# EVALUATION OF ASTM TIME DOMAIN REFLECTOMETRY METHOD FOR SOIL WATER CONTENT AND IN-PLACE DENSITY

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## Abstract

The use of time domain reflectometry to measure soil density and water content in geotechnical engineering is relatively new. The ASTM Standard Method (D6780-02) outlines the procedure for obtaining the water content and the dry density of a given soil. The method relies on the measurement of an electromagnetic wave that is propagated through the soil. Each soil exhibits a unique wave reflection that is a function of its composition, density and water content. The apparent dielectric constant can be extracted from the unique wave form that is obtained. Upon calibrating the soil at different water contents, the dielectric constant can be measured in the field to obtain an accurate field water content measurement. The dry density is then calculated by removing the soil and measuring the dielectric constant in a field mold. The University of South Florida, in conjunction with the Florida Department of Transportation, has carried out an extensive research program to obtain the calibration constants for sandy soils commonly encountered in Florida. A critical assessment of the method's accuracy and precision has been conducted. A correlation between the energy required to drive the TDR spikes and the soil's CBR/LBR was developed. Cost comparisons with other commonly used methods are presented.

## Introduction

It is critical to monitor both compaction and water content to ensure quality control in earthwork construction projects. Time domain reflectometry measurement is a relatively new method that can be used to measure both water content and in-place soil density. A variety of methods currently exist to measure both water content and in-place density. Most of these methods measure soil density and water content independently on separate soil samples. The dry density of the soil is then calculated.

The use of the nuclear method (ASTM D3017) to find water content is common. This method relies on applying a fast neutron source to the surface and is largely sensitive to the water contained only in the top 2 to 3 inches of the material. The "speedy moisture content" method (ASTM D4944) is also commonly used to determine in-situ water content. The method relies on a chemical reaction using calcium carbide to determine the amount of water contained in the specimen. The method is not accurate for highly plastic clays and measures highly flammable acetylene gas. Methods such as the "oven dry" (ASTM D2216) and the microwave oven method (ASTM D4643) require that the sample be taken off site to be dried. These drying methods often take more time than is desirable to complete.

The sand-cone method (ASTM D1556) was widely used before development of other methods. The sand cone method replaces the unknown material with calibrated sand and then a calculation is made to find the in-place soil density. The sand cone method results vary considerably as the density of the calibrated sand is not constant. The rubber balloon method (ASTM D2167) relies on the same principle as the sand cone method. The unknown soil is excavated, while the volume of the excavation is determined by the inflation of a rubber balloon. Abnormalities in the excavation and the inability of the balloon to completely fill the excavated walls create a significant source of error in measured results. A shallow depth nuclear method (ASTM D3017) operates on the same basis as the water content method mentioned earlier. Another nuclear method (ASTM D5195) involves the insertion of a radiation tube with a gamma radiation source. Voids around the excavation can influence results as well as variability of the mineralogy in the soil. The nuclear methods appear to give fairly accurate results; however, the operation of such equipment requires special licensing for the operators that is required to reduce the hazardous potential that comes with the use of nuclear testing. Methods such as the dry sleeve method (ASTM

D4564) and the drive-cylinder method (ASTM D2937) are based on extracting undisturbed samples directly from locations of interest. These methods are not applicable in certain soils, such as dense sand and gravel, where it is unfeasible to insert cylinders or sleeves into the soil.

Time domain reflectometry (TDR) has been used in geotechnical applications to find volumetric water content. A development by Topp in the early 1980's led to a universal relationship between volumetric water content and the apparent dielectric constant. Studies by Siddiqui and Drnevich (1995) on the factors which influence wave transmission led to the development of reliable equipment that could be used to measure in-place soil density and gravimetric water content. Part of research done by Siddiqui and Drnevich included a calibration equation relating the soil apparent dielectric constant with soil gravimetric water content. A standardized field procedure was then developed (ASTM D6780), which consists of two steps: 1) four spikes are driven into the soil and the reflected TDR wave form is recorded; and 2) a second measurement is taken in a compaction mold using the same soil in the first step after it is rapidly excavated. The gravimetric water content for both tests is the same, and the two TDR wave forms are then used to determine the gravimetric water content and the in-place soil density. The results reported herein are part of a Beta testing program to assess the accuracy of the TDR method. Results indicate the method is sufficiently accurate for geotechnical applications.

## Experimental Program

The objectives of the testing program were 1) to evaluate the soil calibration constants of typical soils and to evaluate the consistency and accuracy of the TDR method; 2) to determine the accuracy of the TDR method; and 3) to establish a relationship between the TDR spikes driving process to the soil strength as defined by the CBR (California Bearing Ratio) test. The tests reported in this paper were primarily focused on the evaluation of typical soil constants for granular materials commonly encountered in Florida. In order to accurately determine field measurement of in-place density and water content the TDR system had to be calibrated. TDR calibration constants "*a*" and "*b*" in the Siddiqui and Drnevich (1995) equation vary significantly between soil types. However, the constants for comparable materials are similar. For this research study, granular soil samples were taken from materials used in highway construction projects. Over 150 tests were carried out on various soils. The resulting "*a*" and "*b*" values were determined and recommendations were made for typical values.

A series of tests were also developed to assess the accuracy of the TDR method. Control boxes were developed in which the water content and density were known. These known values were based on the oven dry method for water content and a density calculation based on weight and volume. TDR measurements were taken from the control boxes and then compared to the known values. Error for the TDR measurements was then calculated based on the control values. Additional studies including compaction variability and operator dependency were undertaken as well. Theoretical studies were also undertaken to estimate the amount of inherent error as well as the effect of variation on both water content and soil density due to changes in soil constants "*a*" and "*b*."

Due to the similarity of the TDR spike driving process to other methods used to determine soil strength, a correlation is proposed between the energy required to drive the TDR spikes and a common procedure used to characterize soil strength. The Limerock Bearing Ratio (LBR) test is one such procedure that is common to the state of Florida. This test is very similar to the CBR test, the only major difference being in the strength of the standard material to which the soil is compared. Equipment was procured to carry out the in-place LBR test and a series of tests were performed at different sites. The data obtained from these tests was then used to develop a correlation between the energy required to drive the TDR spike and the LBR value.

## Materials

The majority of soil types included in the study were sandy soils. The USCS (Unified Soil Classification System) classification for these soil types is SP and SW (poorly-graded and well-graded sand). The equivalent AASHTO classification is A-1-b and A-3. These soil types are typical throughout the state of Florida and are most commonly used in earthwork construction projects. The present research did not include significant data from plastic material such as clay or silt to substantiate any viable calibration recommendations. However, further research of plastic materials is currently being carried out and could greatly benefit other geographical areas outside of Florida.

## Calibration of Parameters

There are basic empirical equations, which have been developed to correlate the volumetric or gravimetric moisture content to the soil dielectric constant. Topp et al. (1980) developed an equation to describe the relationship between volumetric moisture content ($\theta$) and apparent dielectric constant $K_a$:

$$\theta = -0.053 + 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^{\ 2} + 4.3 \times 10^{-6} K_a^{\ 3} \qquad \textit{(Eqn. 1)}$$

As an alternative to Eqn. 4-1, Ledieu et al. (1986) and Alharthi and Lange (1987) proposed a linear calibration equation as:

$$\sqrt{K_a} = a + b\theta \qquad \textit{(Eqn. 2)}$$

where *a* and *b* are calibration constants: *a* = 1.545 and *b* = 8.787 in Ledieu et al. (1986); *a* = 1.59 and *b* = 7.83 in Alharthi and Lange (1987).

Ledieu et al. (1986) demonstrated that an improvement could be added if the bulk dry density is included in the equation as:

$$\sqrt{K_a} = a\rho_d + b\theta + c \qquad \textit{(Eqn. 3)}$$

where *a*, *b*, and *c* are calibration constants: *a* = 0.297, *b* = 8.79, and *c* = 1.344.

By normalizing the effect of density, Siddiqui and Drnevich (1995) developed an equation similar to Eqn. 3, with *c* = 0. In their equation, the relationship between apparent dielectric constant and gravimetric moisture content is expressed as follows:

$$\sqrt{K_a}\,\frac{\rho_w}{\rho_d} = a + bw_c \qquad \textit{(Eqn. 4)}$$

The Siddiqui and Drnevich (1995) relationship (Eqn. 4) has been used to determine the soil constants "*a*" and "*b*" as discussed previously. The process relies on performing the TDR method on a particular soil in the mold at different moisture contents. In this case the soil dielectric constant in the mold $K_{a,mold}$ is measured as an output from the TDR measurement. The wet density is readily measured since the mold's volume and weight are known a priori. The moisture content can be determined by the oven-dry method, ASTM D2216. The two unknowns in this equation are, therefore, the constants "*a*" and "*b*". If the left hand side of the equation is plotted against the moisture content, the results could be regressed to a straight line with a slope equal to the constant "*b*" and an intercept equal to the constant "*a*". This procedure has been performed on eleven soils from highway construction projects, one soil from a local source at the University of South Florida in Tampa, and one standard ASTM (Ottawa) sand sample.

The results from this testing phase are reported in Table 1. In order to ensure accuracy, two different operators performed the tests and, in selected cases, the test was performed by both of them to ensure consistent testing procedures.

The results from all the tests are shown collectively in Fig. 1. Values of 0.99 and 8.48 were determined for constants "*a*" and "*b*" respectively. The correlation factor, or R-value, for the trend line used for all data was 0.983, indicative of a strong correlation. The "*a*" value of 0.99 is considerably close to 1.00, the value proposed by Lin et al. (2000). The study also revealed that the value of "*b*" varies between 7.73 and 9.83, with an average value of 8.48. The value proposed by Lin et al. (2000) for the same parameter is 9.0. Based on the current results, it is recommended to use a value of 1.0 for soil constant "*a*" and a value of 8.5 for soil constant "*b*" for clean sands such as those found in Florida. No recommendation is made for silt or clay materials.

*Table 1. Values of constants "a" and "b" for clean sands*

| Test | Description | Operator | USCS | AASHTO | a | b | Comment |
|---|---|---|---|---|---|---|---|
| 1 | Ottawa Sand | Amr | SP | A-1-b | 1.22 | 11.68 | Discarded |
| 1-a | Ottawa Sand | Brian | SP | A-1-b | 0.95 | 9.00 | Accepted |
| 1-b | Ottawa Sand | Both | SP | A-1-b | 0.91 | 9.41 | Accepted |
| | | | | Average | **0.93** | **9.21** | |
| 2 | Outside Lab | Amr | SP | A-3 | 1.00 | 8.20 | Accepted |
| 2-a | Outside Lab | Brian | SP | A-3 | 1.03 | 8.35 | Accepted |
| | | | | Average | **1.02** | **8.28** | |
| 3 | MP-1 | Amr | SP | A-1-b | 0.93 | 8.78 | Accepted |
| 3-a | MP-1 | Brian | SP | A-1-b | 1.01 | 7.48 | Accepted |
| 3-b | MP-1 | Brian | SP | A-1-b | 0.98 | 8.21 | Accepted |
| | | | | Average | **0.97** | **8.16** | |
| 4 | Sample # 515 | Both | SP | A-3 | 1.05 | 8.19 | Accepted |
| 4-a | Sample # 515 | Brian | SP | A-3 | 1.01 | 8.93 | Accepted |
| 4-a | Sample # 515 | Brian | SP | A-3 | 1.03 | 8.73 | Accepted |
| | | | | Average | **1.03** | **8.62** | |
| 5 | Sample # 2 | Amr | SP | A-1-b | 1.10 | 7.40 | Accepted |
| 5-a | Sample # 2 | Both | SP | A-1-b | 1.04 | 8.06 | Accepted |
| | | | | Average | **1.07** | **7.73** | |
| 6 | Sample # 6944 | Amr | SP | A-3 | 1.08 | 8.09 | Accepted |
| 6-a | Sample # 6944 | Brian | SP | A-3 | 0.99 | 8.65 | Accepted |
| | | | | Average | **1.04** | **8.37** | |
| 7 | Sample with # 6944 | Brian | SP | A-1-b | **0.99** | **8.80** | Accepted |
| 8 | Sample # 6965 | Both | SW | A-1-b | 0.99 | 8.80 | Study the effect of compaction |
| 8-a | Sample # 6965 | Both | SW | A-1-b | 1.04 | 8.03 | Study the effect of compaction |
| 8-b | Sample # 6965 | Both | SW | A-1-b | 0.99 | 8.31 | Study the effect of compaction |
| 8-c | Sample # 6965 | Both | SW | A-1-b | 1.00 | 7.96 | Study the effect of compaction |
| | | | | Average | **1.01** | **8.28** | |
| 9 | Sample With # 6965 | Brian | SP | A-1-b | **1.02** | **8.20** | Accepted |
| 10 | Sample # 6974 | Brian | SP | A-1-b | **0.99** | **8.27** | Accepted |
| 11 | Sample # 6978 | Brian | SP | A-1-b | **1.02** | **7.93** | Accepted |
| 12 | Sample # 6926 | Brian | SP | A-1-b | 0.90 | 9.24 | Accepted |
| 13 | Sample # 6927 | Brian | SP | A-1-b | 0.87 | 9.83 | Accepted |

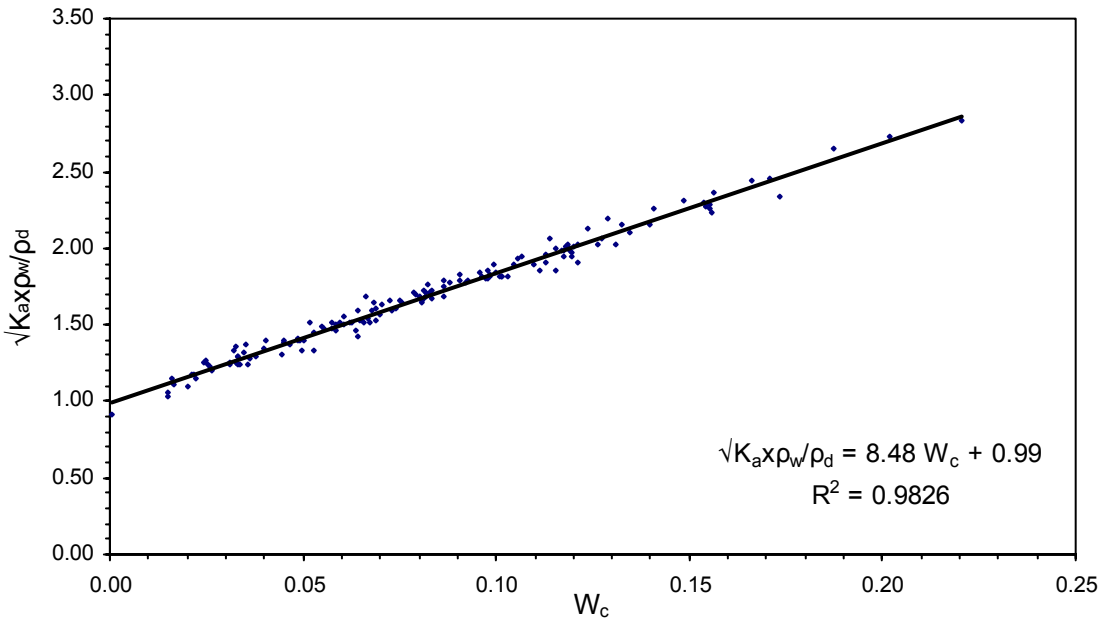


*Figure 1. Final results of the TDR test in-mold for clean sands*

## Evaluation of the Method's Accuracy

### Laboratory Setup

Two control boxes were created to act as a known standard to which TDR measurements could be compared. The larger one is 24×24×20 inches, and is made up of plywood ¾" thick. A movable extension collar (4" high) is mounted to the top, as shown in Fig. 2. A similar smaller box, 16×16×20 inches, was also made up of plywood ¾" thick with a similar collar attachment.

*Figure 2. Calibration box with the extension collar*

Both boxes were insulated with fiberglass mats and hardening resin on the inner surface to prevent moisture loss or absorption through the box connections or cracks in the plywood. The boxes were calibrated by filling them with tap water. Knowing the empty weight of the box and measuring the weight of the box after filling, the box volume can be determined. This process was repeated three times to ensure accuracy. The volume of the small box was determined to be 2.2917 $ft^3$ and the volume of the larger box was 5.2644 $ft^3$.

A series of tests were run on the calibrated boxes. Utmost care was taken to compact the test soil as uniformly as possible. The soil was also thoroughly mixed to create uniformity in the soil water content. Several TDR measurements were then taken from the calibrated boxes. The measurements were then compared to the known calibrated values.

## Results and Discussion

In order to assess the accuracy of the method, results from the TDR measurements on the calibrated boxes were compared to the "actual" values, as calculated based on the weight and volume of the box and the oven dry moisture content. The results are presented in Figs. 3 and 4, respectively, together with a 1:1 line on each graph to evaluate the deviation from the actual value. The error in water content was relatively small, mostly within 2 percentage points. However, errors up to 7 pcf, corresponding to approximately 7% of the actual value, were encountered in the density. It also appears that the water content measurements were biased on the negative side whereas density errors were concentrated more on the positive side. However, in order to assess the suitability of the TDR as an alternative to other field density methods, the results must be compared and the accuracy assessed for all methods. Preliminary data underway indicate that the TDR measurements are far superior to sand cone, whereas the accuracy is fairly comparable to that of the nuclear density gauge.

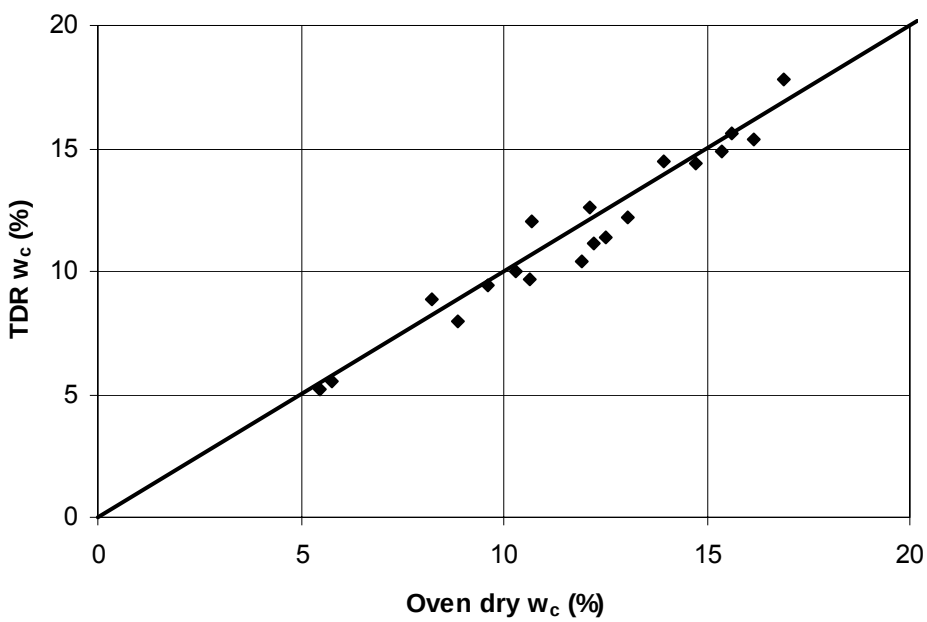


*Figure 3. Comparison between oven dry and TDR measurements of water content*

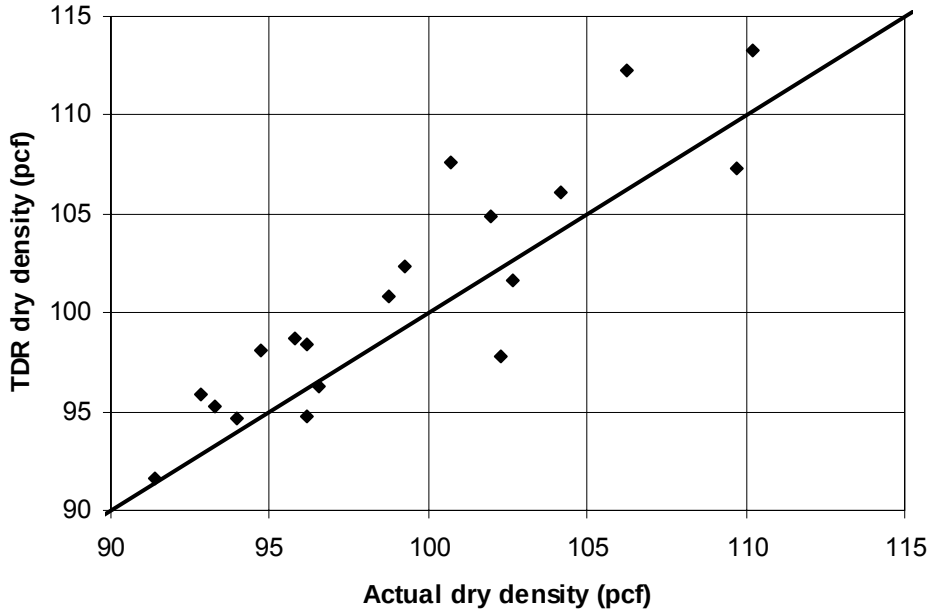


*Figure 4. Comparison between actual and TDR measurements of dry density*

## Correlation with CBR/LBR

### Procedure and Equipment

The California Bearing ratio test is commonly used to evaluate the strength of a material as it applies to highway design. The CBR test compares the strength of the tested material to that of crushed rock. Due to the wide spread use of limestone as a base material in the state of Florida, the resistance of crushed limestone to penetration is used as the standard value against which the soil resistance is compared, and the test is referred to as the Limerock Bearing Ratio. LBR tests are frequently used to establish guidelines for the use of materials in pavement and highway design. The LBR testing procedure is essentially the same as the CBR test, with the only critical difference coming in the calculation portion of the data analysis. The CBR test calls for a division of the 0.1 inch penetration of 1,000 psi and a division of 1,500 psi at the 0.2 inch penetration. The LBR values are calculated only using 800 psi at 0.1 in. penetration. This reduction in the denominator is accredited to the reduction in the CBR value when limerock is used as the standard as opposed to the standard crushed rock. It follows that the LBR value is simply the CBR number multiplied by a factor of 1.25. In this paper, the more common CBR values are reported.

The testing procedure developed to generate the CBR/TDR correlation is largely based on ASTM standard D 4429-93, which is the standard test method for California Bearing Ratio of soils in place. The components of the in-place CBR test according to ASTM standard D 4429-93 include a mechanical screw jack, proving rings, a penetration piston, dial gages, and a truck capable of transmitting a 7000 lbf reaction force. Figure 5 shows the setup used to perform the in place CBR tests.

The TDR method requires that three spikes be driven around a central spike to obtain a TDR waveform. A brass hammer is used to drive the spikes into the ground. The effort required to drive the spikes into the soil varies depending on the soil resistance to penetration. Instead of using the brass hammer to drive the spikes, a modified standard proctor hammer is used to measure the amount of effort required to drive the spikes. A steel cap with a groove having the same dimensions as the spike head is attached to the standard hammer (Fig. 6). This allows for uniformity in the measurement of the energy required to drive the TDR spike through the template. Further modification can be introduced to the standard hammer to allow changes in drop height depending on the anticipated soil strength.

*Figure 5. CBR in-place equipment setup.*

*Figure 6. The standard Proctor hammer with the machined head.*

Before the in place CBR test was run, a TDR spike test was performed. Each test was carried out as close as possible to the CBR test location. However, no test was performed closer than the ASTM recommended distance of 15 inches to avoid disturbing the CBR test location. The first spike was placed into the TDR template and then driven with the modified Proctor hammer. The number of Proctor hammer drops was recorded. To ensure that the hammer drops were being applied perpendicularly to the ground and in alignment with the spike, a second person was monitoring the process at ground level while holding the spikes in position. Figure 7 displays the TDR spike driving technique used. The process was repeated until all 4 stakes are driven. The number of blows required to drive each stake to the template was recorded. The average value of blows required to drive the stakes was then calculated.

Figure 7. TDR spike driving procedure.

## Results and Discussion

Results indicate that a strong correlation exists between the TDR spike driving energy and the in place CBR test. The results and corresponding relationship are displayed in Fig. 8. The relationship in Fig. 8 compares favorably with previous efforts to obtain correlative relationships to CBR values from tests similar to the TDR spike driving procedure done by Harison (1989) and Livneh (1989). After examination and analysis of the data collected it is proposed that the transformation equation used to estimate the in-situ CBR number from the average number of blows required to drive the TDR stakes is:

$$CBR = 0.1013\ TDR^2 - 1.0937\ TDR - 0.3925 \qquad \textit{(Eqn. 5)}$$

where TDR is the average number of blows required to drive the 12 inch TDR spikes into the TDR template.

## Cost Comparisons

The TDR method for compaction control is comparable in cost to other methods currently used. Generally two tests need to be performed to ensure quality compaction: 1) moisture content and 2) in place density. Most methods require two separate measurements to perform these tests independently of one another. Several methods, such as the nuclear density gauge, require calibration on different soil samples. Obviously, a method combining the two tests into one would lessen the error that arises from running two independent tests. The cost associated as far as time and resources is concerned would also be reduced. The only existing method that is capable of measuring the in place density and moisture content is the shallow depth nuclear method (ASTM D3017). However, the results of the shallow depth nuclear method are biased toward measuring only the top few inches of the soil.

The costs for running moisture content tests are fairly similar. The shallow depth nuclear method equipment is more costly in terms of an initial investment than the oven dry method (ASTM D2216) or the speedy moisture method. However, the oven dry method requires a 24 hour period to run. Waiting for lab results to ascertain the compaction quality at a particular site may be very costly and highly undesirable. Other methods, such as the direct heating method and microwave method may be faster, but results are not as reliable when compared to the oven dry method (ASTM D4643). The speedy moisture content method can be run comparatively quickly. One of the main shortcomings of the nuclear method is that special licensing or certification is required for the test operator.

With respect to density measurements, the sand cone method was widely used in the past but has become almost obsolete in recent years. Wide variability in results of the sand cone method, as well as the destructive nature of the test, can be cited as causes for its decline. The shallow depth nuclear method can also be used to measure in place density, but the same limitations apply to this test as mentioned previously. The benefit of the shallow depth nuclear method is that it is a nondestructive test and can be used to measure both required parameters. Another nuclear method (ASTM D5195) involves the drilling of hole and placement of a radiation probe. This test is destructive as well as costly.

The ASTM Standard Method (D6780-02) for TDR combines both tests into one procedure. The entire test takes around twenty minutes to complete. This time is less than most of the methods described above and, when taking into account that in most cases two tests must be run, the TDR method typically requires less time to run. The cost for the equipment to run this test initially is about twice the cost than the shallow depth nuclear method. However, the TDR equipment only needs to be calibrated once and does not require special licensing to operate. Savings over time suggest that the TDR method would be cost effective when compared to the nuclear method. The present TDR test method is, however, destructive and requires the excavation of soil in the second portion of the test. Current research is focused on eliminating the second step of the test, which would make the TDR method non destructive as well as rapid. The elimination of the discrepancy encountered when running separate tests alone may justify any initial cost associated with TDR equipment.

## Summary

Research on the evaluation of ASTM time domain reflectometry method for soil water content and in-place density indicated that a value of 1.0 for soil constant "*a*" and a value of 8.5 for soil constant "*b*" are appropriate for use with clean sands such as those found in the state of Florida. The TDR method also proved to be sufficiently accurate for geotechnical applications, with water content results being more reliable than density. The method appears to slightly underestimate water content values, while variable scatter levels were encountered in density measurements. A correlation has been formulated for the purpose of predicting CBR values based on the energy required to drive the spikes in the ground. The use of time domain reflectometry in geotechnical applications can greatly reduce the time needed to evaluate the quality of compacted fills. Given the recent introduction of the technology in the geotechnical field, further research into the TDR method could result quicker and more accurate measurements in water content and density.

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