same process that was utilized for the Dover and Middletown soils, it is possible to calculate soil unit weight and moisture content values from the recorded electrical properties for the 12 EDG mold tests using the calibration equations that are shown in Fig. 7. Comparisons can then be made between the measured mold soil proper-

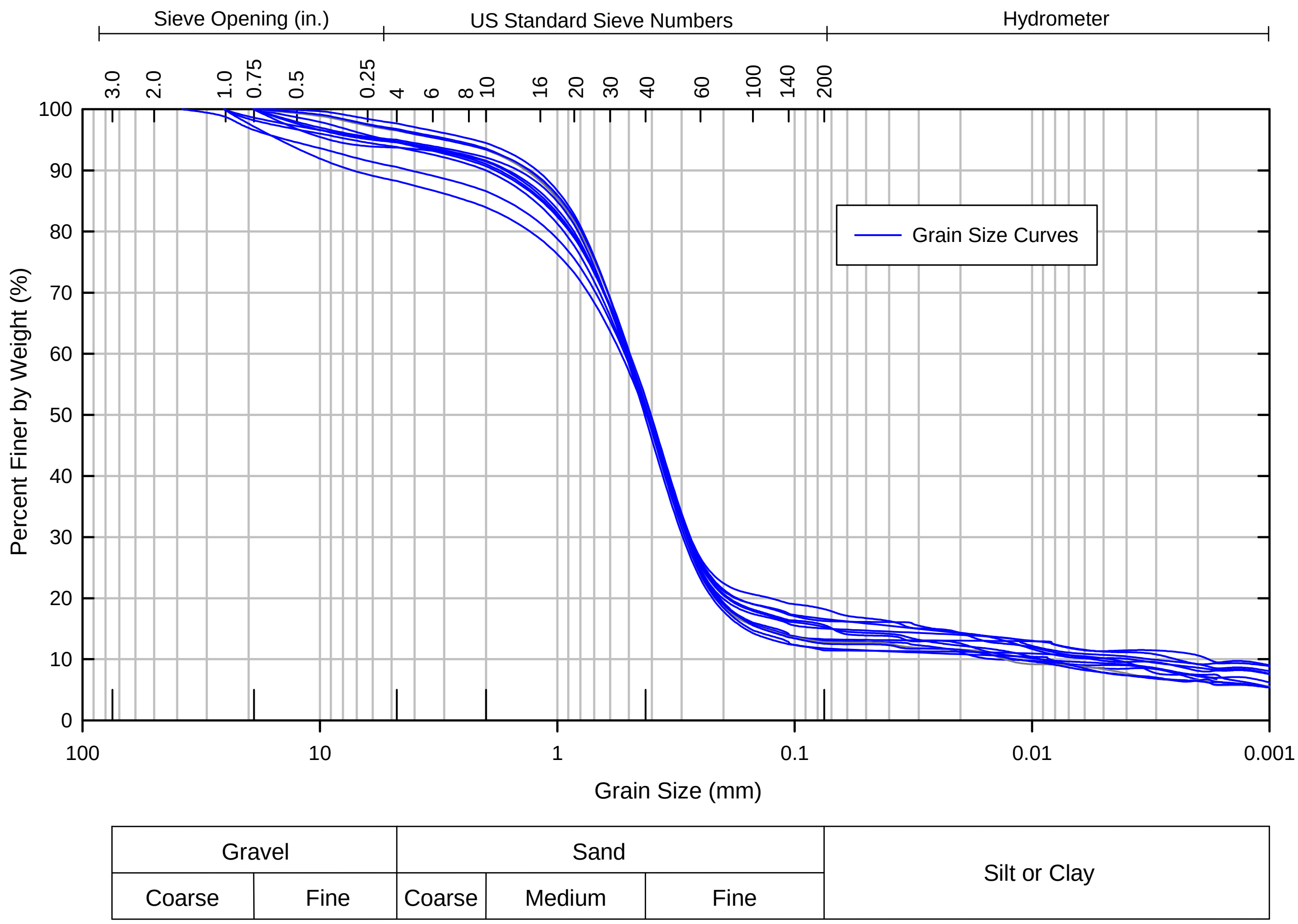

Fig. 6: Gradation distributions for soil samples from mold tests.

ties and the predicted EDG soil properties. A series of 1:1 plots that compare the measured mold values to the predicted EDG values are presented in Fig. 8; the soil properties of interest that are shown in this figure are moist unit weight (γ_m), dry unit weight (γ_d), and moisture content (w). For comparison purposes, values are presented with and without the proprietary temperature correction.

4.5 *Discussion of Results*

The mold calibration procedure described here has a few advantages over field calibration: (1) premixing of the soil helps to ensure soil uniformity, which typically leads to more consistent calibration readings, (2) adding measured amounts of water allows target moisture contents to be more precisely achieved, (3) having a consistent tamping process might allow for the establishment of a more uniformly compacted soil throughout the soil volume, making it easier to achieve target densities than if field compaction techniques are used, and (4) compaction mold results are generally more trustworthy than results from field in situ tests such as the NDG test (which are typically more scattered), as direct measurements of mass and volume are being made. The major disadvantages of the mold approach are (1) that it requires some significant additional effort for EDG calibration beyond what would be required in the field, (2) that there are some boundary effects imposed by the edges of the mold that can cause an uneven distribution of soil compaction in the mold, and (3) perhaps most significant, that having an insulator (the PVC plastic) in the soil close to the electrical probes can have an effect on the electrical readings that are made by the EDG, as it could possibly affect the shape of the electrical field between the probes. The effect of disadvantage 3 is unknown, but it could be quantified in a future study in which an EDG is placed in the ground, a series of readings is taken, and a series of concentric insulator rings (of decreasing diameter) are driven in around the EDG to determine how much the electrical readings change as the insulator rings get closer to the outside edges of the electrical probes.

In any case, as shown in Fig. 8, it is evident that the mold calibration procedure also yields a significant amount of error in forward prediction, on par with or even larger than that from field calibration (if the RMSE values from Fig. 8 are compared with those from Fig. 4 for the Dover and Middletown soils). It can also be observed that the temperature correction that was used did not significantly

Table 1: Proctor Mold Calibration Data

Mold Number	1	2	3	4	5	6	7	8	9	10	11	12
Lifts	10	5	2	5	3	2	5	3	2	10	5	2
Blows/lift	100	100	50	100	50	25	100	50	25	100	100	50
γ_m, kN/m^3	20.05	19.61	18.65	21.04	19.68	18.87	21.02	20.38	19.37	20.59	19.18	18.35
γ_d, kN/m^3	18.44	17.96	17.11	18.88	17.71	16.92	18.47	17.87	17.03	18.82	17.49	16.73
W_w, kN/m^3	1.62	1.65	1.54	2.16	1.97	1.94	2.55	2.51	2.34	1.77	1.70	1.62
w, %	8.8	9.2	9.0	11.5	11.1	11.5	13.8	14.0	13.7	9.4	9.7	9.7

Table 2: Electrical Density Gauge Test Results, Mold

Test Number	V_{avg} (V)	I_{avg} (mA)	θ_{avg} (deg)	T_{avg} (°C)	Z_{raw} (Ω)	$(C/R)_{raw}$ (pF/Ω)	Z_{corr} (Ω)	$(C/R)_{corr}$ (pF/Ω)
1	1.731	2.150	-67.81	16.32	804.9	0.0286	821.7	0.0278
2	1.683	2.244	-61.67	16.42	750.2	0.0394	769.1	0.0381
3	1.756	2.001	-68.49	16.18	877.5	0.0235	891.3	0.0229
4	1.668	2.381	-62.51	17.89	700.4	0.0443	751.7	0.0406
5	1.707	2.233	-65.29	18.00	764.4	0.0345	818.2	0.0315
6	1.701	2.246	-64.79	19.78	757.5	0.0356	850.4	0.0305
7	1.622	2.584	-60.63	20.78	627.6	0.0576	742.5	0.0476
8	1.632	2.497	-59.94	20.58	653.6	0.0538	764.2	0.0448
9	1.670	2.325	-61.81	20.54	718.3	0.0428	828.0	0.0357
10	1.710	2.233	-66.33	21.00	765.6	0.0333	885.4	0.0273
11	1.662	2.321	-59.88	21.22	716.2	0.0449	840.9	0.0366
12	1.740	2.039	-66.79	20.97	853.3	0.0264	972.5	0.0217

improve the overall EDG results - at least, not enough temperature correction improvement was observed to move the EDG results into the range of "good agreement" with the mold data. Unfortunately, as the soils that were compared in these three separate studies (Dover, Middletown, and the mold study) were not the same, it cannot be definitively concluded from these results alone whether using a mold calibration procedure with the EDG is more or less reliable than a field calibration procedure.

What might be a more accurate overall assessment of the results is that neither the field nor mold calibration procedures yielded EDG results that were in strong agreement with the values that were being calibrated against. This certainly might not be true for all soils that the EDG is used with, but it was observed for the three soils that were examined in this study (the Dover, Middletown, and mold soils). Furthermore, the proprietary temperature correction did not appear to significantly improve results - at least, not enough temperature correction improvement was observed to move the EDG results into the range of "strong agreement" with the NDG and mold values. Consequently, perhaps alternative EDG calibration procedures other than the "default calibration approach" that is described in this paper could be used to achieve better results with the Delaware soils that were tested in this study. This hypothesis will be the focus of a future publication that will provide a more detailed study of alternative EDG calibration procedures.

5 A Comparative Assessment of the Electrical Density Gauge Using a Series of "Field Box" Compaction Tests

Although the preceding paragraph can be read as somewhat critical of the EDG, this would not be a completely fair assessment of this device. In particular, all of the currently accepted compaction QA/QC tests are known to exhibit significant scatter in a given lift of compacted soil (even if the soil is very uniform), and all are susceptible to certain situations in which they might yield unreliable results (e.g., large-particle soils, micaceous soils, etc.). Furthermore, the use of electrically-based technologies for QA/QC of soil compaction is still in its relative infancy, and as these devices gain more widespread utilization, the calibration approaches will become more refined, and the database of known electrical soil behaviors will become better established. This will hopefully allow for the creation of more "global" soil models, of the type that are currently used by the NDG.

In any case, in order to perform a more "fair" assessment of the EDG, the scatter of the test results in a given soil should (at a minimum) be compared against those from other currently accepted compaction QA/QC tests. However, as illustrated by our experience at the Dover and Middletown sites, it can sometimes be difficult to perform a fair assessment of the EDG on an active project site, largely because of challenges in controlling the tempo of typical field operations, as well as difficulties in establishing uniform soil and moisture conditions. As an alternative to assessment of the EDG on an active project site, the authors elected to mix, place, and compact soil outside in a

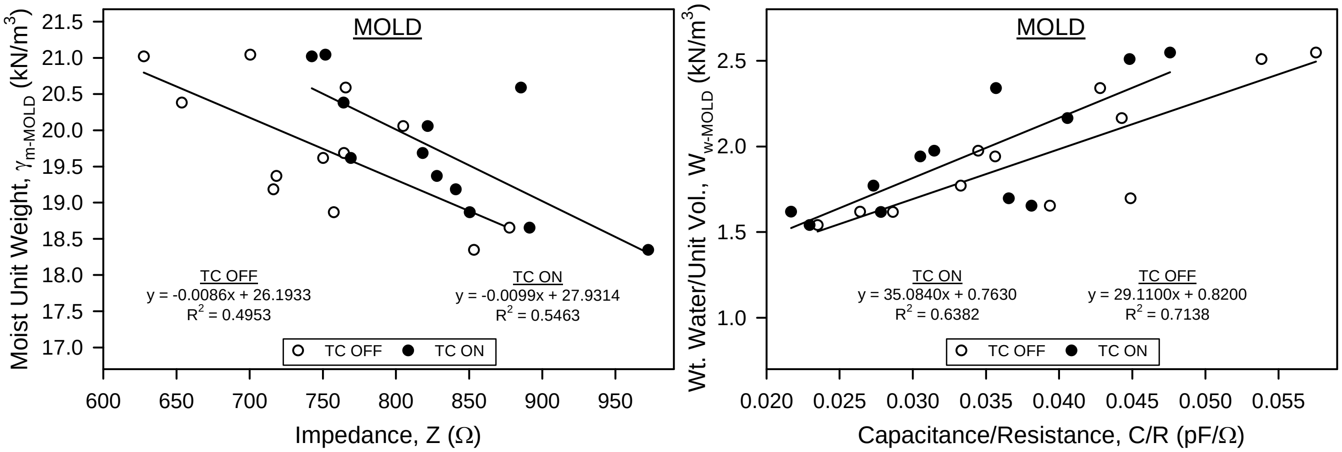

Fig. 7: EDG calibration for the mold soil (mold calibration procedure).

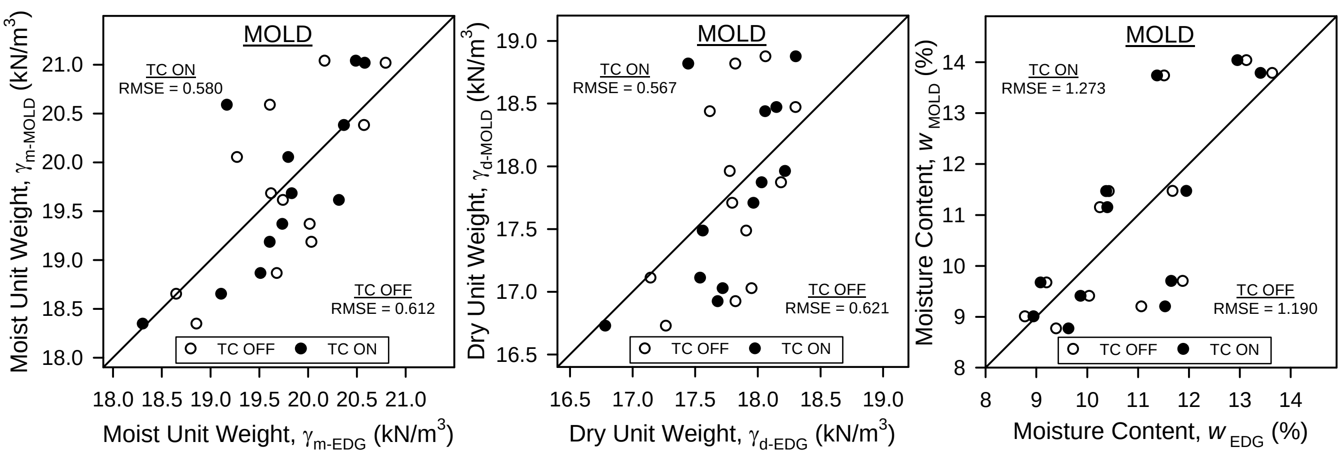

Fig. 8: A comparison of NDG- and EDG-measured moist unit weight, dry unit weight, and moisture content values for the mold soil (mold calibration procedure).

large "field box" using a vibratory plate compactor. Side-by-side EDG, NDG, sand cone, and drive cylinder tests were then performed in each compacted box of soil for a number of field boxes prepared over a range of densities and moisture contents. The following sections describe the results from these tests and show comparisons of in situ soil unit weight and moisture content measurements that were made using the different compaction QA/QC test devices.

5.1 *Field Box Test Procedure*

The goal of the field box testing described in this section was to have a process for gathering simulated field compaction data. To accomplish this task, a large, relatively stiff wooden box having inside dimensions of 1.5 m (5.0 ft) in length, 0.6 m (2.0 ft) in width, and 0.3 m (1.0 ft) in depth was constructed. For each series of field box tests, soil was placed in the rigid box and compacted with a walk-behind vibratory plate compactor prior to performing in situ tests. The following detailed test procedure was followed when performing field box tests for this research study:

1. Mix the soil thoroughly to ensure uniformity. Add water or air dry as needed to prepare soil to the desired moisture content, and store the soil for 30 min in a sealed container to help ensure moisture equilibration. A tow-behind concrete mixer was used for mixing purposes in this research study.
2. Place and spread the soil in a uniform lift in the field box. Varying the lift thickness (over a small range) was found to be one of the easier ways to achieve the desired range of soil unit weights. In this study, soil was placed in uniform lifts ranging from 2.5 cm (1 in.) to 10 cm (4 in.) in thickness.
3. Compact the soil with a walk-behind vibratory plate compactor. Typically, three to six passes were performed to yield the desired density for a given lift.
4. Perform four different compaction QA/QC tests at a given location in the field box, within a closely defined area (at "the same location"). In order, these tests were an EDG test utilizing 152.4 mm (6 in.) tapered electrical probes (ASTM D7698-11), a NDG test in

direct transmission mode (ASTM D6938-10), a sand cone (SC) test (ASTM D1556-07), and a drive cylinder (DC) test (ASTM D2937-10). (Prior to the in situ testing in this study, the NDG and SC test equipment was calibrated following the procedures outlined in ASTM D6938-10 and ASTM D1556-07.)

5. Repeat the in situ testing procedure above for a total of three distinct test locations in each field box of compacted soil. Repeat the entire compaction procedure and in situ testing process for a variety of box compaction energies and soil moisture contents.

5.2 *Field Box Soils*

As noted previously, the soil that was used for the field box tests that are described in this section was part of a large bulk sample taken from a relatively uniform borrow pit in Delaware. This large bulk sample was delivered by a dump truck to the field box testing location and mixed thoroughly, and a representative portion was set aside for the mold calibration tests that were described previously. Visual-manual classification of the soil in the bulk sample from the borrow pit indicated that this soil was generally a brown silty sand (SM) with trace amounts of fine gravel (ASTM D2488-09a).

Sieve analysis tests were conducted in general accordance with ASTM D6913-04 on samples taken from each of the 42 in situ field box test locations (Fig. 9). A few Atterberg limit tests (ASTM D4318-10) indicated that the fines in these soils were non-plastic. From these tests, 34 of the soil samples were classified as silty sand (SM), and 8 samples were classified as poorly-graded sand with silt (SP-SM), according to the Unified Soil Classification System (ASTM D2487-10). From Fig. 9, the following important conclusions can be drawn: (1) the soil at each of the in situ test locations in the field box tests was quite uniform (e.g., the mixing procedure that was used yielded a relatively uniform soil), and (2) the field box test soils and the soils used in the mold calibration tests are essentially the same, for all practical purposes.

5.3 *Field Box Calibration Equations*

As shown in Fig. 9, the field box soils and the mold calibration soils are essentially the same. Consequently, there are two calibration approaches that may be used in order to generate EDG results. The first is to use the calibration constants that are generated using the mold calibration procedure; this represents a "blind prediction" approach, which will likely be a more challenging and rigorous assessment of the EDG's prediction abilities. The resulting calibration equations that would be used if the mold calibration were employed are shown in Fig. 7.

The second approach that could be used follows the "field calibration" methodology that was utilized at the Dover and Middletown sites. For the field box tests, results from the NDG, SC, or DC tests could be used for calibration purposes. Because the data will later be compared to the DC results as the baseline for comparison, the DC data set was selected for "field calibration" purposes.

Table 3 presents the EDG test results that were recorded during the field box study. Table 4 presents the corresponding results from the NDG, SC, and DC tests that were conducted at each of the EDG test locations. Following the field calibration methodology discussed in the preceding paragraph, in order to achieve the highest quality calibration matrix, all 42 of the measured EDG and DC field points were used to build the field box soil model. Figure 10 shows the associated soil model that was developed, with and without the proprietary EDG temperature correction applied.

5.4 *A Comparison of Traditional Compaction QA/QC Tests and Electrical Density Gauge Results*

Following the approach that was used for the Dover, Middletown, and mold soils that were presented previously (e.g., Figs. 4 and 8), it is possible to calculate soil unit weight and moisture content values from the recorded electrical properties for each of the 42 EDG field box tests (Table 3). Comparisons can then be made between the field box soil properties that are predicted by the EDG and those that are measured using the other, more traditional compaction QA/QC tests that were conducted. The DC test was selected for purposes of baseline comparison. Figure 11 shows a series of 1:1 plots that compare the measured DC values with those from the EDG, NDG, and SC tests; the soil properties of interest that are shown in this figure are moist unit weight (γ_m), dry unit weight (γ_d), and moisture content (w).

A number of calibration approaches can be utilized to generate EDG results from the field box data set. In particular, this process can be performed using either the calibration equations that are shown in Fig. 10 (the field-developed calibration equations), which yield the results shown in Fig. 11(a), or the calibration equations that are shown in Fig. 7 (the mold-developed calibration equation), which yield the results shown in Fig. 11(b). It is possible to use other data sets for field calibration of the EDG, such as the NDG or SC data sets; however, these data sets were not selected because they exhibited more scatter than the DC data set, and also because it was particularly desirable to have side-by-side comparisons of the EDG, NDG, and SC results. For comparison purposes, EDG-calculated values are presented both with and without the proprietary temperature correction. Figures 11(c) and 11(d) show a series of 1:1 plots that compare the measured drive cylinder values to those from the NDG and SC tests, respectively; side-by-side comparison of the EDG results with the results from these tests is necessary to show the scatter that can be observed with other conventional compaction QA/QC test approaches.

5.5 *Discussion of Results*

As shown in Fig. 11, for the moist unit weight values measured in the field box tests, the closest agreement was ob-

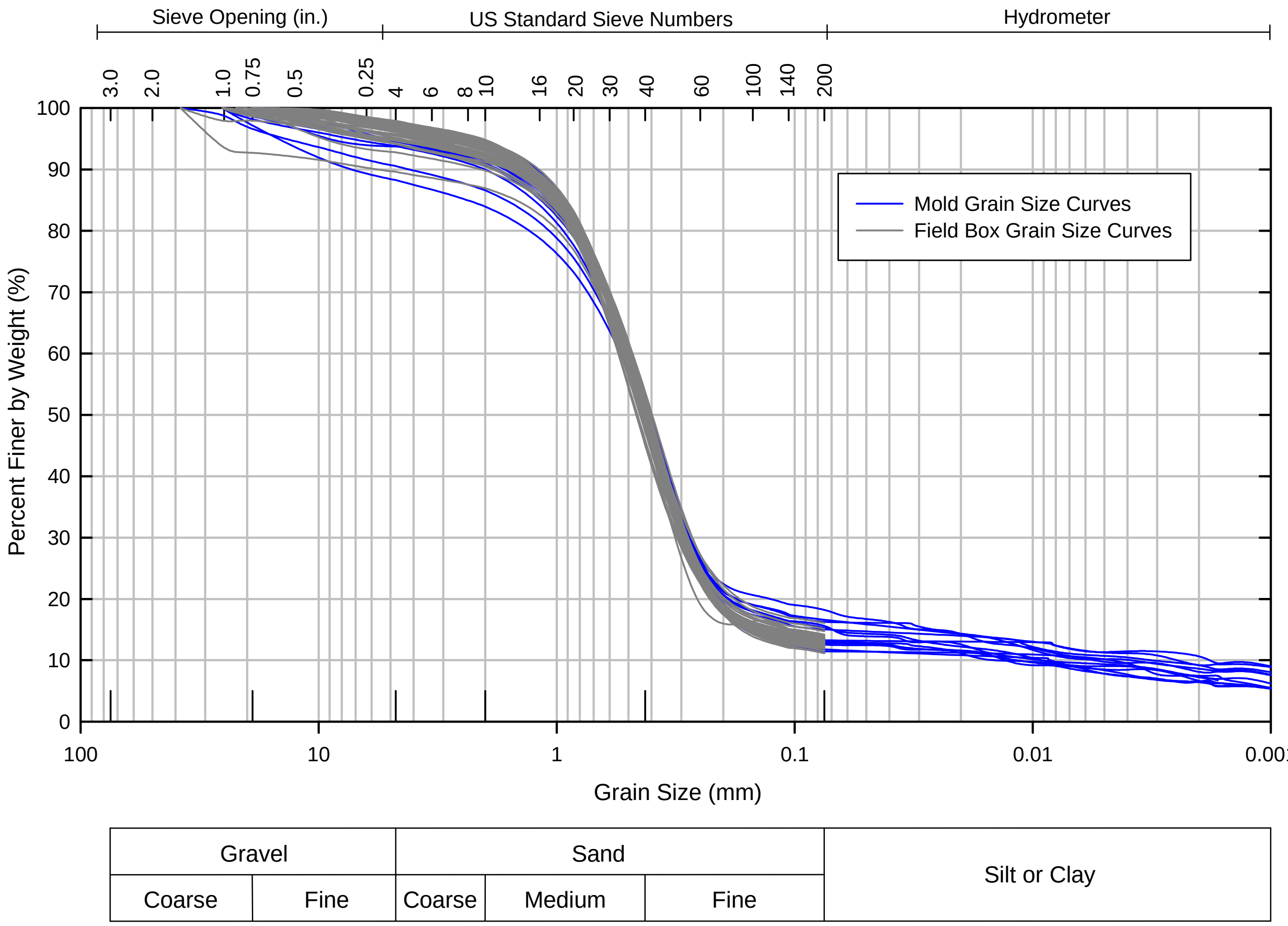

Fig. 9: Gradation distributions for soil samples from field box tests.

served between the NDG and DC data sets, followed by the EDG and DC (field calibration), the EDG and DC (mold calibration), and finally the SC and DC data sets. For the measured dry unit weight values, the closest agreement was observed between the NDG and DC data sets, followed by the EDG and DC (field calibration), the EDG and DC (mold calibration), and finally the SC and DC data sets. For the measured moisture content values, the closest agreement was observed between the SC and DC data sets, followed by the NDG and DC, the EDG and DC (field calibration), and finally the EDG and DC (mold calibration) data sets.

The challenge in interpreting field compaction QA/QC results of this type is that the "real" in situ soil unit weights and moisture contents are not known. The implicit approach that is used in Fig. 11 is to assume that the DC values are "correct"; however, this is clearly not the case. The DC data set was chosen for purposes of baseline comparison primarily because it appeared to be the least scattered of all the in situ compaction QA/QC tests that were conducted. Among all the data sets that were recorded, the closest overall agreement was observed between the DC and NDG data sets, lending some validity to the results from these two test approaches. Given its relatively low scatter and strong agreement with the NDG test, the DC test is believed to be the most accurate representation of the in situ unit weight for the purposes of this study. The SC unit weight results tended to be consistently higher than the other conventional compaction QA/QC tests that were conducted, although the oven moisture contents measured using the SC were in excellent agreement with those measured in the DC test (not a surprising finding).

With respect to the EDG results, and operating under the assumption that the DC test values provide a fairly reasonable approximation of the in situ unit weight and moisture content, the data shown in Fig. 11 lead the authors to the following conclusions:

1. For measurements of in situ unit weight, the EDG test exhibits more scatter than the results from NDG tests (relative to the DC test) and less scatter than the SC test. For measurements of in situ moisture content, the EDG test exhibits more scatter than the results from either NDG or SC tests.
2. Results that are roughly comparable to those obtained with the NDG device can be achieved using the EDG, provided that a good soil model is chosen (this assessment is true at least in terms of total RMSE, although it is possible that individual EDG and NDG point

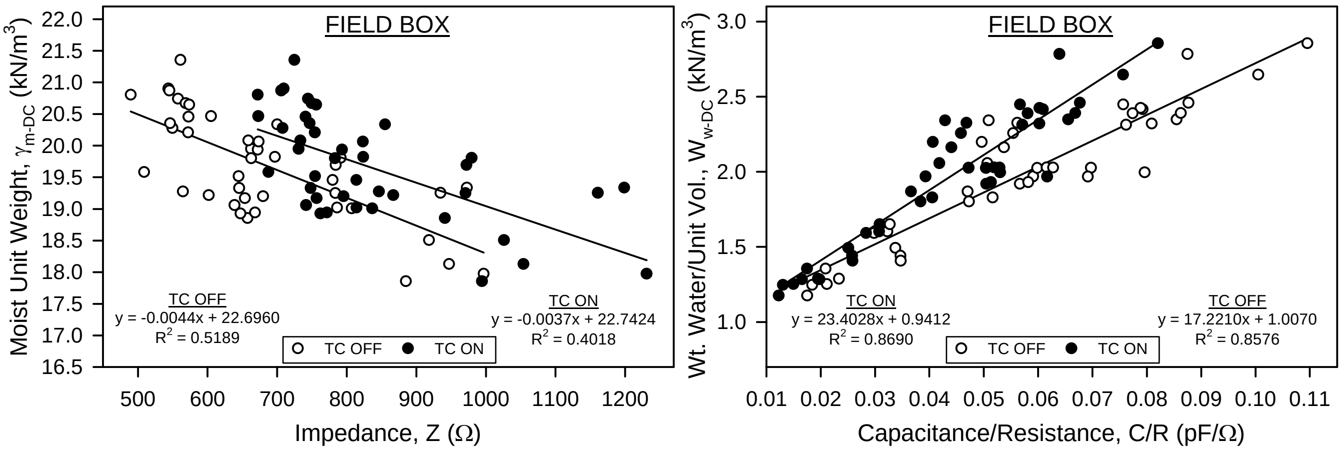

Fig. 10: EDG calibration for the field box soil (field calibration procedure).

values will be significantly different). Note that the RMSE values shown in Fig. 11(a) are not that much higher than those shown in Fig. 11(c). However, there is a significant caveat that should be noted here: the "calibration" data set shown in Fig. 11(a) is the same as the "assessment" data set, which means that the results shown in Fig. 11(a) are based upon a *soil-specific* calibration relationship. This approach is in contrast to that utilized with the NDG, in which a *global soil model* was used. It is possible that closer agreement and less scatter with the NDG could be achieved if a soil-specific calibration were performed.

3. The use of "blind" assessment comparisons, of the type shown in Figs. 11(b), 11(c), and 11(d), represent a more robust challenge to device assessment than those cases in which the calibration data set is the same as the assessment data set [e.g., Figs. 4, 8, and 11(a)]. In those cases in which "blind" assessment is being performed, rather than soil-specific calibration and assessment, it is reasonable to expect more scatter and higher RMSE values. Although the use of blind prediction testing might yield higher RMSE values, it is probably a better approach for assessing how a device will actually perform in the field, as typically field QA/QC procedures using the EDG involve relatively blind assessment using soil models that are built using only a few test points relatively early on in the compaction control process (for compaction purposes, the full benefit of the entire compaction data set cannot be realized until the end of the field study, when it is no longer needed).
4. The RMSE values for field calibration were significantly lower than those for mold calibration, indicating that the field calibration approach might be superior to the mold calibration approach that is presented in this paper. However, these data are not conclusive on their own, as the mold calibration represents a blind assessment approach and the field calibration approach does not (see the discussion in the preceding paragraph about why it is not appropriate to directly compare these two sets of results). However, it is clear that more exploration of various mold calibration procedures is warranted in future studies to see whether the benefits from this approach can be realized by other researchers.
5. The manufacturer's proprietary temperature correction did not significantly improve the EDG test results for the Delaware soils that were tested. Note that the RMSE values for the results that are presented with the temperature correction turned on (TC ON) are roughly the same as, or sometimes even more than, those without the temperature correction (TC OFF). One possible explanation for this is that the effect of temperature on EDG results might be somewhat soil specific, and the default on-board temperature correction for the EDG might not work well with Delaware soils. This phenomenon will be explored more in a future study.

6 Summary and Conclusions

The study described herein focused on the use of a relatively new electrically-based in situ soil test device that uses measurements of soil complex impedance, soil capacitance, and soil resistance to infer in situ soil unit weight and moisture content. This device is commonly referred to as a complex-impedance measuring instrument (CIMI); it is also sometimes known more generically as the electrical density gauge (EDG). This paper provides a detailed explanation of current CIMI device operating principles, and the study utilized a CIMI for field- and laboratory-based testing. The EDG used in this study was calibrated and assessed on two field compaction projects in which different silty sands were used for construction. A mold-based calibration approach was also developed for building an electrically based soil model using the EDG; this approach provides an alternative to field calibration of the device. In order to perform a more complete assessment of the EDG in a controlled environment, a series of EDG tests were conducted in a large field box, and the resulting in situ measurements of soil unit weight and moisture content made using the EDG were compared with the results from NDG, SC, and DC tests. Based on the results of the tests that were conducted, the following conclusions were drawn:

- All conventional compaction QA/QC test results exhibit some scatter when compared to one another. A well-calibrated EDG device yields unit weight results that are more scattered than those from NDG and DC tests but less scattered than those from the SC test. EDG moisture content results tended to be more scattered than those from the other conventional compaction QA/QC tests.
- Results that are roughly comparable to those obtained with the NDG device can be achieved using the EDG, provided that a good soil model is chosen. This assessment is made with respect to the total RMSE values that may be measured; it is expected that the individual EDG and NDG point values will be significantly different.
- "Blind" assessment approaches that use one data set for calibration and a different data set for assessment are more rigorous than approaches that use a calibration data set that is the same as the assessment data set. They should consequently yield more significant scatter. They are also likely a better representation of the behavior that will be observed if a given device or test approach is used in the field.
- The mold calibration procedure that is presented offers a number of practical advantages over field calibration of the EDG. Unfortunately, so far, it also appears to yield results that are more scattered than those obtained with field calibration. A variety of potential factors might be contributing to this scatter, and more research in this area is warranted.
- Overall, the manufacturer's proprietary temperature correction did not significantly improve the EDG test results for the Delaware soils that were tested in this study (although some improvement in results was observed for the Dover soil).

Looking forward, the authors expect to see increasingly greater utilization of electrically-based alternatives to conventional compaction QA/QC test approaches. The end user is strongly searching for an alternative to conventional nuclear-based test equipment, with its heavy burden of regulatory compliance. In the short term, some users might be willing to trade some decreases in accuracy for the convenience that comes with avoiding this regulatory burden; it is expected that this technology will also make in-roads in international construction markets in which nuclear-based technologies are not freely available. In the long term, it is hoped that field utilization of electrically-based compaction QA/QC devices will lead to an improved understanding of electrical soil models, which will lead to improved calibration procedures, a greater database of known soil behavior, and improved device accuracy.

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Table 3: Electrical Density Gauge Test Results, Field Box

Test Number	V_{avg} (V)	I_{avg} (mA)	θ_{avg} (deg)	T_{avg} (°C)	Z_{raw} (Ω)	$(C/R)_{raw}$ (pF/Ω)	Z_{corr} (Ω)	$(C/R)_{corr}$ (pF/Ω)
B1.1	1.784	1.834	-69.47	25.83	972.7	0.0525	1198.8	0.0372
B1.2	1.768	1.891	-67.92	25.83	934.8	0.0563	1160.9	0.0398
B1.3	1.788	1.794	-69.51	26.19	996.9	0.0500	1230.9	0.0351
B1.4	1.707	2.158	-63.61	24.11	791.2	0.0759	979.4	0.0564
B1.5	1.704	2.173	-63.23	24.10	784.2	0.0770	972.1	0.0572
B1.6	1.703	2.173	-63.26	24.06	783.7	0.0771	970.6	0.0574
B1.7	1.776	1.875	-69.04	20.42	947.1	0.0552	1054.0	0.0462
B1.8	1.772	1.929	-69.18	20.44	918.4	0.0588	1025.9	0.0492
B1.9	1.758	1.986	-68.20	20.53	884.9	0.0629	994.3	0.0525
B2.1	1.560	2.780	-54.97	23.00	561.1	0.1380	724.8	0.1061
B2.2	1.544	2.839	-53.81	23.08	543.9	0.1448	709.4	0.1110
B2.3	1.556	2.791	-54.31	24.06	557.4	0.1387	744.4	0.1032
B2.4	1.530	2.807	-50.43	22.86	545.2	0.1376	705.8	0.1062
B2.5	1.535	2.793	-50.51	22.75	549.5	0.1356	707.7	0.1051
B2.6	1.553	2.712	-51.46	23.19	572.7	0.1265	740.7	0.0967
B2.7	1.503	2.954	-50.65	23.68	508.8	0.1585	687.5	0.1193
B2.8	1.481	3.024	-49.07	23.85	489.7	0.1672	672.0	0.1252
B2.9	1.529	2.798	-50.16	24.68	546.2	0.1365	746.9	0.0998
B3.1	1.581	2.627	-53.98	27.61	601.7	0.1185	866.8	0.0803
B3.2	1.555	2.755	-53.48	28.36	564.6	0.1337	846.3	0.0891
B3.3	1.607	2.443	-52.78	28.44	657.6	0.0977	941.1	0.0650
B3.4	1.561	2.580	-53.65	18.64	605.2	0.1167	673.0	0.1040
B3.5	1.609	2.429	-55.21	18.67	662.5	0.0992	731.0	0.0884
B3.6	1.605	2.437	-53.94	18.94	658.7	0.0988	733.3	0.0872
B3.7	1.594	2.438	-52.73	20.24	653.7	0.0988	756.7	0.0832
B3.8	1.589	2.462	-52.41	20.22	645.5	0.1009	748.2	0.0850
B3.9	1.591	2.491	-52.55	20.22	638.9	0.1032	741.6	0.0870
B4.1	1.646	2.448	-61.16	21.06	672.2	0.1029	793.2	0.0843
B4.2	1.631	2.460	-58.58	21.03	662.8	0.1030	783.2	0.0845
B4.3	1.641	2.415	-59.03	20.82	679.7	0.0984	795.5	0.0813
B4.4	1.649	2.367	-60.06	21.33	696.7	0.0947	823.8	0.0769
B4.5	1.636	2.428	-59.00	22.36	673.5	0.1002	823.2	0.0786
B4.6	1.653	2.360	-59.83	22.60	700.2	0.0935	855.1	0.0728
B5.1	1.701	2.107	-66.46	16.89	807.3	0.0746	836.7	0.0710
B5.2	1.696	2.157	-65.65	16.82	786.2	0.0782	814.0	0.0746
B5.3	1.698	2.177	-65.73	17.11	779.7	0.0796	813.9	0.0750
B6.1	1.620	2.424	-60.49	20.25	668.4	0.1033	771.6	0.0870
B6.2	1.607	2.492	-59.18	20.56	644.7	0.1096	754.6	0.0913
B6.3	1.613	2.492	-59.48	20.78	647.4	0.1090	762.2	0.0902
B6.4	1.563	2.732	-55.00	23.83	572.1	0.1328	754.1	0.0995
B6.5	1.560	2.744	-54.72	23.79	568.5	0.1340	749.7	0.1005
B6.6	1.565	2.728	-55.08	23.85	573.7	0.1322	756.1	0.0990

Table 4: Nuclear Density Gauge, Sand Cone, and Drive Cylinder Test Results, Field Box

Test Number	Nuclear Density Gauge γ_m (kN/m^3)	γ_d (kN/m^3)	W_w (kN/m^3)	w (%)	Sand Cone γ_m (kN/m^3)	γ_d (kN/m^3)	W_w (kN/m^3)	w (%)	Drive Cylinder γ_m (kN/m^3)	γ_d (kN/m^3)	W_w (kN/m^3)	w (%)
B1.1	18.22	17.14	1.08	6.3	20.29	18.95	1.35	7.1	19.34	18.09	1.25	6.9
B1.2	18.14	17.11	1.04	6.1	18.32	17.10	1.22	7.1	19.25	18.00	1.25	7.0
B1.3	18.24	17.23	1.01	5.8	18.67	17.42	1.24	7.1	17.97	16.80	1.18	7.0
B1.4	19.75	18.28	1.46	8.0	22.15	20.61	1.54	7.5	19.81	18.31	1.49	8.2
B1.5	18.96	17.61	1.35	7.7	20.53	19.05	1.47	7.7	19.70	18.26	1.44	7.9
B1.6	19.42	18.00	1.41	7.9	19.15	17.76	1.39	7.8	19.25	17.84	1.41	7.9
B1.7	17.94	16.78	1.16	6.9	18.20	16.90	1.30	7.7	18.13	16.84	1.28	7.6
B1.8	18.14	16.95	1.19	7.0	18.74	17.38	1.36	7.8	18.51	17.15	1.36	7.9
B1.9	17.81	16.65	1.16	7.0	17.54	16.25	1.29	7.9	17.85	16.57	1.29	7.8
B2.1	20.74	18.32	2.42	13.2	21.25	18.73	2.53	13.5	21.35	18.94	2.42	12.8
B2.2	20.28	17.85	2.43	13.6	21.91	19.29	2.62	13.6	20.90	18.55	2.35	12.7
B2.3	20.83	18.28	2.54	13.9	20.20	17.87	2.34	13.1	20.74	18.42	2.32	12.6
B2.4	19.87	17.63	2.25	12.7	19.13	16.86	2.28	13.5	20.87	18.41	2.46	13.4
B2.5	19.92	17.69	2.23	12.6	20.34	17.94	2.40	13.4	20.28	17.89	2.39	13.4
B2.6	20.06	17.88	2.18	12.2	20.00	17.67	2.33	13.2	20.46	18.03	2.42	13.4
B2.7	19.89	17.06	2.83	16.6	20.94	17.92	3.01	16.8	19.58	16.94	2.65	15.6
B2.8	20.03	17.19	2.84	16.5	22.21	19.11	3.10	16.2	20.80	17.95	2.86	15.9
B2.9	19.71	17.04	2.67	15.7	20.61	17.81	2.80	15.7	20.35	17.57	2.78	15.8
B3.1	19.24	17.41	1.84	10.6	19.66	17.63	2.03	11.5	19.22	17.19	2.03	11.8
B3.2	18.99	17.15	1.84	10.7	20.32	18.24	2.09	11.4	19.27	17.28	2.00	11.5
B3.3	19.34	17.53	1.81	10.3	19.23	17.28	1.96	11.3	18.85	16.88	1.97	11.7
B3.4	20.28	18.41	1.87	10.2	20.73	18.73	1.99	10.6	20.47	18.50	1.97	10.6
B3.5	20.61	18.77	1.84	9.8	21.57	19.59	1.98	10.1	19.95	18.03	1.92	10.6
B3.6	20.63	18.69	1.93	10.3	19.89	17.97	1.92	10.7	20.08	18.15	1.93	10.6
B3.7	19.60	17.56	2.04	11.6	19.48	17.44	2.04	11.7	19.17	17.14	2.02	11.8
B3.8	19.18	17.28	1.90	11.0	19.22	17.20	2.02	11.7	19.33	17.30	2.03	11.7
B3.9	19.26	17.36	1.90	11.0	20.07	17.98	2.08	11.6	19.06	17.03	2.03	11.9
B4.1	19.38	17.34	2.04	11.8	20.79	18.47	2.32	12.6	19.94	17.74	2.20	12.4
B4.2	19.73	17.74	2.00	11.2	20.49	18.23	2.26	12.4	19.80	17.64	2.16	12.3
B4.3	19.56	17.52	2.04	11.7	20.65	18.37	2.28	12.4	19.20	17.14	2.06	12.0
B4.4	20.42	18.65	1.78	9.5	21.93	19.93	2.00	10.0	19.82	18.02	1.80	10.0
B4.5	20.53	18.79	1.74	9.3	22.86	20.81	2.05	9.8	20.06	18.23	1.83	10.0
B4.6	20.78	18.94	1.84	9.7	21.86	19.90	1.96	9.8	20.34	18.47	1.87	10.1
B5.1	19.12	17.56	1.56	8.9	20.78	19.01	1.77	9.3	19.01	17.42	1.59	9.1
B5.2	19.13	17.56	1.57	8.9	21.44	19.61	1.83	9.3	19.02	17.42	1.60	9.2
B5.3	19.43	17.81	1.62	9.1	21.00	19.25	1.75	9.1	19.45	17.80	1.65	9.3
B6.1	18.98	16.87	2.10	12.5	20.48	18.00	2.48	13.8	18.94	16.60	2.34	14.1
B6.2	18.50	16.29	2.21	13.6	21.18	18.59	2.59	13.9	19.52	17.19	2.33	13.5
B6.3	18.85	16.70	2.15	12.9	21.03	18.49	2.54	13.8	18.93	16.67	2.26	13.5
B6.4	20.63	18.08	2.54	14.1	22.93	20.14	2.79	13.8	20.21	17.90	2.31	12.9
B6.5	20.69	18.07	2.62	14.5	23.07	20.32	2.75	13.5	20.67	18.28	2.39	13.1
B6.6	21.02	18.49	2.53	13.7	22.63	19.94	2.69	13.5	20.65	18.20	2.45	13.4

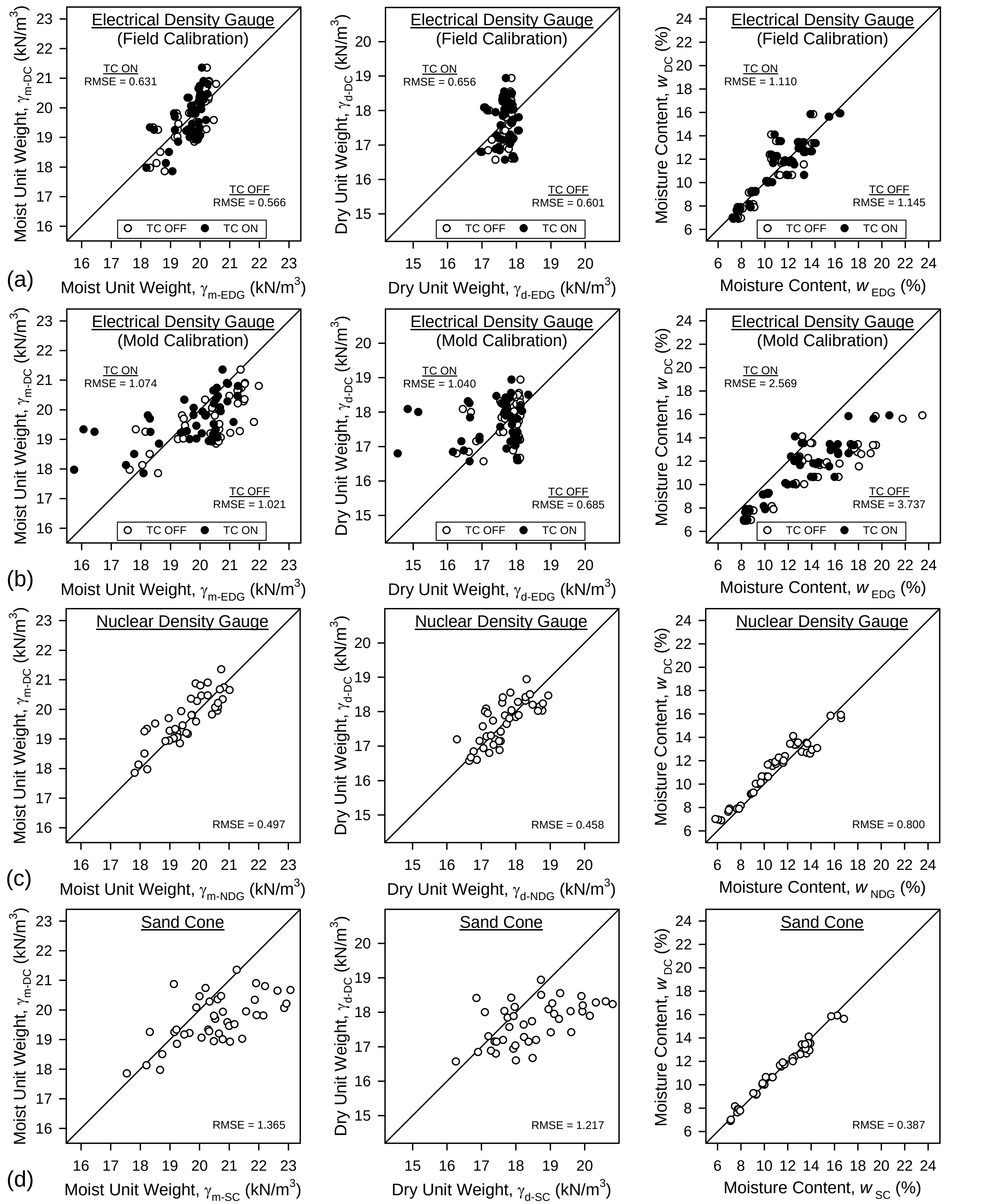

Fig. 11: A comparison of measured moist unit weight, dry unit weight, and moisture content values obtained via the drive cylinder test and the (a) electrical density gauge test (using the field calibration procedure), (b) electrical density gauge test (using the mold calibration procedure), (c) nuclear density gauge test, and (d) sand cone test.