Rapid Field Testing Techniques for Determining Soil Density and Water Content

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ABSTRACT

Proper control of soil water content and soil compaction during earthwork construction operations is critical in achieving adequate performance of structural fills. Conventional methods (e.g., sand cone, rubber balloon, nuclear density gauge) are not always reliable and may require more time than is available to expedite construction. To improve upon the current approach, new rapid and reliable field testing technologies are needed. As part of this effort, this paper describes an evaluation of relatively inexpensive equipment that uses time domain reflectometry (TDR) and capacitance measurement techniques to determine soil density and water content in the field. Comparisons were made to the conventional nuclear and drive core methods for four different soil types and were used to estimate the accuracy and precision of each device and grounds for their successful use. The devices used were an IMKO TRIME TDR, Campbell Scientific DMM600 Duff Moisture Meter, and Humboldt nuclear moisture-density gauge. Gravimetric sampling via drive cores was used as the reference test method. Results show that TDR measurements of volumetric soil moisture are accurate without soil-specific calibration and, given a priori knowledge of gravimetric moisture content, could be used to estimate soil dry unit weight. The Duff Moisture Meter was used in conjunction with a modified drive core developed by the author to measure both volumetric moisture content and the total unit weight of a soil sample. For moisture content determination relative to oven-dried moisture content, the nuclear and TDR methods were less erratic overall than the DMM600. No method compared favorably to drive core dry unit weight; the nuclear method had the lowest RMSE and SEP values, but also the lowest R^2 values overall compared to the TDR and DMM600 methods. The average time to perform each test was two to three minutes for the DMM600, less than one minute for the TDR (two replications), and two to five minutes for the nuclear moisture-density gauge (two replications).

Key words: capacitance— nuclear density gauge— soil moisture—time domain reflectometry

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Proceedings of the 2005 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2005. © 2005 by Iowa State University. The contents of this paper reflect the views of the author(s), who are responsible for the facts and accuracy of the information presented herein.

INTRODUCTION

Soil moisture content and unit weight measurements are key elements to any soil compaction quality control program. The nuclear moisture-density gauge has been the standard tool in geotechnical engineering in recent years. However, regulatory burden, recurring costs, and safety concerns have made alternative techniques to the nuclear gauge very attractive. In 1980, Topp et al. popularized time domain reflectometry (TDR) as a method to measure soil water content using soil electromagnetic properties. Since that time, electronic methods of soil characterization have seen much development (Veenstra et al. 2005). The TDR method has been used extensively in long-term data acquisition experiments, where the inability to leave a nuclear type instrument unattended was prohibitive. In the past few years, new commercial offerings developed specifically for geotechnical engineering applications have been released. The objective of this study was to compare TDR, capacitance, nuclear moisture-density gauge, and drive core methods of moisture and density measurement.

BACKGROUND AND DEFINITIONS

Soil is considered to be a three phase system consisting of soil solid particles, water, and air, as illustrated in Figure 1.

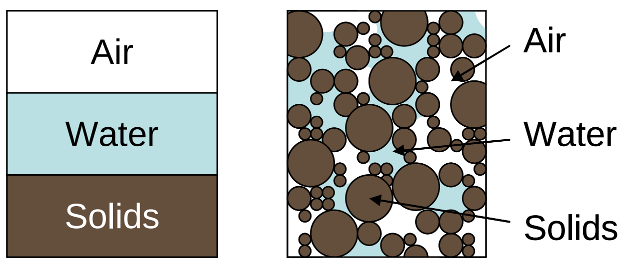

Figure 1. Soil phase diagram (left) and generalized illustration of a soil cross-section (right)

The following definitions are used throughout this paper:

Gravimetric soil water content is defined as

$$\theta_g = \frac{\text{Mass of Water}}{\text{Mass of Solids}} \tag{1}$$

Volumetric soil water content is defined as

$$\theta_v = \frac{\text{Volume of Water}}{\text{Total Volume}} \tag{2}$$

Dry unit weight is defined as

$$\gamma_{dry} = \frac{\text{Weight of Solids}}{\text{Total Volume}} \tag{3}$$

To convert between gravimetric and volumetric water content

$$\frac{\theta_v}{\theta_g} = \frac{\gamma_{dry}}{\gamma_{water}} \tag{4}$$

Where $\gamma_{water} = 9.8$ kN/m^3.

METHODS AND MATERIALS

Equipment

Time Domain Reflectometry

Time domain reflectometry (TDR) is an electronic technique that may be used to measure the moisture content of soil (Topp et al. 1980). The method works by applying a voltage signal to a transmission line (metal rods) inserted into the soil. The time required for the voltage signal to travel from the source to the end of the transmission line and back again is determined principally by the moisture content. The TDR instrument used in this study was an IMKO TRIME®-EZ probe with coated rods 16 cm long by 6 mm IN diameter (Figure 2). A comprehensive review of TDR theory and techniques is given by Robinson et al. (2003), Ferre and Topp (2002), and O'Connor and Dowding (1999).

Figure 2. IMKO TRIME-EZ probe (left) and inserted into soil (right) with TRIME Data Pilot

DMM600 Moisture Meter

The DMM600, a capacitance-based dielectric moisture sensor, is manufactured by Campbell Scientific, Inc., (Logan, Utah) and is traditionally marketed for use in the forestry service. The DMM600 was designed to measure the moisture content of the upper layer of soil covering the forest floor, known as duff, a highly organic soil containing detritus, vegetation, etc. Moisture measurement consists of placing duff loosely into the sample chamber then compressing the material to a preset pressure against a sensor plate containing the waveguides (see Figure 3) used to measure the dielectric constant of the material. In this study, a modified procedure was developed in which a special soil cutter containing an intact soil sample is placed into the DMM600 chamber. The DMM600 provides the moisture content while the cutter is used to determine the sample density from the known volume and mass as measured on a portable electronic balance.

Figure 3. DMM600 components: (a) sensor plate/waveguides; (b) electronics housing; (c) sample chamber; (d) sample chamber cap, including compression knob (right) and compression plate; (e) special soil cutter tool (0.75 inches high by 2.88 inches in diameter)

Nuclear density gauge

The nuclear density gauge used in this study was manufactured by Humboldt Manufacturing, Inc., (Model 5001) (see Figure 4). For this study, the nuclear tests averaged a measurement over the top six to eight inches of the soil. Moisture content measurement was performed according to ASTM D3017 and density measurement according to ASTM D2922.

Figure 4. Humboldt Model 5001 nuclear density gauge

Drive core

Drive core and/or bag samples were collected at each test location to determine water contents using the oven method. The soil density was determined from the drive core volume. The nominal dimensions of drive cores used in this study were three inches in diameter by three inches in height (see Figure 5). The drive core samples were taken in the top two to five inches of the soil.

Figure 5. Drive core sampling device

Materials

The names and engineering properties of soils evaluated in this study are provided in Table 1.

Table 1. Schedule of testing materials

Soil name	Kickapoo topsoil (1)	Kickapoo fill clay (2)	Edwards till (3)	Kickapoo sand (4)
Texture	Silty clay loam	Silty clay loam	Loam	Sand/Loamy sand
USCS	ML Silt	CL Lean clay	CL Sandy lean clay	SW-SM Well graded sand with silts
AASHTO (GI)	A-6 (13)	A-7-5 (25)	A-6 (7)	A-3
F_{200} (%)	96.9	97.7	67.8	10.0
LL (PI)	38 (12)	47 (22)	29 (15)	NP
$w_{natural}$ (%)	30.1	29.9	6.3	9.8
Standard Proctor:	---	---	---	---
γd, max (kN/m^3)	15.79	16.02	18.61	17.99
w_{opt} (%)	19	20	12	9
Modified Proctor:	---	---	---	---
γd, max (kN/m^3)	17.36	18.14	20.74	18.69
w_{opt} (%)	17	12	8	9
Cation Exchange Capacity (%)	22.5	17.6	14.2	---
Organic Matter (%)	2.8	1.8	3.1	---

Experimental Setup

Test strips were established in the native Edwards till of the test site and the strip bases were stabilized with liberal compaction. Test soils (Kickapoo Topsoil, Kickapoo Fill Clay, Edwards Till, and Kickapoo Sand) were placed in the strips and mixed in situ to achieve relatively uniform, homogeneous soil conditions, inclusive of moisture content. Prior to construction, achievement of appropriate moisture content was verified by drying select soil samples in a microwave. The moisture content was accepted once the moisture content from spot tests was within 2% of the desired moisture for each test strip. Water and/or wet soil were added to test strips containing soil too dry for testing. Soil too wet for testing was air-dried and occasionally mixed.

For testing, 10 test points were established for each test strip at 1.52-m intervals. Density and moisture values for the uncompacted fill were determined with a nuclear density gauge. Tests were performed for one pass, two passes, four passes, and eight passes of the roller. Following the eighth roller pass, drive cores were excavated for a direct measurement of density and moisture.

Average moisture contents and dry densities of the soil measurements are provided in Table 2, as determined by drive core. These moisture contents represent typical values encountered in earthwork construction operations.

Table 2. Nominal moisture contents and dry densities of soils tested after eight roller passes, determined by drive core

	Strip 1			Strip 2			Strip 3		
Soil Name	**θ_g (%) (cov*)**	**γ_{dry} (kN/m^3) (cov)**	**N†**	**θ_g (%)**	**γ_{dry} (kN/m^3)**	**N**	**θ_g (%)**	**γ_{dry} (kN/m^3)**	**N**
Kickapoo Topsoil	23.2 (2.8)	15.43 (1.6)	18	16.0 (3.8)	15.16 (4.1)	10	18.8 (4.1)	15.65 (3.2)	34
Kickapoo Fill Clay	23.9 (3.1)	15.57 (1.5)	24	15.8 (9.7)	16.04 (4.4)	10	20.0 (8.9)	16.20 (1.9)	10
Edwards Till	7.9 (4.2)	15.61 (1.9)	19/4	16.4 (5.4)	17.41 (2.2)	18	10.9 (8.3)	16.97 (6.4)	18
Kickapoo Sand	5.6 (8.2)	16.97 (1.9)	20	8.8 (5.6)	17.78 (3.1)	20	---	---	---

* coefficient of variation † number of samples

RESULTS AND DISCUSSION

Tests were performed to compare the relative accuracies of TDR, DMM600, and the nuclear density gauge with respect to drive core results for soil moisture and density.

Determination of Moisture Content by Time Domain Reflectometry

The TDR system was used to determine the volumetric moisture content at each test point and then was converted to gravimetric moisture content using equation (4) and the soil density, as determined by drive core. The TDR-determined moisture content was then linearly regressed against oven-determined moisture contents from the drive core samples, hereafter referred to as the drive core moisture. The results for topsoil, till, and sand are shown in Figure 6. The clay soil is not included because insufficient TDR data points were collected; this was because the clay lift thicknesses were less than the length of the TDR probe. The average time to perform each test was less than one minute (two replications).

TDR moisture determination showed strong correlation relative to drive core moisture measurements (oven drying method). The soil density must be known to calculate gravimetric moisture content, and therefore error in soil density measurement will propagate into the calculated gravimetric moisture content. For this reason, the drive core was taken as close to the TDR measurement site as reasonable.

Unlike the nuclear density gauge, which may use man-made materials (e.g., metal, plastic) for calibration, TDR requires calibration in soil. In this study, it was not practical to perform a material-specific calibration prior to field testing, so the factory calibration was used and the calibration performed after the data was collected.

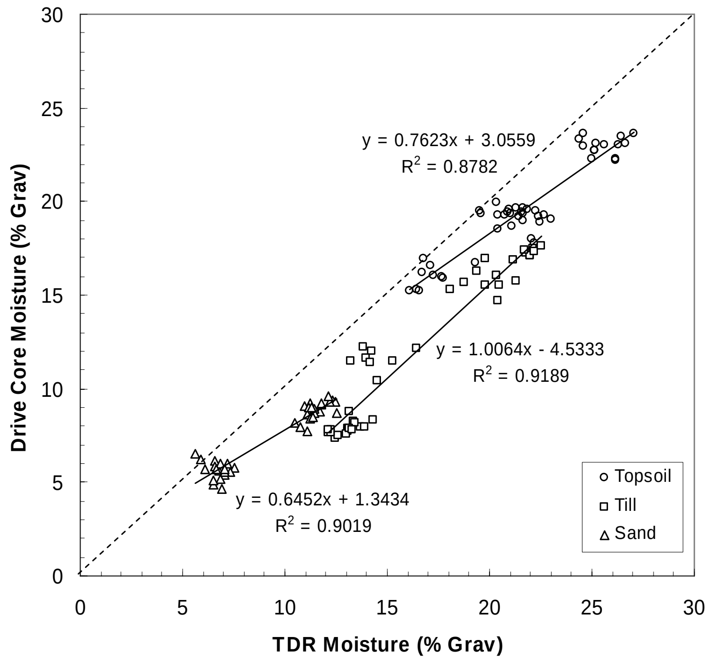

Figure 6. TDR vs. drive core moisture content for topsoil, till, and sand soils

Determination of Moisture Content by DMM600

The DMM600 frequency output is plotted against the drive core volumetric moisture content. A second-order polynomial fit is used per the manufacturer's calibration instructions. The DMM600 volumetric moisture content is then converted to gravimetric moisture content using equation (4) with soil density as determined by drive core. The DMM600 moisture content is then plotted against the drive core moisture content, as shown in Figure 7.

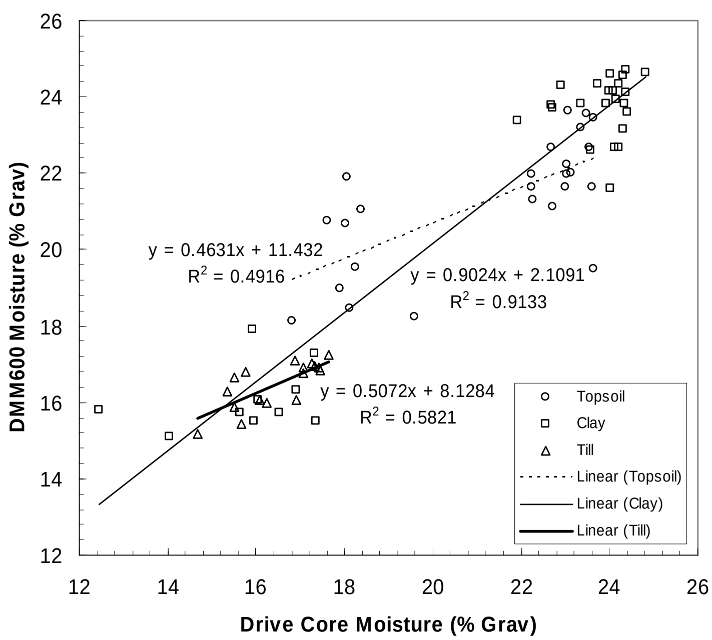

Figure 7. DMM600 moisture content vs drive core moisture content for topsoil, clay, and till soils

DMM600 results were not as well correlated as the TDR and nuclear gauge results and were relatively poor compared to a laboratory study using the same methodology (Veenstra et al. 2005). Compared to laboratory-prepared samples, field soils were much coarser and less structurally homogeneous, resulting in large gaps in the sample surface and prohibiting full contact between the soil sample and the sensor plate. Also, large stones in the sample would considerably lower the measured permittivity, resulting in anomalously low moisture content. These conditions were especially true for the till, which was very stiff and crumbly at a low moisture content. It was not possible to use the DMM600 with the sand because the sand would not stay within the soil cutter. The average time to perform each test was about three minutes.

Determination of Moisture Content by Nuclear Moisture-Density Gauge

Nuclear gauge moisture content is plotted against drive core moisture content in Figure 8–9. Nuclear gauge measurements had good correlation with drive core moisture measurements, comparable to TDR moisture measurements. The accuracy of moisture content determination using a nuclear gauge is directly proportional to the measurement time, with longer measurement times producing higher accuracy. The measurement time in this study was 15 seconds; the total time for two replications is about 2 to 5 minutes.

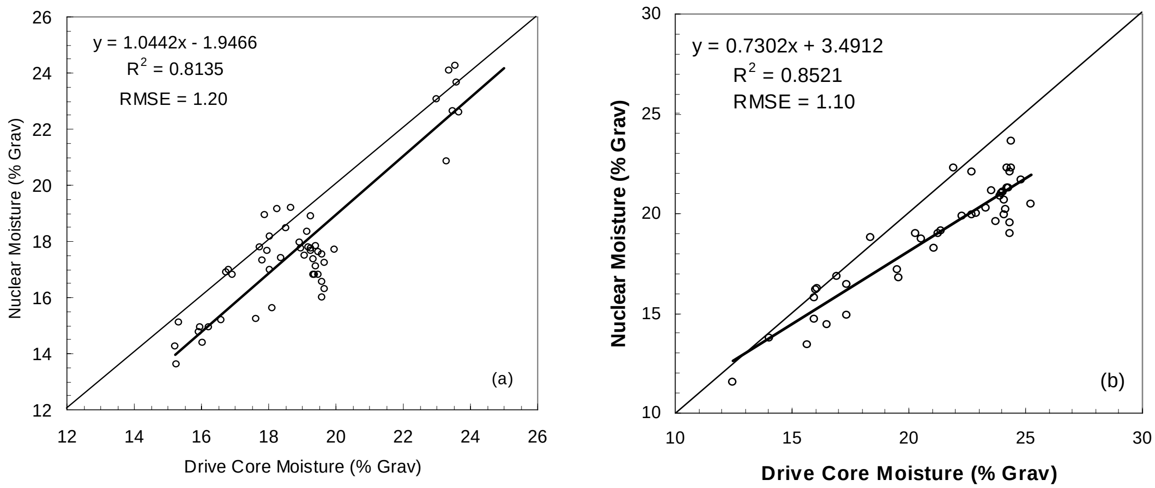

Figure 8. Nuclear moisture gauge vs. drive core moisture for topsoil (a) and clay (b)

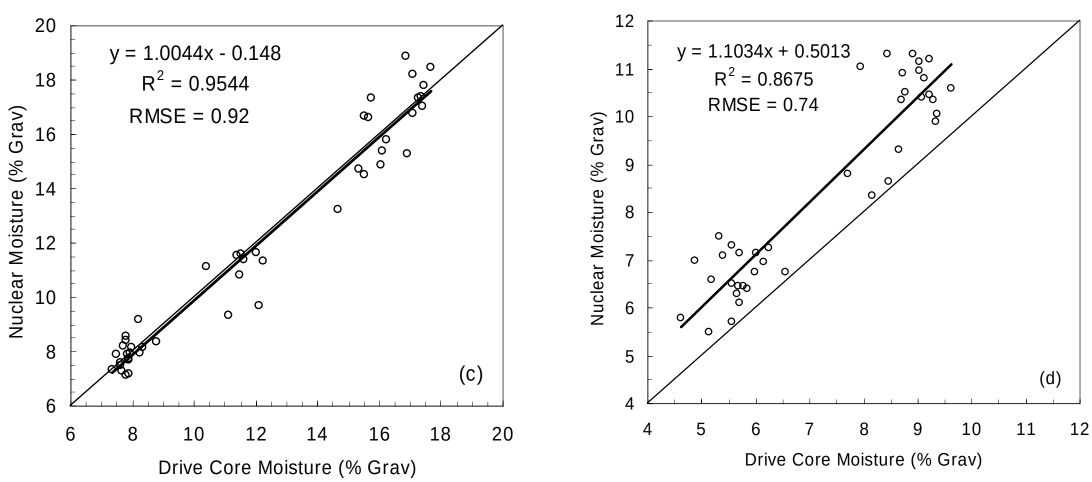

Figure 9. Nuclear moisture gauge vs. drive core moisture: till (c) and sand (d)

Determination of Dry Unit Weight by Time Domain Reflectometry

Knowing the gravimetric moisture content and assuming that it stays constant throughout the compaction process, the volumetric moisture content determined by TDR will reflect changes in soil density. The TDR-determined dry unit weight is calculated using Equation (5), where $\theta_{v\ (tdr)}$ is the TDR-determined volumetric moisture content.

$$\gamma_{\text{dry (TDR)}} = \frac{\theta_{v_{(TDR)}} \cdot \gamma_{water}}{\theta_{g_{(Nuc)}}} \tag{5}$$

The calculated TDR dry unit weight is plotted against nuclear gauge-determined dry unit weight in Figure 10. TDR dry unit weight is compared to nuclear gauge density because this allows more data points over a wider range than if compared solely to drive dry unit weight. Insufficient data points were collected to calculate the TDR dry unit weight for clay because the lift thickness was often too shallow for TDR measurement.

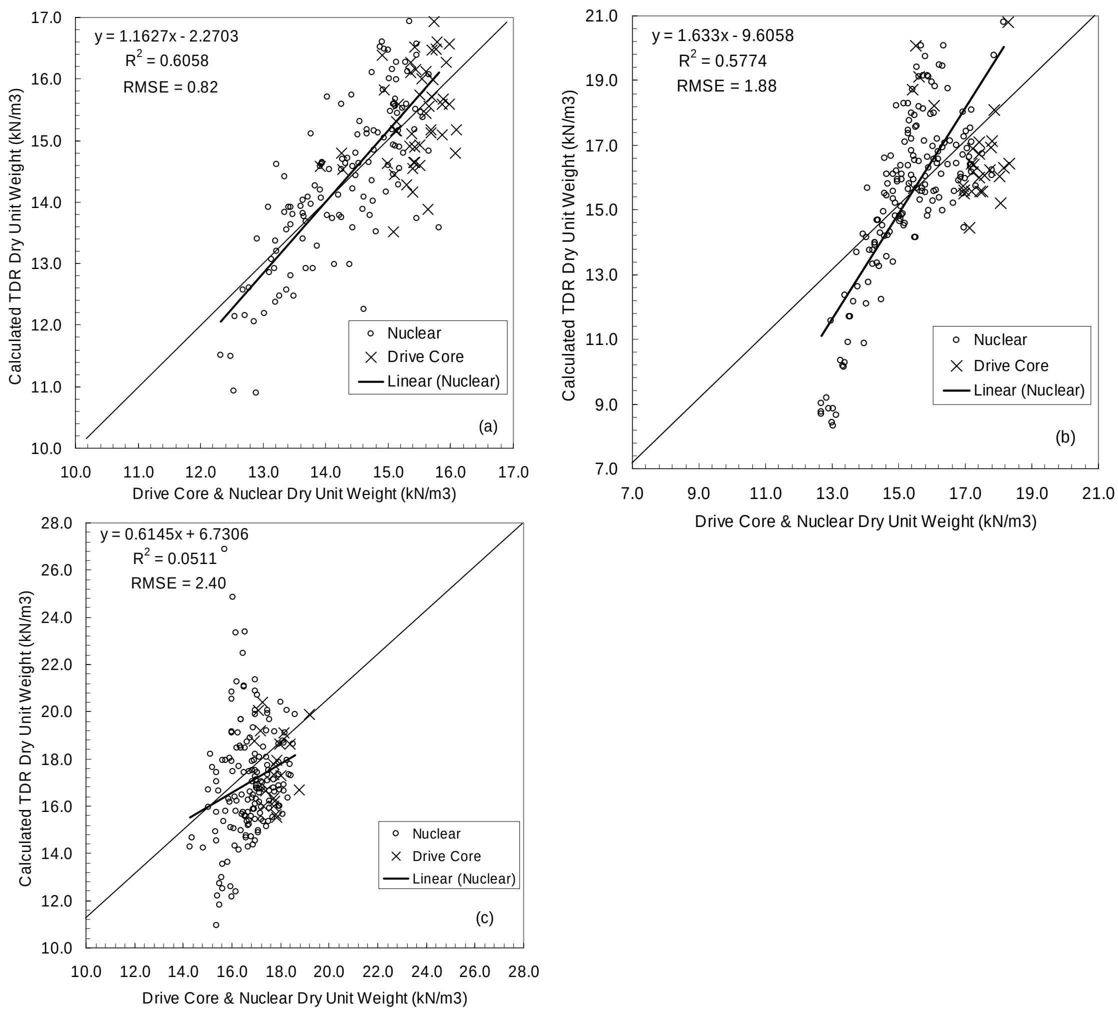

Figure 10. Drive core and nuclear-determined dry unit weight vs. TDR dry unit weight for topsoil (a), till (b), sand (c); linear regression based on nuclear data

A major difference between the TDR and nuclear methods of unit weight determination is sample volume. A nuclear density gauge has a sample volume of about 6,200 cm^3 depending on source depth (Humboldt Mfg. Co. 2004); the TDR measurement volume is estimated to be less than 200 cm^3. Thus, TDR is more sensitive to small-scale variation in soil unit weight than the nuclear density gauge.

Determination of Dry Unit Weight by DMM600

The DMM600 dry unit weight is determined using the mass of the soil, the soil cutter volume, and the corresponding drive core moisture content. The DMM600 dry unit weight is plotted against the dry unit weight determined by drive core, as in Figure 11. The sand was not tested because it failed to stay within either the drive cores or the soil cutter.

The measurement volume of the drive core is 320 cm^3, while that of the soil cutter is only 80.1 cm^3; thus, the soil cutter is more sensitive to spatial variation in soil density than the drive core. Also, trimming the soil cutter samples was problematic because the draw knife would often pull material out of the soil cutter. Because of the difference in measurement volume, soil unit weight determined by the soil cutter is more sensitive to errors in soil mass measurement than the drive core. An error of 1 gm (e.g., due to soil falling out of the soil cutter or drive core) soil mass will result in an error of only 0.03 kN/m^3 unit weight for the drive core but 0.13 kN/m^3 for the soil cutter.

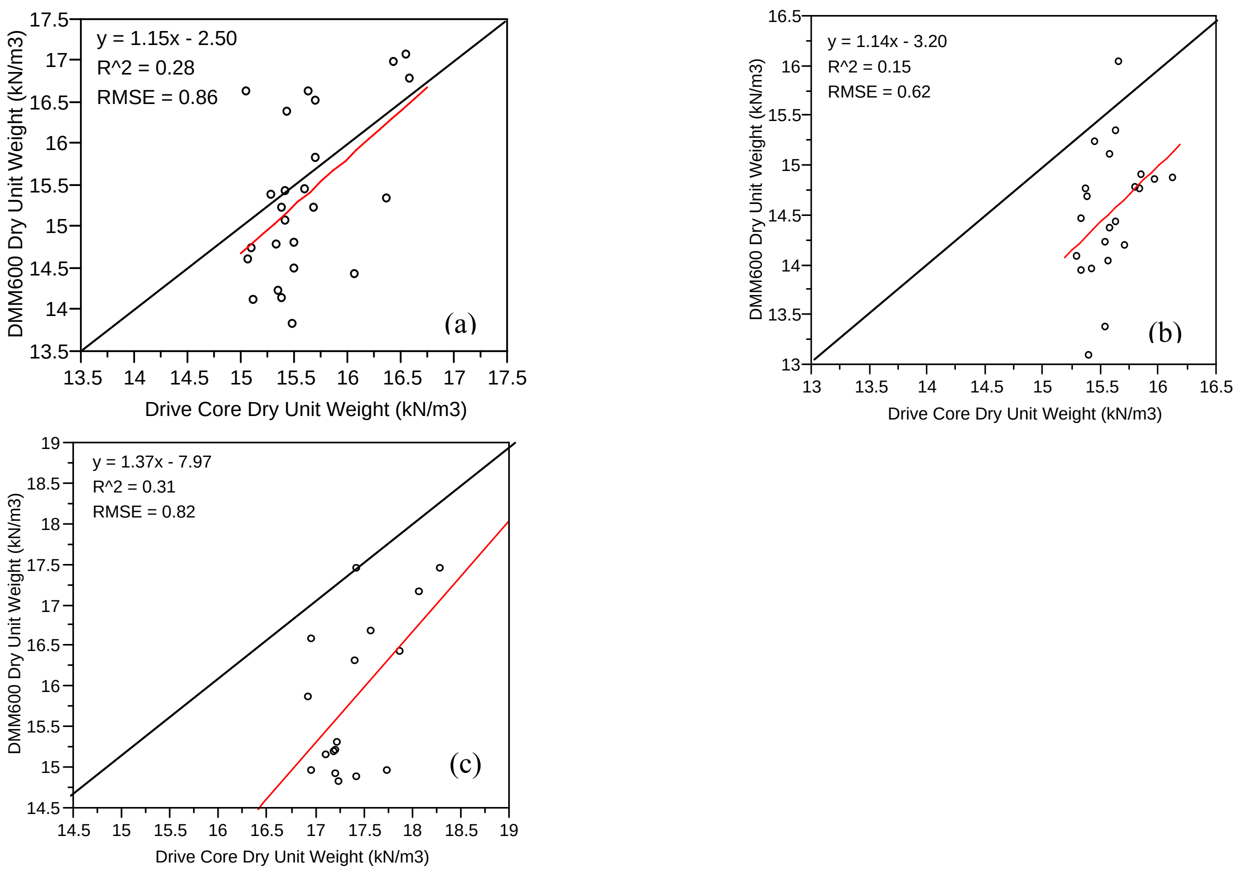

Figure 11. Drive core dry unit weight vs. DMM600 dry unit weight for topsoil (a), clay (b), till (c)

Determination of Dry Unit Weight by Nuclear Moisture-Density Gauge

The dry unit weight as determined by nuclear density gauge is plotted against drive core determined dry unit weight in Figures 12–13. There is very poor correlation between nuclear density gauge and drive-core–determined dry unit weight. Again, to account for this poor correlation, it is important to consider the difference in measurement volume of the nuclear gauge and drive core. To increase the accuracy of nuclear measurements, a longer measurement time could be used.

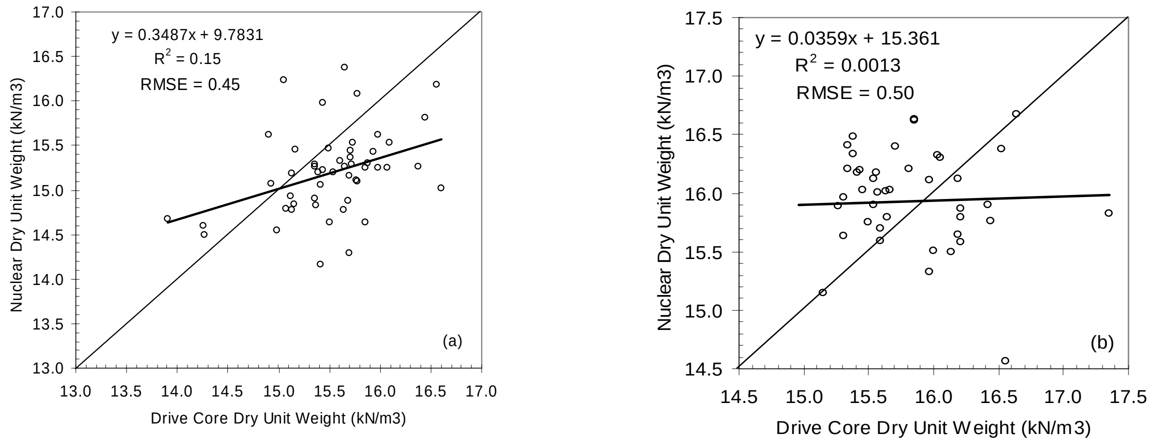

Figure 12. Nuclear density gauge vs. drive core dry unit weight for topsoil (a) and clay (b)

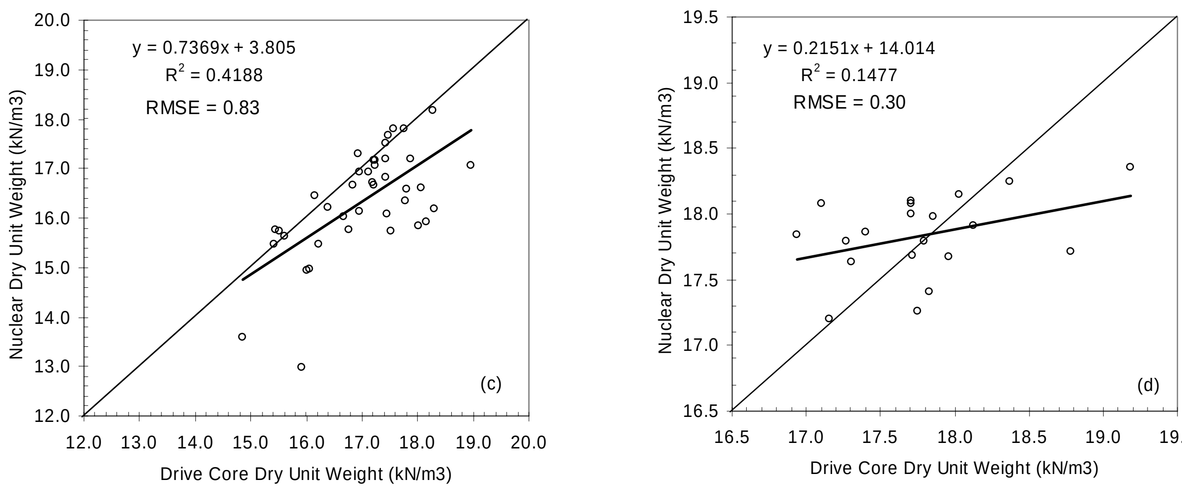

Figure 13. Nuclear density gauge vs. drive core dry unit weight for till (c) and sand (d)

Summary of Results

A summary of results is provided in Table 3 for moisture content and Table 4 for dry unit weight. For each method and soil type, the coefficient of determination (R^2), root mean square error (rmse), and standard error of performance (SEP, i.e., the standard deviation of the error) are provided relative to drive-core–determined values; also, the number of samples, N, is provided. The 95% confidence interval (CI_{95}) for a particular method and soil type may be calculated using Equation 6.

$$CI_{95} = \pm 2 \cdot \mathrm{SEP} \qquad (6)$$

Table 3. Summary of moisture content results for each method relative to drive core values

Method	Topsoil				Clay				Till				Sand			
	R^2	rmse	SEP	N	R^2	rmse	SEP	N	R^2	rmse	SEP	N	R^2	rmse	SEP	N
Nuclear	0.8	1.2	1.2	52	0.9	1.1	1.4	44	0.9	0.9	0.9	55	0.9	0.7	0.8	40
TDR	0.8	0.9	1.2	48	--	--	--	--	0.9	1.1	1.1	44	0.9	0.5	1.0	39
DMM	0.5	1.2	1.8	25	0.9	1.9	1.1	33	0.6	0.4	0.6	17	--	--	--	--

Table 4. Summary of dry unit weight results for each method relative to drive core values

Method	Topsoil				Clay				Till				Sand			
	R^2	rmse	SEP	N	R^2	rmse	SEP	N	R^2	rmse	SEP	N	R^2	rmse	SEP	N
Nuclear	0.2	0.4	0.6	51	0.0	0.5	0.7	43	0.4	0.8	1.1	40	0.1	0.3	0.5	20
TDR	0.6	0.8	0.8	123	--	--	--	--	0.6	1.9	1.9	168	0.1	2.4	2.2	165
DMM	0.3	0.9	0.8	25	0.2	0.6	0.6	22	0.3	0.8	0.8	17	--	--	--	--

SUMMARY AND CONCLUSION

Moisture measurements using the nuclear moisture-density gauge and TDR compared favorably to oven-dried samples. The DMM600 did not compare as well, but it is wrong to conclude that the capacitance method is inferior to the TDR or nuclear gauge methods; rather, the measurement technique employed in this study was probably unsuitable. No technique compared favorably to the drive-core–determined unit weight; however, it is apparent that the scale of measurement volume has a significant influence on unit weight determination. The most rapid technique was TDR (~ one minute), then nuclear density gauge (~ two to five minutes), and finally the DMM600 (~ three minutes).

Electromagnetic techniques such as TDR provide sufficient accuracy compared to oven-dried samples to be used in place of the nuclear moisture-density gauge. However, unlike the nuclear moisture-density gauge, the TDR cannot simultaneously measure unit weight without additional measurements. A major disadvantage of TDR to nuclear moisture-density gauge is the need for soil-specific calibration.

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