Synthesis of Nondestructive Testing Technologies for Geomaterial Applications

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16. Abstract

Current monitoring techniques for determination of compaction of earthwork and asphalt generally involve destructive testing of the materials following placement. Advances in sensor technologies show significant promise for obtaining necessary information through nondestructive and remote techniques. To develop a better understanding of suitable and potential technologies, this study was undertaken to conduct a synthesis review of nondestructive testing technologies and perform preliminary evaluations of selected technologies to better understand their application to testing of geomaterials (soil fill, aggregate base, asphalt, etc.).

This research resulted in a synthesis of potential technologies for compaction monitoring with a strong emphasis on moisture sensing. Techniques were reviewed and selectively evaluated for their potential to improve field quality control operations. Activities included an extensive review of commercially available moisture sensors, literature review, and evaluation of selected technologies. The technologies investigated in this study were dielectric, nuclear, near infrared spectroscopy, seismic, electromagnetic induction, and thermal.

The primary disadvantage of all the methods is the small sample volume measured. In addition, all the methods possessed some sensitivity to non-moisture factors that affected the accuracy of the results. As the measurement volume increases, local variances are averaged out providing better accuracy. Most dielectric methods with the exception of ground penetrating radar have a very small measurement volume and are highly sensitive to variations in density, porosity, etc.

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SYNTHESIS OF NONDESTRUCTIVE TESTING TECHNOLOGIES FOR GEOMATERIAL APPLICATIONS

Final Report
May 2005

Principal Investigator
Vernon R. Schaefer, Professor
Department of Civil, Construction and Environmental Engineering, Iowa State University

Co-Principal Investigators
David J. White, Assistant Professor
Department of Civil, Construction and Environmental Engineering, Iowa State University

Edward J. Jaselskis, Associate Professor
Department of Civil, Construction and Environmental Engineering, Iowa State University

Joseph N. Gray
Physicist, Center for Nondestructive Evaluation, Iowa State University
Adjunct Associate Professor, Department of Mechanical Engineering, Iowa State University

Research Assistant
Matt Veenstra

Authors
Matt Veenstra, David J. White, and Vernon R. Schaefer

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Center for Transportation Research and Education
Iowa State University
2901 South Loop Drive, Suite 3100
Ames, IA 50010-8634
Phone: 515-294-8103
Fax: 515-294-0467
www.ctre.iastate.edu

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EXECUTIVE SUMMARY

Project Overview

This research resulted in a synthesis of potential technologies for compaction monitoring with a strong emphasis on moisture sensing. Techniques were reviewed and selectively evaluated for their potential to improve field quality control operations. Activities included an extensive review of commercially available moisture sensors, literature review, and evaluation of selected technologies.

The following is a list of technologies investigated in this study:

- Dielectric
- Nuclear
- Near infrared spectroscopy
- Seismic
- Electromagnetic induction
- Thermal properties

This research provides groundwork for researchers interested in the current state of the art in alternative moisture sensing technologies. From this preliminary research, recommendations for fuller development of technologies are provided.

Commercial Moisture Sensing Technologies

Commercially available technologies designed for moisture sensing, or that can be used for soil moisture sensing, can be grouped into seven principle techniques: (1) gravimetric, (2) dielectric, (3) nuclear, (4) spectroscopic, (5) ultrasonic, (6) electromagnetic induction, and (7) thermal methods.

1. Gravimetric methods consist of weighing a wet soil mass, removing the water by drying, and reweighing the soil mass to determine the mass of water lost. This is the only direct method of moisture measurement and is the basis by which the accuracy of all other methods is compared.

2. Dielectric methods mainly use time domain reflectometry or frequency domain reflectometry (capacitance) type instruments. These instruments provide an estimate of the bulk dielectric constant of the soil. The dielectric constant of water is about 81, while that of the soil solids are 4-8, and that of air is about 1. Because of its relatively high dielectric constant, the moisture content of soil may be empirically or semi-empirically determined from the soil bulk dielectric constant.

3. Nuclear methods have been used for many years for irrigation management and compaction monitoring in earthwork projects. Moisture content is determined from the thermalization of neutrons by hydrogen atoms while traveling through a soil mass. Soil density is determined by lowering a radioactive source into the soil and measuring the attenuation of gamma radiation as a function of soil density. Nuclear methods are the most common nondestructive soil compaction monitoring techniques.

4. The type of spectroscopy used in soil moisture monitoring is near infrared spectroscopy because of its high speed and little need for sample preparation. This method measures the change in absorbance of near infrared light by the soil due to changes in moisture content.

5. Seismic methods make use of the propagation time of mechanical waves in the soil to measure changes in soil properties. The principal use of seismic methods is to measure the location of material discontinuities, primarily changes in stiffness and density. Because soil moisture affects both stiffness and density, and because free water in the soil supports seismic wave propagation, changes in soil moisture should affect the seismic wave propagation.

6. Electromagnetic induction is a resistive method. This method assumes that soil conductivity increases with moisture content. Methods of measuring soil conductivity can be direct or indirect. The direct method consists of applying a voltage through the soil and measuring the voltage drop over a distance. The indirect method utilizes electromagnetic induction. The resistive method has not seen widespread use as variations in soil conductivity due to non-moisture sources are common and have high spatial variance, making calibration difficult or impossible. For example, soluble salts will cause significant increase in conductivity with increased moisture content as the salts dissolve.

7. Thermal methods include measurement of the thermal properties of a soil, including thermal conductivity, heat capacity, and thermal diffusivity. Moisture content is one of the primary variables determining the thermal properties of a soil mass with both heat capacity and thermal conductivity increasing with increased moisture content.

Evaluation

The main disadvantage of these methods is the small measurement volume. Because all of these methods are sensitive to non-moisture factors, spatial variability in soils is the greatest source of measurement variability. As the measurement volume increases, local variances are averaged out providing better accuracy. Most dielectric methods with the exception of ground-penetrating radar have a very small measurement volume and are highly sensitive to variations in density, porosity, etc. Nuclear methods tend to have a large measurement volume and are less sensitive to variations in density (neutron thermalization), resulting in low variability. Near infrared method is capable of measuring a large surface area very quickly but cannot be expected to measure at depths more than several millimeters.

Four techniques were subjected to further evaluation: (1) time domain reflectometry (TDR) (2) capacitance, (3) seismic, and (4) thermal properties. The TDR was easily employed in the field, except in very stiff, dry soils; though, it was highly variable relative to the nuclear moisture-density gauge. The capacitance sensor was evaluated using soil samples contained in confining rings; laboratory results were favorable but no field evaluation was performed. Seismic testing showed promise in monitoring the change in void ratio due to compression and consolidation. Moisture content did have an influence, but there are no general calibrations for seismic methods. Thermal properties measurement showed trends for both changes in moisture content and bulk density, but no general calibration was used or formulated.

Further Research

The review of technologies conducted has identified some potential technologies for research for fuller development of technologies studied. Technical goals for additional research include identification and development of techniques (e.g., x-ray/nuclear, ultrasound, capacitance, magnetic, thermal, optical, microwave, sound, infrared, and spectroscopy) or hybrid systems (i.e., combinations of techniques) that will enable moisture content determination in situ from construction equipment and/or portable testing devices.

INTRODUCTION

Problem Statement

Current monitoring techniques for determination of compaction of earthwork and asphalt generally involve destructive testing of the materials following placement. Advances in sensor technologies show significant promise for obtaining necessary information through nondestructive and remote techniques. If such technologies can be found to apply to geomaterial applications, such as monitoring of water content during soil compaction processes, then such applications could potentially be managed and controlled to improve quality, reduce rework, maximize productivity, and minimize costs. To develop a better understanding of suitable and potential technologies, this study was undertaken to conduct a synthesis review of nondestructive testing technologies and perform preliminary evaluations of selected technologies to better understand their application to testing of geomaterials (soil fill, aggregate base, asphalt, etc.).

Current practices in most geomaterial applications rely primarily on method specifications (i.e., sheepsfoot walkout) or field spot testing (i.e., nuclear density gauge) that may or may not provide adequate quality control/assurance. Recent advances in nondestructive testing (NDT) and evaluation (NDE) show significant promise in obtaining necessary information that could significantly improve field quality control operations related to geomaterials construction by (1) increasing the coverage area in lieu of spot tests, (2) providing engineering parameter values that provide better estimates of "quality," and (3) speeding up the inspection process and providing real time results in computer format. This study provides a review of innovative, nondestructive, end-result tests that could significantly improve quality control while providing reduced inspection personnel time and increased coverage.

Project Scope and Objectives

This project aims to identify, document, and selectively evaluate innovative testing technologies that can be applied to geomaterial applications. Technologies investigated include, but are not limited to the following:

- Nuclear methods
- Seismic methods
- Dielectric measurements
- Magnetic methods
- Thermal methods
- Spectroscopy

In addition to civil engineering systems, other areas such as the power generation industry (e.g., nuclear and coal), oil exploration industry, soil science, material science, commercial and military aviation, and aerospace were investigated.

The overall objective of this project was to conduct a literature review and synthesis of current nondestructive testing technologies used or that could be used to monitor geomaterial engineering properties and to carry out preliminary field and/or laboratory tests to evaluate technologies suitable for use in Iowa. Due to budget constraints, the focus of the project was confined primarily to investigation of methods of moisture measurement. It is anticipated that recommendations will result from this study for development, application, and field-testing of various innovative technologies in a Phase II project.

Overview of Tasks

The proposed research was organized into five tasks: (1) literature search for innovative nondestructive technologies for potential application to geomaterial property measurement, (2) evaluation of technologies for suitability for application to geomaterial property measurement, (3) preliminary feasibility testing of selected technologies for application to geomaterial property measurement, (4) preparation of the final report, and (5) presentation of the project findings.

Task 1 entailed the primary effort of the first part of the study. A comprehensive search of the literature was conducted using both web-based and non-web-based search techniques. A concerted effort was made to look outside of the traditional engineering sources to areas such as the power generation industry, oil exploration industry, soil science, agriculture engineering, material science, commercial and military aviation, and aerospace. The project team included a PI from ISU's Center for Nondestructive Evaluation to aid in the search and evaluation process. A product from this task was a discussion of the physical principles by which the specific technologies work and advantages and limitations of each technology. The measured property areas to be investigated included determination of moisture content, stiffness, strength, density, volumetric stability, grain-size distribution, and other engineering parameters useful to predicting geomaterial performance.

Task 2 entailed the critical review of the technologies for application to specific geomaterial applications. The review was targeted primarily to technologies and their application to moisture measurement. The evaluation phase allowed identification of existing market technologies that showed promise for the measurement of water contents in soils. The costs of primary and ancillary equipment will be identified to the extent possible.

The result of Tasks 1 and 2 is (1) a presentation (summary) of the physical principles of each technology; (2) a summary of the application of technologies in specific fields such as geology, soil science, engineering, etc.; and (3) a critical evaluation of the potential of specific technologies for application to geomaterial property determination or potential for development of such applications.

For Task 3, selected technologies were subjected to preliminary feasibility testing. Limited trials of selected technologies for specific geomaterial property determinations were conducted. From these preliminary trials, recommendations for fuller development of technologies are made. Tasks 4 and 5 consist of preparation of the final report and presentation of the study findings.

REVIEW OF COMMERCIALLY AVAILABLE SOIL MOISTURE SENSORS

Commercially available technologies designed for moisture sensing, or that can be used for soil moisture sensing, can be grouped into seven principle techniques: (1) gravimetric, (2) dielectric, (3) nuclear, (4) spectroscopic, (5) ultrasonic, (6) electromagnetic induction, and (7) thermal methods.

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7. Thermal methods include measurement of the thermal properties of a soil, including thermal conductivity, heat capacity, and thermal diffusivity. Moisture content is one of the primary variables determining the thermal properties of a soil mass with both heat capacity and thermal conductivity increasing with increased moisture content.

Agriculture is the primary motivator for the commercial development of soil moisture sensors. This is especially true in the irrigation industry where soil moisture sensors are used to increase the efficiency of irrigation. As a result, most commercial moisture sensors are intended for in situ data logging operations in conjunction with on-demand irrigation scheduling. Spot testing sensors are designed for moisture sensing at root depth and consist of two or more probes which are inserted into the soil.

A review of the literature reveals much conflicting information and confusion over the terminology used to describe soil moisture sensors. The following tables provide side-by-side comparisons of the most common moisture sensors (gravimetric, dielectric, and nuclear methods) available on the market today.

Table 1 is a review of time domain reflectometry sensors, which are a type of dielectric moisture sensor. Table 2 is a review of capacitance sensors, which are also a type of dielectric moisture sensor. Some of the instruments grouped under capacitance are not technically capacitance type sensors. These include so called frequency domain reflectometry (FDR) probes and the Theta Probe ML2x. The Theta Probe ML2x is a standing wave ratio type sensor that measures an impedance change due to the dielectric constant of the soil.

Table 3 is a review of commercially available nuclear, electromagnetic induction, and microwave moisture sensors. Nuclear methods are well established and have seen considerable use in both irrigation monitoring and civil engineering applications, such as compaction monitoring using a nuclear density gauge. The electromagnetic method is not used much for soil moisture sensing, though several studies have been conducted using the Geonics EM-38 instrument. Microwave sensors have not seen application in soils but are commonly applied toward low density organic materials.

Table 1. Commercially available dielectric soil moisture sensors: time domain reflectometry

Manufacturer / Sensor Trade Name	**Automata / AQUA Tel AT210**	**Campbell Scientific / CS616**	**Campbell Scientific / CS620 & CD620 (hydrosense)**
Installation Method / Intrusiveness	Buried in situ or pushed into soil	Buried in situ or pushed into soil	Buried in situ or pushed into soil
Ruggedness		Buriable	Moderate /high?
Calibration	Travel time to moisture content	Travel time to moisture content	Travel time to moisture content
Capital Cost ($)	Probe: 99 Reader: 150		
Output	0 – 1 mA, or voltage via shunt.	+/- 0.7V sq. wave, freq dep. On w%	VWC or water deficit
Accuracy (% vwc)		2.5	3
Precision (% vwc)		0.05	
Resolution (% vwc)	Infinite	0.1	0.25
Probe length	Length is 69 cm Measures over final 46 cm	30 cm	12 – 20 cm
Measurement olume	Length is 27 in. Measures over final 18 inches.	300 mm x 32 mm spacing	120 mm or 200 mm x 32 mm spacing
Response Time		0.50 msec	<50 msec
Affected by Salinity	Absolute value affected 1% per 1000 µ-Siemens	Yes	Yes
Measuring Range (% vwc)		0 - 50	0 - Saturation
Comments	Absolute reading affected by high dielectric constant materials		
Logging capability	Yes	Yes with logger	Yes with logger
Best Soil Type	Stated independent of soil texture		

Table 1 (continued)

Manufacturer / Sensor Trade Name	**IMKO / TRIME-GW**	**IMKO / TRIME-EZ**	**Meteolabor / Lumbricus**
Installation Method / Intrusiveness	Surface, V form, pipe	Buried in situ or pushed into soil	Single probe
Ruggedness	Suited to high temp grain drying environment	Buriable. Frost resistant.	
Calibration	Travel time to moisture content	Travel time to moisture content	Freeze soil w/ liquid N, reference values taken frozen and thawed (Ka h20 is 78, Ka ice is 3.1)
Capital Cost ($)	2000		16700
Output	VWC	Nanoseconds calibrated to VWC	
Accuracy (% vwc)	1	1 for 0-40 vwc 2 for 40-70 vwc	1.5
Precision (% vwc)	0.3		
Resolution (% vwc)			
Probe length	Flat plate, surface contact probe	16 cm	250 cm, 1 – 2 cm resolution
Measurement Volume	Field 10cm beyond plates (both sides of sensor)		2.5 m x 127 mm diam.
Response Time	0.5 sec running average	~ 10 sec	
Affected by Salinity	Contact/orientation variability	Yes	
Measuring Range (% vwc)	0 - 45	0 - Saturation	
Comments			
Logging capability		Yes with PC or DataPilot	
Best Soil Type			

Table 1 (continued)

Manufacturer / Sensor Trade Name	Soilmoisture Equip. Corp. / TRASE	Spectrum / TDR 300/200/100	Tektronix 1502
Installation Method / Intrusiveness	Buried in situ or pushed into soil	Pushed into soil.	Buried in situ or pushed into soil
Ruggedness	Waveguides buriable	?	Waveguides buriable
Calibration	Includes universal cal. Customizable		Travel time to moisture content
Capital Cost ($)	QTY 1: 12475 QTY 2: 8550 QTY 3: 8500	TDR 300: 1195 TDR 200: 945.00 TDR 100: 795.00	15000 + PC and software
Output	Nanoseconds calibrated to VWC	VWC	Nanoseconds calibrated to VWC
Accuracy (% vwc)	1	3	1
Precision (% vwc)			
Resolution (% vwc)		1	
Probe length	15 cm – 70 cm	12 cm or 20 cm	Custom
Measurement Volume	~3 cm radius around length of probes (<0.8 L)	3.3 cm spacing by 12 or 20cm	~3 cm radius around length of probes (<0.8 L)
Response Time			
Affected by Salinity	Yes	Yes	Yes
Measuring Range (% vwc)	0 - 50	0 - Saturation	5 - 50
Comments	True TDR cable tester customized for soil moisture		Requires a logger or PC to operate.
Logging capability	Logging available	Yes: TDR 300 (and GPS connectivity)	Yes with PC or logger
Best Soil Type	Not suited to dense, salt or clay soils		Not suited to dense, salt or clay soils

Table 1 (continued)

Manufacturer / Sensor Trade Name	**Campbell Scientific TDR100**	**ESI / Gro-point**	**Streat Instruments / Aquaflex**
Installation Method / Intrusiveness	Buried in situ or pushed into soil	Buried in situ or pushed into soil	Buried in situ or pushed into soil
Ruggedness	Waveguides buriable	Waveguides buriable	Waveguides buriable
Calibration	Universal calibration curves included.	Probes factory calibrated with a stated accuracy of 1%. Cannot custom calibrate.	Several calibration equations may be applied in PC software. May do specific calibration.
Capital Cost ($)	8000	Probe: 351	Sensor: 740 Reader: 530
Output	Nanoseconds calibrated to VWC	VWC	VWC
Accuracy (% vwc)	1	1	2
Precision (% vwc)			
Resolution (% vwc)		9.5 x 3.8 x 24 cm	3 m x 50 mm diam. = 6 liter
Probe length	Variable		300
Measurement Volume	~3 cm radius around length of probes (<0.8 L)	Using in sand to silt soils. Sand up to 3.0 dS/m silt to 1.0 dS/m	Adjusted for salinity and temp
Response Time			
Affected by Salinity	Yes	Yes	Instrument adjusted to conductivity
Measuring Range (% vwc)		8 - 42	0 - 70
Comments		Probe design precludes insertion in disturbed soil.	
Logging capability	Yes with logger	Yes with logger	Yes with logger
Best Soil Type		Not suited to dense, salt or clay soils	All

Table 2. Commercially available dielectric soil moisture sensors: capacitance

Manufacturer / Sensor Trade Name	Campbell Consulting Dielectric Probe	Delta-T / ThetaProbe ML2x	Decagon / ECHO
Installation Method	Pushed into soil	Pushed into soil or buried.	Buried in situ
Ruggedness	Immersible	May be buried, not damaged by frost	Buriable
Calibration	K curve	Two point (linear voltage to SWC relationship) May be done in spreadsheet.	Moisture calibrated to voltage
Capital Cost ($)	180 per probe; 250 per probe with temperature output	995 probe and reader kit, 495 probe only.	Probes: 150; 100 for 5+ units Reader: 375
Output	Dielectric constant, Temp (optional)	Voltage calibrated to % VWC	375 mV – 1000 mV dry soil
Accuracy (% vwc)	2	5 uncalibrated 1 calibrated	3 typical, 1 max
Precision (% vwc)			
Resolution (% vwc)			0.2
Probe length (cm)		6	
Volume (length x diameter)	6 cm x 12 cm	6 cm x 2.65 cm	
Response Time (msec)			10 msec
Affected by Salinity		0.01% up to 2000 mS.m^-1	
Measuring Range (% vwc)	0 - Saturation		0 - Saturation
Comments		Reader: (ThetaMeter) only gives VWC with 5% accuracy, also gives raw voltage	
Logging capability		Em5 5 channel remote data recorder. Em5R is radio capable. Rm1 is radio receiver for Em5R	Yes
Best Soil Type	All	All	All

Table 2 (continued)

Manufacturer / Sensor Trade Name	**GENEQ / Aquaterr 300**	**SDEC / HMS9000 / Microterm Portable Display**	**Sentek / Diviner 2000**
Installation Method	Pushed into soil	Placed into augured hole	PVC access tube
Ruggedness			
Calibration		Linear calibration	
Capital Cost ($)	M-300: 695 T-300: 795 EC-300: 195	Probe: 700 Reader: 565	2159 (does not include access tubes and field kit)
Output	% VWC	VWC (microterm 4800), dielectric permittivity, temperature	
Accuracy (% vwc)	Semi-quantitative	0.10 of water content point	0.5 calibrated
Precision (% vwc)	2		
Resolution (% vwc)		0.1	
Probe length (cm)		2.5	
Volume (length x diameter)	2-3 cm radius sphere	2.5 cm radius sphere	10 cm radius sphere (95% within 4 cm)
Response Time (msec)	3 sec		Two seconds to measure a 1.6 m tube
Affected by Salinity	Unclear	Max conductivity 5 mS/cm	Minimal
Measuring Range (% vwc)	0 - Saturation	0 - Saturation	0 - Saturation
Comments	Displays qualitative moisture content on 0 -100 scale		
Logging capability	No		No
Best Soil Type	All	All	All

Table 2 (continued)

Manufacturer / Sensor Trade Name	**Campbell Scientific / DMM600**	**Vitels / Hydraprobe**
Installation Method	N/A	Pushed into soil
Ruggedness	Very rugged	Buriable, immersible
Calibration	Frequency calibrated to soil moisture content	Not required, though soil-specific calibration may achieve +/-0.005 wfv (water fraction by volume. Calibration of probe not needed, calibration done in software.)
Capital Cost ($)	1200	Probe: 349 Reader+cables+software: 985 Total: 1334
Output	Raw frequency and calibrated moisture content	Complex permittivity, temp, temp corrected complex permittivity, water content, salinity, conductivity, temp corrected soil conductivity, temp corrected soil water conductivity
Accuracy (% vwc)	5	3
Precision (% vwc)		
Resolution (% vwc)	1	
Probe length (cm)	N/A	12.4
Volume (length x diameter)		3 cm x 6 cm
Response Time (msec)	Instant	Immediate
Affected by Salinity	Yes	Operating temp is freezing to 65 C
Measuring Range (% vwc)	0 - Saturation	
Comments	Frequency resolution is 0.1 MHz. Display moisture resolution is 1%	Uses data reduction algorithm. Optional data reader.
Logging capability	No	
Best Soil Type	Fine	All

Table 3. Commercially available nuclear, electromagnetic induction, and microwave moisture sensors

Manufacturer / Sensor Trade Name	**Troxler / Neutron Moisture Meter**	**Nuclear Moisture-Density Gauge**	**Geonics EM-38**
Installation Method / Intrusiveness	Access Tube		Non-intrusive, surface
Ruggedness			?
Calibration	Six factory calibrations		
Capital Cost			10000
Output			
Accuracy (% vwc)	3		Report cited 2% w/ add. Data
Precision (% vwc)	15 sec: 4.90 kg/m3 30 sec: 3.40 kg/m3 1 min: 2.40 kg/m3 4 min: 1.20 kg/m3		
Resolution (% vwc)			
Depth (cm)			1.5m vertical dipole. 0.75m horizontal dipole.
Volume (cm3)			1m x 1.5m x ?
Response Time	15 sec - 240 sec		Instant. At least 3000 points/hr
Affected by Salinity			YES
Measuring Range (% vwc)			N/A
Comments	Cannot log data because NMM may not be left unattended		
Logging capability	No		
Best Soil Type	All		

Table 3 (continued)

Manufacturer / Sensor Trade Name	**MOIST 200 with Surface Probes**	**MOIST BIO**
Installation Method / Intrusiveness	Surface	Single probe penetration
Ruggedness		Designed for low density high organic materials?
Calibration	Material specific calibration possible.	
Capital Cost		
Output		
Accuracy (% vwc)	1 to 2% with material specific calibration	1% achievable in fine granulated bulk goods
Precision (% vwc)		
Resolution (% vwc)		
Depth (cm)	Probe and material specific	Material specific, up to 10 in.
Volume (cm3)	Moist-P probe: 20 to 30 cm. Moist-R probe: 3 to 5 cm.	Active zone: 2 in – 2.5 in.
Response Time	<1 sec	
Affected by Salinity	Sensitive to surface contact and orientation	Temp range of 0C to 70C. Sensitive to material type.
Measuring Range (% vwc)	0% < F < 400% dry basis, material specific.	0% < F < 100% dry basis, material specific. Wider range possible
Comments	Designed for building materials with smooth, flat surfaces	
Logging capability	Yes	Yes
Best Soil Type	Not designed for soil moisture measurements	Designed for bulk goods, food compost, bio-materials, and other customer specific materials.

PRINCIPLES OF OPERATION

In the sections below, the principles of operation of a variety of devices for moisture sensing/measurement are discussed. For each device, a short introduction is provided, the methods and/or theory of operation of the equipment is described, a discussion of the equipment and test procedures is provided, advantages and disadvantages are discussed, and a short conclusion is made. Gravimetric, soil dielectric, nuclear, nuclear magnetic resonance, near infrared spectroscopy, seismic, electromagnetic induction, and thermal methods are discussed.

Gravimetric Methods

Introduction

A moist soil sample is extracted and dried using a heating method such as convection oven, incandescent heating, and microwave heating. The gravimetric moisture content, θ_g, is measured as the loss in mass upon drying compared to the mass of moist soil sample, or the mass of soil water divided by the mass of soil solids.

$$\theta_g = \frac{Mass\,Water}{Mass\,Solids} \qquad (1)$$

Methods

Materials

- Soil sampling/extraction tools
- Air tight containers or bags
- Numbered tins
- Convection oven capable of controlled temperature 100ºC-110ºC
- Balance/scale accurate to 0.05 gm (or to precision corresponding to desired accuracy)

Procedure

1. Extract sample
2. Place in air tight container or bag
3. Weigh numbered tin
4. Weigh tin and moist soil sample

5a. Place tin containing moist soil sample in oven for 24 hours
5b. If using microwave, oven dry to constant weight

6. Weigh tin and dried soil
7. Calculate moisture content, θ_g:

$$\theta_g = \frac{(mass\ of\ moist\ soil + tin) - (mass\ of\ dry\ soil + tin)}{(mass\ of\ dry\ soil)} \qquad (2)$$

Minimum moist soil sample masses for moisture content determination are given in Table 4.

Table 4. Minimum moist soil sample masses for moisture content determination (ASTM Designation D 2216-98)

Maximum particle size (100% passing)	Standard sieve size	Minimum moist soil sample mass for moisture content reported to ±1%
2 mm or less	No. 10	20
4.75 mm	No. 4	50
9.5 mm	3/8 in.	100
19.0 mm	3/4 in.	500
37.5 mm	1 1/2 in.	2,500

Discussion

The gravimetric moisture content of soil determined by oven drying is the most common method of soil moisture measurement. It is also the reference by which all other methods are compared. Gardner (1986) set an upper limit of error of 0.3%. If the volumetric moisture content, θ_{vol}, is desired, the bulk density must be known; the error in bulk density subsequently increases the error in volumetric moisture content.

$$\theta_{vol}=\theta_g \frac{\rho_{bulk}}{\rho_{H_2O}} \tag{3}$$

If the soil contains volatile organic matter, it may burn, leading to a mass reduction not attributable to soil water. Also, the temperature may not be consistent throughout the oven, leading to uneven drying of samples placed in the same oven at the same time.

Advantages

- Very accurate
- Very simple

Disadvantages

- Timely (~24 hours)
- Destructive
- Cannot measure the same soil volume/location over time

Summary / Conclusions

The gravimetric method of soil moisture determination is both highly accurate and simple. Because of its high accuracy it is the method by which all other soil moisture measurements are compared. Even so, inaccuracies due to uncertainty in bulk density, the volatilization of organic matter, and inconsistent drying can cause errors in gravimetric measurements.

Soil Dielectric Methods: Time Domain Reflectometry

Introduction

Time domain reflectometry (TDR) is an electrical measurement technique to determine the spatial location and nature of various objects. Radar is a well known type of TDR; however, in soils TDR is typically restricted to coaxial transmission lines (Andrews 1994). The first use of TDR to measure material properties was done by Fellner-Felldeg (1969), who used it to measure the dielectric constant of various liquid solvents. Davis and Chudobiak (1975) developed a procedure using TDR to measure the relative permittivity of soils. In 1980, Topp et al. (1980) used TDR to measure the permittivity of a wide range of agricultural soils and developed an empirical equation relating TDR measured apparent permittivity to volumetric moisture content. It was this work that lead to the popularization of TDR in soil moisture sensing applications. A later innovation was to use TDR to measure soil conductivity simultaneously with soil moisture (Dalton et al. 1984).

Theory

If the bulk permittivity of a soil mass is known, then the moisture content of that soil can be determined with good accuracy. This is accomplished by exploiting the relatively high dielectric constant of water. The dielectric constant of water is about 81, while that of soil solids is between 4 and 8, and that of air is about 1 (Hillel 1998). Thus, for a three-phase soil mass consisting of solids, water, and air, the permittivity is significantly affected by the volumetric water content (VWC), θ_v.

The permittivity of soil is commonly measured using a technique called time domain reflectometry (TDR). In TDR, a voltage signal is applied to a transmission line 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 by the material permittivity (Figure 1). A comprehensive review of TDR theory and techniques is given by Robinson et al. (2003). The reader is also referred to Ferre and Topp (2002) and O'Connor & Dowding (1999).

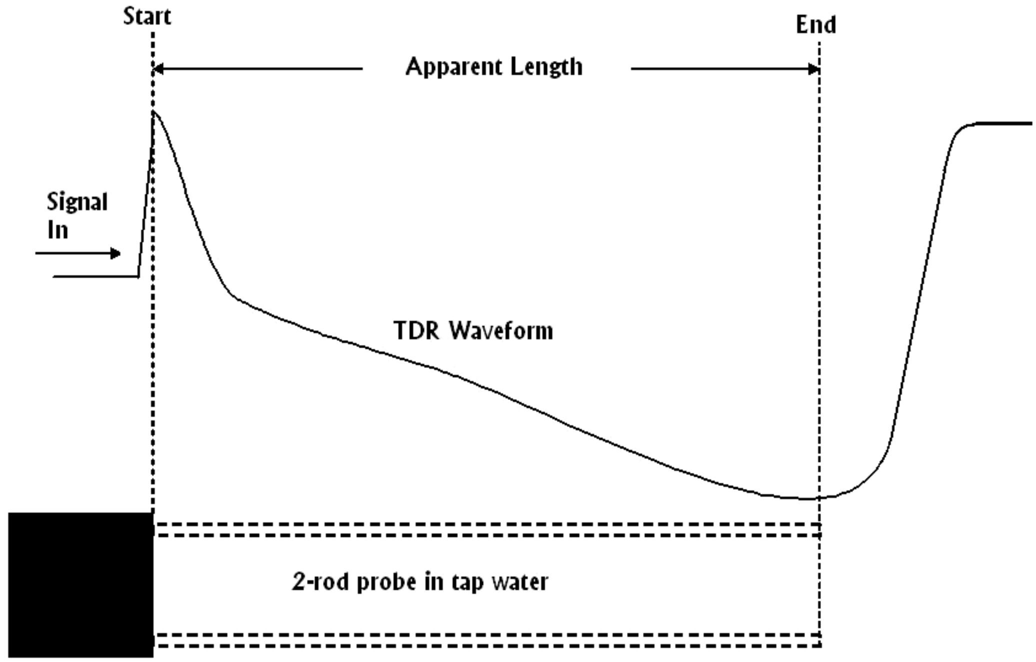

Figure 1. TDR waveform for a two-rod probe immersed in tap water. The apparent length of the rod is determined by the two-way travel time of the input signal, which is dependent on the soil permittivity. Adapted from Bilskie and Ritter (2004)

Literature Review

Kestler et al. (2001) used TDR probes in conjunction with temperature sensors to evaluate when heavy loading could be resumed on low-volume roads following seasonal restrictions. The temperature sensors provided a quantification of the beginning and progression of thaw, while the TDR sensors provided a quantitative determination of drainage. The degree of drainage is then related to the degree of recovery from thaw-weakened conditions.

TRASE TDR probes were used along with Topp's equation as a general calibration for all soil types and conditions. Probes were installed in the base and subgrade of roads at four sites, including Ochoco, Oregon; Kootenai, Montana; and White Mountain, New Hampshire. The probes were placed vertically and horizontally into the soil lifts with best results for probes placed horizontally mid-depth of an uncompacted layer. Readings were taken after construction of every lift.

Laboratory tests were conducted on representative soils from these locations. These soils were non-plastic rexus loam, aggregate, elastic silt, and silty sand with gravel. Accuracy of moisture content measurement and durability from freeze-thaw cycling were evaluated. In this study, the TDR probes provided good agreement with actual moisture contents for all soil types. The probes also proved durable, reliable, and repeatable when subjected to freeze-thaw cycling.

Look et al. (1994) installed two different types of probes in a roadbed during construction. The 500 mm long probes were positioned horizontally in the middle third of each test section in crushed rock pavement over sound subgrades. The probes were located 2.5 m from the road centerline to avoid paver tracks that could damage the probes. Heavy compaction equipment was used to compact the base layer containing the probes.

Ten of the installed probes had an internal cable-probe connection sealed entirely in epoxy; the other ten probes had external connections sealed in heat shrink and silicon. Only four of the latter probes survived the construction process, and after a three-year period, only two were still operational. The epoxy-sealed probes all survived the construction process and all were still operational after three years.

During construction, the TDR probes volumetric moisture content was compared to nuclear density moisture gauge with good agreement. The TDR probes used Topp's equation to calculate the volumetric moisture content. The TDR moisture values were well within three standard deviations of the average nuclear density gauge readings over moisture contents of 10% to 20%. This accuracy was deemed acceptable for engineering applications where ease of monitoring and change of moisture content are most important. This study resulted in over 100 hundred TDR probes being installed in expansive clay embankments to monitor moisture changes responsible for movements and distress in pavement surfaces.

Rada et al. (1994) describes the installation of TDR probes at 64 pavement test sections throughout North America. The objective of the study was to measure the magnitude of changes in moisture in pavement structures and to gain better understanding in the effects of moisture variation on long-term pavement performance. The study is part of the Seasonal Monitoring Program (SMP) undertaken by the Federal Highway Administration's (FHWA's) Long-Term Pavement Performance (LTPP) studies.

TDR was the method of choice for moisture sensing because it provided the most reasonable and reliable moisture content measurements of the techniques evaluated. It was found that a flat three-pronged probe provided the best signal strength and quality. The equipment used to take measurement data was a Tektronix 1502B cable tester, multiplexers, a data logger, additional cables, a power supply, and a laptop computer.

The TDR probe installation configuration and procedure is given in detail by Look et al. (1994). Briefly, ten TDR probes are placed horizontally into a 250 mm (10 inch) diameter borehole every 152 mm, except for the final two probes that are placed at 305 mm intervals. The original soil is placed over the top of every probe and compacted. The borehole is located in the outer wheel path at least 1.2 m away from joints and/or cracks.

Initial results indicated that use of Topp's equation for moisture content determination yielded differences from gravimetric measurements of up to 10%. From these results, it was decided that material specific calibrations should be constructed for each test site.

Types of TDR Sensors

One of the first uses of TDR in soil moisture applications used a Tektronix 1502 TDR cable tester designed for network analysis. It consists of a pulse generator, sampler, and oscilloscope. A computer and relevant software are necessary to capture and analyze the waveform, as well as to control and monitor an array of probes. The TRASE TDR by Soilmoisture Equipment Corporation is a newer version of the Tektronix-based system. The TRASE system incorporates all the hardware and software necessary for soil moisture analysis in a single unit. Campbell Scientific also manufactures a TDR processor built specifically for soil moisture applications. All of these TDR systems have the advantage of high accuracy and easy expansion via multiplexing. Due to their high cost, they are best suited towards long-term monitoring of a large array of in situ probes or when capture of the TDR waveform is desired as in research applications.

Less costly TDR sensors do not allow analysis of the TDR waveform by the end user. Pulse generation, sampling, and calculation of the transit time are user-independent processes. The output is a transit time and/or a moisture content value based upon a manufacturers calibration or a user-specified, material-specific calibration. The IMKO TRIME-EZ incorporates the waveguides and TDR circuitry into a single unit which may be buried in situ for monitoring applications or used as a hand-held meter for taking manual readings at multiple sites. Such a probe requires a PC or meter available from the manufacturer to read the probe output.

The Campbell Scientific CS616 is a water content *reflectometer*. This is actually a variation of the TDR method but is usually labeled a TDR type instrument anyway. This type of sensor does not capture and analyze the waveform, but the reflected signal triggers a new pulse. The period of the pulses can then be directly related to water content.

For further information refer to the soil moisture sensor matrix, Table 1.

Installation/Configurations

TDR probes (used synonymously with *waveguides*) may be buried in situ for long-term monitoring applications or inserted manually for taking readings at multiple sites. A simple waveguide can be constructed from stainless steel rods and attached to the TDR unit via a coaxial cable. This is the case for the Tektronix, TRASE, and Campbell Scientific systems. Waveguides may be purchased inexpensively or constructed. The low cost of such waveguides makes these systems ideal for monitoring a large area or volume of soil via a multiple waveguide multiplexing configuration. A TDR system of this type is represented schematically in Figure 2.

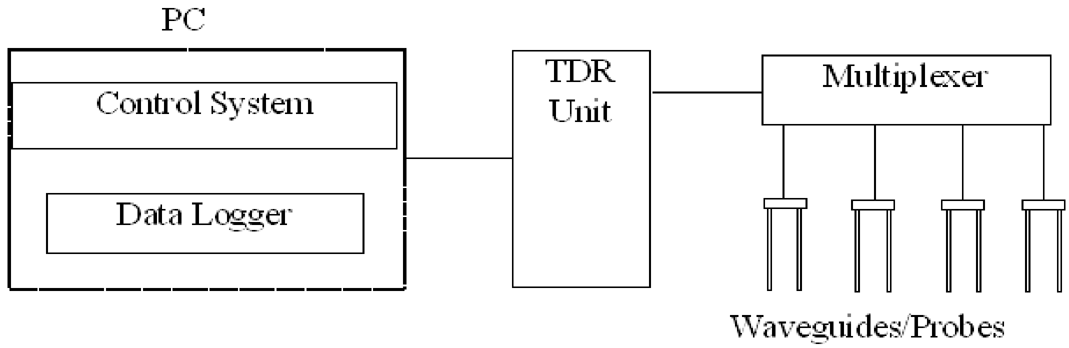

Figure 2. TDR system consisting of four constituent parts: control system, data logger, TDR unit, and waveguides. A PC is often used to control the TDR unit and serve as data logger.

A system incorporating the TDR circuitry and waveguides into a single unit is not suitable for large sensor arrays as the cost would quickly exceed that of a multiplexed system. An instrument such as the IMKO TRIME-EZ (Figure 3) is suitable for short term, in situ, monitoring and manual spot-checking.

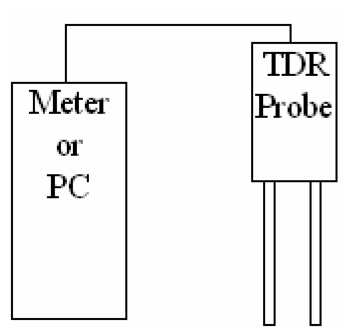

Figure 3. TDR system incorporating the TDR circuitry and waveguides into a single unit. The TDR output is read by a hand-held meter or PC.

Probe Considerations

In theory, probe length does not affect accuracy; in practice, substantial error in moisture determination may be introduced using probes less than 0.1 m (Noborio 2001). Topp et al. (1984) give a standard deviation +/- 3.7% m^3 m^{-3} using a probe length of 0.05 m and recommends probes lengths greater than 0.1 m to achieve a standard deviation of +/- 2% m^3 m^{-3}. Furthermore, as probe length increases, the sample volume increases; however, conductive and polarization losses also tend to increase resulting in an inverse relationship between probe length and measurement error (Ferré and Topp 1999).

Probe configuration is typically two or three wire probes with the three wire probes giving better signal definition. Three wire probes are preferred for saline soils and soils with several layers of high moisture variation. However, the reflections from the beginning of the probe in dry and wet soils are very different, making automated waveform interpretation difficult (Noborio 2001).

The spacing and diameter of the probe rods significantly affects the impedance of the probe. Noborio (2001) reports that increased wire spacing increased attenuation of the high-frequency content of the TDR signal. The ratio of wire diameter, *d*, to wire spacing, *s*, in two- and three-wire probes can be correlated to the concentration of energy surrounding the probe wires. As the ratio of d/s decreases, the concentration of energy immediately surrounding the wires increases, increasing sensitivity to local non-uniformities and air gaps. It is suggested that TDR probes be constructed using a $d/s > 0.1$ to reduce errors in moisture determination.

Air gaps between the rods and soil can significantly affect moisture content determination (Annan 1997), and care should be taken to insert the probe without introducing air gaps. Air gaps may also develop when an initially moist soil dries after insertion of the waveguides (Charlesworth 2000). Pilot holes are often used to aid probe insertion in stiff soil. Topp et al. (1982) reported no significant affects due to pilot holes, though Roth et al. (1997) reported higher moisture content using pilot holes due to a 5%-20% increase in soil bulk density immediately surrounding the probes.

Data Management

Most TDR systems require a PC for data logging and/or control of the TDR unit. The Tektronix 1502 requires a PC to control operation, store data, and process the TDR waveform. Several software programs (O'Connor and Dowding 1999) have been developed for the Tektronix 1502. *WinTDR*, developed by Utah State University, is available free of charge (Utah State University). TDR systems developed specifically for soil applications will often have custom software applications for data processing, logging, calibration, etc. The Tektronix 1502 is notable because it has become a standard in laboratory research; unfortunately, it is aged technology and is no longer manufactured by Tektronix.

Environmental Considerations (weather, freezing)

The dielectric constant of free water is around 80, while the dielectric constant of ice is about 3. Because soil moisture is determined by correlating the bulk soil dielectric constant with moisture constant, freezing is an obvious concern.

Probe-cable connections should be sealed against moisture. Epoxy is a common sealant for in situ applications.

Factors Affecting Time Domain Reflectometry

Conductivity

Bulk soil conductivity is the sum of particle conductivity (relatively small), bulk fluid conductivity, and surface conduction. In soils, conduction is primarily due to electrolytes in the soil solution and occurs within the contiguous pore spaces of the soil. Thus, porosity, saturation, and the conductivity of the electrolyte determine the bulk conductivity in low specific surface soils. In high specific surface soils, conduction due to local ion movement in the Stern layer (a thin layer of adsorbed cations fixed immediately adjacent to surface of a particle) will become significant at higher frequencies (Santamarina et al. 2001).

Increased conductivity can result in an increase in the TDR measured apparent dielectric constant, resulting in an overestimation of moisture content. Furthermore, as the conductivity increases, the signal reflection becomes less discernible and automated waveform analysis may not be able to distinguish the reflection (O'Connor and Dowding 1999).

Rods coated in plastic have been shown to reduce sensitivity to conductivity. However, as opposed to uncoated rods, coated rods incorrectly measure the weighted average of the soil moisture profile along the length of the rods. Also, the sampling area of the coated probes decreases rapidly with increasing water content (Ferré and Topp 1999).

Soil Texture

Coarse soils such as sand and gravel can pose a problem. Generally, calibration models for soils of similar texture perform similarly (Ponizovsky et al. 1999). Because bound water exhibits different dielectric constants than free water, the amount of clay in a soil tends to decrease the bulk dielectric constant. Ponizovsky et al. (1999) show that for a range of soils with different textures, no single model is adequate. Rather, a model with empirically based fitting parameters is needed to fit soils of varying texture.

Bulk Soil Density

Increased bulk density may cause an increase in apparent permittivity due to increased specific surface area around the waveguide rods.

Temperature

Whether temperature has a significant effect on TDR measurements is a function of the soil type and water content, and there is little agreement among researchers (O'Connor and Dowding 1999). The range of temperature, soil specific temperature sensitivity of the bulk dielectric constant, and desired accuracy must be taken into consideration by the individual user.

Water Content

Water content will affect the fluid ionic concentration, which in turn affects the conductivity of the soil. Furthermore, soil water that is bound to soil particles does not respond as readily as free water and exhibits relaxation over a large range of frequencies. If a large portion of the soil moisture is in a bound state, the moisture content will be underestimated; this is especially a concern in soils with clay minerals (O'Connor and Dowding1999).

Accuracy

Stated accuracies from a variety of instrument manufacturers for generic calibrations range from +/- 0.5% to +/- 3% of volumetric water content. Higher accuracies are achievable using soil-specific calibrations and high-end, more expensive TDR units (e.g., the Soilmoisture Equipment Corporation TRASE instrument). Accuracies of +/- 3% are easily achievable for a fairly wide range of soils with the less expensive, self-contained systems using the manufacturer provided calibration. For further information, refer to soil moisture sensor matrix, Table 1. It is important to note that clay content and salinity can lead to lower than expected accuracies, and the authors recommend verification of the manufacturer's stated accuracy per application.

Calibration

The most common and broadly applied calibration equation is Topp's equation (Topp et al. 1980):

$$\theta_v = 4.3 * 10^{-6} \epsilon_a^3 - 5.5 * 10^{-4} \epsilon_a^2 + 2.92 * 10^{-2} \epsilon_a - 5.3 * 10^{-2} \tag{4}$$

where ε_a is the apparent bulk permittivity of the soil and θ_v is the volumetric water content.

Topp's equation makes no assumptions about the state of water in the soil and is not reliable below volumetric water contents of 5% m^3m^{-3} (Gregory et al. 1995). Topp's equation underestimates moisture content in organic soils and vermiculite (Noborio 2001) and overestimates moisture content in glass beads and swelling and non-swelling clays (Topp et al. 1980). It may also overestimate moisture content in soils moistened with saline water (Noborio 2001).

A theoretical approach to calibration is to use dielectric mixing models that account for the individual contribution of each soil component's dielectric constant. These models have been used successfully but require prior knowledge of soil properties, such as constituent permittivities, bulk density, geometric correction factor, etc. (O'Connor and Dowding 1999). Jacobsen and Schjønning (1995) suggest using Topp's equation when an accuracy of +/-2%–3% m^3m^{-3} is acceptable.

For commercially available TDR moisture sensors, the instrument manufacturer provides a generic calibration to a stated accuracy. The manufacturer's calibration should first be evaluated, and, if increased accuracy is desired, a soil-specific empirical calibration should be constructed using oven-dried samples (Benson and Bosscher 1999). Because TDR instruments provide volumetric moisture content and oven drying results in gravimetric moisture content, conversions must be made prior to calibration (Topp and Ferré 2002):

$$\theta_v = \frac{\theta_g * \rho_{soil}}{\rho_{water}} \tag{5}$$

where θ_v is volumetric water content, θ_g is gravimetric water content, ρ_{soil} is the density of the dry soil mass, and ρ_{water} is the water density often approximated as 1 and ignored.

Disadvantages

- Relatively expensive
- Small measuring volume
- Attenuation in highly conductive soils may lead to inaccuracies or failure

Advantages

- Precise
- Accurate
- Versatile packaging: from portable, self-contained units to modular systems capable of monitoring several probes and logging data

Summary / Conclusions

Time domain reflectometry has good potential as an alternative means of moisture measurement. The biggest drawback is the high sensitivity to installation and the small measurement volume, which inevitably leads to a higher variance than a method which measures over a larger volume, such as a nuclear moisture-density gauge or ground penetrating radar.

The installation does require pushing the probes into the ground for spot checks; though, long term in situ measurements are easily accomplished over a wide area and depth profile. The effort of pushing the rods into the ground is variable depending on soil stiffness. A template may be used to make insertion easier; though, this takes more time and can cause increased soil disturbance.

Soil Dielectric Methods: Ground Penetrating Radar

Introduction

Ground penetrating radar (GPR) is a promising technique for soil moisture sensing. The velocity of electromagnetic (EM) wave propagation in soils is principally dependent upon the bulk permittivity of the soil. Thus, soil permittivity may be determined by the velocity of GPR EM wave velocities. The relative real permittivity or dielectric constant of water is about 80, while the dielectric constants of soil minerals are about 1-5, and that of air is 1 (Hillel 1998). Due to the relatively high dielectric constant of water relative to other soil constituents, soil moisture may then be empirically related to the EM wave velocity. The underlying principles of GPR soil moisture measurement are identical to those of time domain reflectometry (TDR), with the exception that EM waves are propagated along a waveguide (the parallel rods of a TDR probe), whereas GPR propagated EM waves are unbounded and have the potential to cover a much larger soil volume. Also, GPR can be completely non-invasive, whereas TDR requires penetration of the waveguides into the soil.

Methods

<u>Modes of Measurement</u>

There are five modes of measurement for determination of soil moisture content by GPR (Davis and Annan 2002):

1. Air launched surface reflection
2. Surface launched subsurface reflection and scattering
3. Surface launched multi-offset subsurface reflection
4. Surface launched direct wave arrivals
5. Borehole transillumination
6. Bulk sample lab transillumination

Air Launched Surface Reflection

In this method, a receiver and transmitter are located above the soil-air interface and measure the reflection coefficient from the air-soil boundary. The reflection coefficient is mainly dependent upon the permittivity of the soil which can then be related to moisture content.

This method is highly sensitive to non-uniform field conditions, such as surface roughness and the distribution of water content with depth. As such, it has not seen widespread use.

Surface Launched Subsurface Reflection and Scattering

Both transmitter and receiver are placed directly on the ground and reflections from subsurface reflectors are recorded. This method requires a priori knowledge of the depth to the subsurface reflector. The subsurface reflector may be artificial targets, such as drain tile or conduits or metal plates placed specifically for GPR measurements. Alternatively, a well-defined soil boundary may be used if a sufficient impedance difference between the soil layers exists. Such a boundary may be found in earthwork projects where soil is deposited in layers. The local water table is also a very strong reflector.

Surface Launched Multi-Offset Subsurface Reflection

This method is similar to the previous method, except that multiple offsets between the antennas are used. This method does not require knowledge of the depth to subsurface reflectors, but only that sufficient ground stratigraphy is present. This method has been used on large-scale surveys using multiple antennas with accuracies of 5%–10% of the volumetric water content (VWC). However, multiple channel GPR units are costly and, for small-scale surveys, using a single channel instrument would be too timely for practical use. Both depth to a reflector and water content can be measured with this method.

Surface Launched Direct Wave Arrivals

This is the most common mode of measurement, and it will be treated with greater attention than the other methods.

A receiver and antenna are placed on the ground surface, and the arrivals of both air waves and direct ground waves are detected. The airwave travels at the speed of light and will always precede the direct ground wave. The airwave is then used to provide a reference time for determining the speed of the direct ground wave at a fixed antenna separation (Grote et al. 2003):

$$\textit{(Ground wave travel time) = (Arrival time of ground wave) – (Arrival time of airwave)} \quad (6)$$

and

$$\textit{Velocity = (Ground wave travel time) / (Antenna separation distance)} \quad (7)$$

Once the ground wave velocity is known, the bulk soil permittivity, *K*, may be estimated (Davis and Annan 1989):

$$K \approx \left(\frac{c}{v}\right)^2 \quad (8)$$

where *c* is the velocity of EM propagation in free space, and *v* is the velocity in the soil.

The effective depth that the EM ground wave penetrates may be theoretically approximated by the following formula (Grote et al. 2003):

$$z = \frac{1}{2}\sqrt{\frac{vS}{f}} \quad (9)$$

where *z* is the depth of influence, *v* is the EM wave velocity in soil, *S* is the antenna separation distance, and *f* is the frequency.

In practice, the depth of influence is primarily within the 0 – 10 cm layer of the soil (Grote et al. 2003; Huisman et al. 2001; Chanzy et al. 1996). It is notable that TDR measurements using a 10 cm long probe yields permittivities similar to those measured by GPR, suggesting a correspondence between the depth of GPR and TDR zones of influence (Huisman et al. 2001).

A common physical realization of this method is to place a transmitter and receiver in close proximity upon a sled and pull the sled across the ground.

Borehole Transillumination

In this method, either the transmitter or receiver, or both, are placed beneath the soil surface through either a vertical or horizontal borehole. The distance between antennas is then known and velocity measurements, as well as the subsequent soil moisture estimations, can be made.

The advantage of this method is that it works well and can be used to map water content with depth over the soil profile. However, it is not well-suited to large area surveys and does require the drilling of a borehole(s).

Bulk Sample Lab Transillumination

This is the same as the previous method, except that an extracted field sample is used and the data is taken in a laboratory. This method may be useful for interpretation of field data or calibration.

Discussion

<u>Calibration</u>

The choice of calibration is principally dependent upon the desired accuracy of moisture measurement. In some cases, a universal calibration, such as Topp's equation (Topp et al. 1980), may be used with acceptable accuracy. If high accuracy is desired, unique calibrations should be made for each particular soil and/or GPR instrument. The semi-theoretical model proposed by Herkelrath (1991) is commonly used in GPR moisture sensing:

$$\theta_v = b_2 \sqrt{K} + b_1 \tag{10}$$

where b_2 and b_1 are material-specific calibration coefficients.

Because both GPR and TDR measure bulk soil permittivity as a function of EM wave propagation velocity, it has been suggested (Huisman et al. 2001, 2002; Grote et al. 2003) that calibrations developed for determination of volumetric water content by TDR can be directly applied to GPR techniques. A practical approach to calibration would be to use TDR in a laboratory to determine the calibration equation from field samples and then apply the calibration directly to GPR determined permittivity measurements.

Instrumentation

Geophysical Survey Systems Incorporated
North Salem, NH, USA
Internet: www.geophysical.com

Malå Geoscience
Malå, Sweden
Internet: www.malags.com

Sensors & Software Inc.
Mississauga, ON, Canada
Internet: www.sensoft.on.ca

Field Studies

Grote et al. (2002) performed a study on pavement sections using reflected waves. Any subsurface reflector may be used to determine a travel time which can be used to determine the soil velocity as long as the length of the travel path is known. In the case of soil interfaces, the reflector construction records or borehole surveys can provide depth information. Exploiting a priori knowledge of the depth to the aggregate sublayers in several pavement sections, Grote et al. were able to determine accurate soil velocities. The principal source of error in moisture determination was uncertainty in the thickness of the aggregate layers.

Grote et al. (2003) used GPR ground wave techniques at 900 MHz and 450 MHz in a California vineyard. GPR determined moisture content was compared to gravimetric and TDR measurements. The soil texture ranged from sandy loam to clay loam. The volumetric water content root mean square error (RMSE) of GPR at 900 MHz was 0.011, while the RMSE at 450 MHz was 0.017, compared to gravimetric methods. Comparison between GPR and TDR estimated dielectric constant produced similar results. At low-moisture contents, the GPR dielectric constants were greater than the TDR estimates, and it was recommended that moisture-permittivity calibrations based on TDR measurements be used with caution in dry soils.

Huisman et al. (2001) evaluated GPR and TDR measurements in 25 locations with soil texture classes of loamy sand, loam, silt loam, and sandy. A pulseEKKO 1000 GPR system was used at center frequencies of 225 MHz and 450 MHz, using both wide-angle reflection and refraction (WARR) and single trace analysis (STA) techniques. Calibration equations between aggregated soil water content and refractive index were evaluated for accuracy based upon root mean square error. The accuracy of aggregated TDR measurements was +/- 0.030 m^3 m^{-3} VWC, with calibration being the principal source of error. Calibration equations based on WARR were similar to TDR calibration equations, with the WARR measurements yielding an accuracy of +/- 0.030 m^3 m^{-3} VWC. A likely source of error in WARR measurements was uncertainty in velocity measurements. STA measurements yielded an accuracy of +/- 0.037 m^3 m^{-3} VWC, with the increase in error between WARR and STA likely due to increased error in velocity determination. These data support the applicability of TDR calibrations to GPR permittivity measurements in light-textured soils.

Advantages

- Rapid
- Non-invasive
- Very high spatial data density
- Principles of operation almost identical to TDR

Disadvantages

- Not well established—little work has been done to develop this method
- Depth of measurement varies with soil type and moisture leading to uncertainty in zone of influence or measurement volume
- Relatively expensive

Summary / Conclusions

GPR is a promising technique for large rapid, large-scale soil moisture surveying. Currently, not much development has occurred in this method of soil moisture sensing; though, its similarity to TDR lends a strong foundation for its rapid development. Furthermore, TDR and GPR are highly complimentary in that TDR is sensitive to small-scale spatial moisture variance that GPR averages out. As with neutron moisture meters, the larger measurement volume of GPR necessarily reduces moisture variance and should lead to higher precision and accuracy than TDR.

Soil Dielectric Methods: Capacitance

Introduction

Capacitance sensors base moisture measurements upon an indirect measurement of the soil bulk permittivity from the resonant frequency of an inductance-capacitance tuned circuit, in which soil forms a dielectric material between the two "plates" of a capacitor.

Capacitance probes provide fast measurement times, low cost, and are available in several probe geometries allowing in situ, surface, and access-tube measurements.

Theory

Capacitive sensors measure the resonant frequency of an inductance-capacitance (LC) tuned circuit, in which soil is the dielectric material determining the capacitance. If the inductance is kept constant, the resonant frequency of the circuit is then a function of the capacitance, as shown in equation (11):

$$frequency = (2\pi\sqrt{LC})^{-1} \qquad (11)$$

where L is the inductance and C is the capacitance. The relative bulk dielectric constant of the soil may then be used to empirically determine the moisture content of the soil.

An alternative type of capacitance sensor may output a signal (e.g., voltage) proportional to the amount of charge contained upon the capacitor "plates," where the amount of charge is directly related to the permittivity of the soil. The ECH_2O probe (Decagon Devices, Inc., Pullman, WA) is one such probe.

Literature Review

Typical methods of soil moisture sensing using capacitive methods involve in situ applications in which the sensor consists of two or more probes inserted into the soil. A common application is irrigation scheduling (Starr and Paltineanu 2002). Reviews of the development of capacitance methods are given by Paltineanu and Starr (1997) and Robinson et al. (1998). An overview of current methods, instrumentation, and procedures is given by Starr and Paltineanu (2002).

As with all dielectric moisture sensors, calibration is necessary for accurate determination of moisture content. Typically, one of three methods of calibration is used. One method directly correlates the raw frequency output to the volumetric or gravimetric (dependent upon bulk density) moisture contents. A second method uses a normalization technique in which reference frequencies from air and water are obtained, and a scaled frequency (SF) is calculated according to the following formula:

$$SF = \frac{(F_a - F_s)}{(F_a - F_w)} \tag{12}$$

where F_a, F_s, and F_w are the measured frequencies in air, soil, and water, respectively. This scaled frequency may then be calibrated to soil water content (Paltineanu and Starr 1997). A third method first converts the frequency to relative permittivity by calibrating to solutions of known dielectric constant and then calibrates relative permittivity to soil moisture content (Robinson et al. 1998). The advantage of this method is that it allows the use of general calibration equations, such as Topp's Equation (Topp et al. 1980), and more complex dielectric mixing models. It also allows comparison between published calibration standards.

The principal factors affecting the accuracy of capacitance probes are calibration, probe installation (soil to probe contact), and temperature. Adequate calibration is highly dependent upon accurate measurement of the soil bulk density and gravimetric moisture content in the instruments primary zone of influence (Starr and Paltineanu 2002).

The zone of influence for rod type sensors is integrated along the length of the probe and is highly concentrated between the rods. The field strength beyond the rods dissipates very quickly, and media variations a few centimeters beyond the rods are negligible (Starr and Paltineanu 2002; Bolvin et al. 2004). For a probe using a pair of cylindrical metal rings and inserted into a PVC access pipe (Starr and Paltineanu 2002), the zone of influence of the fringe field is within 10 cm of the access pipe and about 10 cm along the pipe. Flat waveguide geometries, as used by the Campbell Scientific, Inc. Duff Moisture Meter (DMM600) and Decagon Devices, Inc. ECH_2O Dielectric Aquameter, produce a fringe field around the sensor plate. The zone of influence of the ECH_2O is reported by the manufacturer as two cm averaged along the length of the probe. The zone of influence of the DMM600 is not available in the literature.

Advantages

- Relatively inexpensive
- Flat waveguide configuration may hold promise for non-intrusive measurements
- Fast response time

Disadvantages

- Small measurement volume sensitive to small-scale soil variations
- Unlike TDR, probes and circuitry are integral, making large arrays of sensors potentially expensive
- Sensitivity to installation similar to TDR (e.g., poor probe-soil contact)

Summary / Conclusions

Capacitance devices are similar to TDR devices in that they often involve pushing a probe into the ground and measuring the permittivity of the surrounding soil. Unlike TDR, many capacitance probes for soil moisture sensing are capable of non-intrusive measurements—either by pressing the probe against the soil surface (Campbell Scientific, Inc. DMM600) or lowering it into an access pipe (Sentek Diviner 2000).

Capacitance probes possess simpler circuitry and cost less than TDR probes. They are also faster, performing measurements almost instantaneously. Effects of installation and small measurement volume are similar for both capacitance probes and TDR probes.

Nuclear Methods: Neutron Moderation

Introduction

The information summarized in this section is based upon Hignett and Evett (2002). Neutron moisture meters (NMM) use the principle of neutron thermalization or neutron moderation as a means of soil moisture determination. NMM are most commonly used in agricultural applications where continuous monitoring of the soil is used for irrigation scheduling. A profiling NMM consists of a source/detector probe, lowered by a cable into an access tube from a housing that shields the source during transportation, and contains the instrument circuitry. A surface NMM is noninvasive and is simply placed upon the soil surface. The precision of the surface NMM is less than that of the profiling NMM because of surface non-uniformities. The surface NMM is commonly used in engineering practice and may be referred to as the nuclear moisture-density gauge. This instrument is used to measure both soil moisture and density. Density is measured by lowering a gamma ray source into a pre-driven hole (direct transmission method) or by using a surface backscatter method and measuring the gamma ray attenuation due to the soil particles (see section gamma ray attenuation).

Theory

A neutron source emits fast neutrons which are approximately the same size as the nucleus of a hydrogen atom. When a neutron collides with a hydrogen atom, it is either slowed or absorbed. The amount of hydrogen in the soil can then be statistically related to the number of neutrons stopped by hydrogen atoms. That is, the number of neutrons that reach the detector in a soil compared to the number of neutrons that reach the detector in a reference material is indicative of the volumetric moisture content of that soil.

Methods

Profiling NMM Materials

- Access tube
- Neutron moisture meter

- Tools needed to install access tube (e.g., auger)

Profiling NMM Procedure

An access tube must be installed in the desired location(s) of measurement. There are four standard methods for doing this:

1. Ramming: The capped tube is pressed into the soil by force.
2. Sample and ream: An undersized hole is dug and the tube pushed into the hole. An auger is used to extract excess soil from inside the tube.
3. Center tube withdrawal: The tube is alternately pushed into the soil and augured from inside the tube to remove excess soil.
4. Slurry Method: An oversized hole is dug and a slurry of local soil and binder is poured into the hole. The capped tube is then pushed into the hole such that the slurry fills the excess space around the tube.

The NMM must be calibrated to achieve accurate results. If the soil is uniform to a sufficient depth, a laboratory calibration is possible; though, it is more common to do a field calibration. The field calibration should be taken over a wide range of moisture contents in the same soil horizon. The calibration may be derived from multiple access tube installations. If measurements are to be taken near the surface (< 0.3 m), a separate calibration must be made to compensate for neutrons lost to the atmosphere. If a soil has variable clay content (non-water hydrogen) over the depth of measurement or over the horizontal range of measurements, it must be compensated for. For a uniform soil the calibration equation is the following:

$$\theta_v = b_0 + b_1 C_R \tag{13}$$

where C_R is the count ratio defined as

$$C_R = \frac{x}{x_s} \tag{14}$$

where x is the count made in soil compared to a count, x_s, in a standard material. Detailed calibration procedures are given in Hignett and Evett (2002).

Moisture measurements are taken by lowering the probe into the access tube to a particular depth and taking a neutron count. Several measurements may be taken over the soil depth. The minimum time per measurement is about 15 seconds, with higher accuracy obtainable with longer measurement times. Taking measurements can become a timely process if several measurements are to be obtained for each access tube. Unfortunately, measurements cannot be automated because regulations do not allow an NMM to be left unattended, as it is a radioactive hazard.

Surface NMM Materials

- Surface NMM or Nuclear moisture-density gauge (engineering)
- Shovel or similar tool to create a smooth, flat surface for gauge placement
- Standard calibration block (gauge specific)

Surface NMM Procedure

1. Calibrate the gauge according to the manufacturer's instructions
2. Prepare a reasonably smooth, level footprint on the soil surface to accommodate the base of the gauge
3. Place gauge on prepared surface and correct for any large voids between the soil surface and base of the gauge
4. Perform a moisture measurement following the manufacturers instructions
5. Repeat 1 to 2 times and average the results

Unlike the profiling NMM, calibration of a nuclear-density gauge is typically performed using a gauge specific calibration block provided by the manufacturer. This is a two-point calibration using Aluminum or Magnesium for zero moisture and combinations of Aluminum or Magnesium and high density polyethylene for high moisture.

Measurements usually take a minimum of 15 seconds, with greater accuracy achievable for longer measurement times. Unlike the profiling NMM, the surface NMM is calibrated only for operation at the soil surface.

Discussion

The soil volume measured by the profiling NMM varies with moisture content and density as shown in Figure 4. In a wet clay soil, the sphere of influence has a radius of about 0.15 m; though, a radius of 0.5 m may be achieved in a dry soil (~2% m^3m^{-3}). Variation in soil density can cause errors of up to 15%. Furthermore, the large sphere of influence makes variations in moisture content within the measurement volume indistinguishable. Contrariwise, this large measurement volume is what makes the NMM so much more accurate than electronic (TDR, capacitance) and gravimetric methods (Hignet and Evett 2002).

The surface NMM (Figure 5) measures a hemispherical volume about 100 to 300 mm (4 to 12 in) in radius (Humboldt 2004; Hignet and Evett 2002). The effect of air voids between the base of the gauge and the soil surface will result in variability and care should be taken to achieve consistently smooth sites for every measurement. The effect of soil density and moisture content on measurement volume will be similar to that of the profiling NMM. High variability of moisture content in the near surface, uncertainty of measurement depth, and a strong dependency upon calibration coefficients can lead to high uncertainty in moisture measurement accuracy (Hignet and Evett 2002).

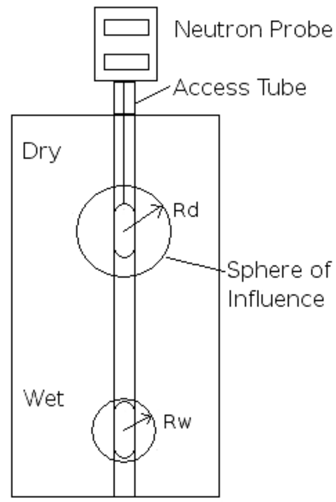

Figure 4. Profiling NMM and effect of moisture on measurement sphere of influence. The dry soil allows a larger sphere of influence (radius, Rd) than the wet soil (radius, Rw). Adapted from Charlesworth (2000)

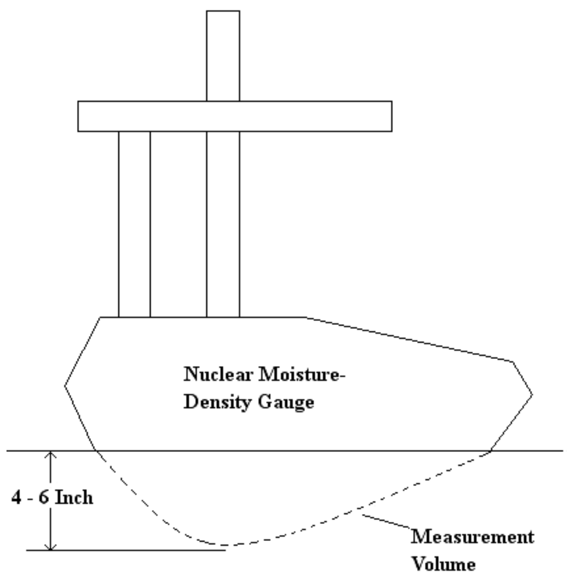

Figure 5. Surface NMM or nuclear moisture-density gauge; dashed line indicates typical measurement volume of radius 100–200 mm (4–8 in).

Hydrogen in soil water is not the only neutron absorber in soil. Hydrogen and carbon in organic matter and clays will affect the NMM calibration if it is distributed non-uniformly throughout the measurement volume (local or global). Other absorbers of neutrons include B, Cd, Cl, Fe, F, Li, and K. Loss of neutrons to the atmosphere is also a concern at depths less than 0.3 m for the profiling NMM.

The access tube used with the profiling NMM may be metal or plastic. The tube material should be chosen to achieve the desired results at a reasonable cost. The hydrogen and carbon in plastic materials increases the NMM count and may have inconsistent wall thickness and inconsistent material properties. Aluminum has little affect on neutron count but is expensive and will corrode in saline or alkaline soils. Mild steel is inexpensive and durable, but it will absorb neutrons; however, this only reduces the sensitivity, not the accuracy of the NMM. Stainless steel is more durable but is also considerably more expensive.

Installation of the access tube must minimize the air gap surrounding the tube while minimizing disturbance of the nearby soil. The presence of an air gap would influence the NMM count and could fill with water, causing uncharacteristically wet soil in the vicinity of the access tube.

Moisture content can vary throughout a site, especially if a large area is considered. To reduce variation, an adequate number of access tubes must be installed and calibrations must be representative for the local measurement locations.

Table 5 provides a summary of the factors that can affect the NMM count and, subsequently, its accuracy. Vertical heterogeneity of bulk density and clay content is a particular problem. Swelling clays can lead to differential movement between the access tube and soil, as well as to large variations in density.

Table 5. Factors affecting profiling NMM neutron count and corresponding explanations

Factor	**Effect on NMM Count**	**Explanation**
Increased moisture	Increases	Increased hydrogen content.
Variable bulk density	Varies with variability of factor	Increased bulk density increases the amount of material available to thermalize neutrons.
Presence of non-water neutron absorbing atoms	Increases	B, Cd, Cl, Fe, Li, and K all aid in thermalization of neutrons.
Access tube material	Increases	Plastic and steel materials thermalize neutrons. Al has minimal influence.
Variable organic matter content	Varies with variability of factor	Non-water carbon and hydrogen thermalize neutrons.
Variable clay content	Varies with variability of factor	Non-water hydrogen thermalizes neutrons
Atmosphere-soil interface	Varies with variability of factor	Near surface measurements lose neutrons to the atmosphere.
Decay of source	Decreases	Less neutrons are emitted. Standard count should be recalibrated every 8 months.

Advantages

- Large measurement volume produces high precision
- Nondestructive access tube has been installed (profiling NMM)
- Works well in stony soils and expansive clays
- Very accurate
- Air gaps and soil disturbance during access tube installation has minimal effects (profiling NMM)
- Can take measurements at greater depths than other instruments (profiling NMM)

Disadvantages

- Costly
- Cannot be automated because radioactive source may not be left unattended
- Involves cost of regulation and licensing of a radioactive source
- Large sphere of influence makes near surface measurements difficult (profiling NMM)
- Requires installation of access tube (profiling NMM)
- Bulky, heavy device makes measurements at several access tubes strenuous (profiling NMM)

Summary / Conclusions

The neutron moisture meter is a very accurate and precise method of soil moisture sensing, owing primarily to its very large measurement volume. Electronic moisture meters have a much smaller measurement volume, making them subject to high local variability in moisture content, and are also more sensitive to soil disturbance during installation. Once installed, an access tube may be used for several years and measurements can be made to great depths of 10 m or more. The greatest limitation of the NMM is that it cannot be left unattended due to its radioactive source, making automated soil moisture monitoring impossible.

Nuclear Methods: Gamma Ray Attenuation

Introduction

The information summarized in this section is based on "Radiation Safety Training Class" (Humboldt Mfg. Co. 2004). The nuclear moisture-density gauge is capable of both moisture measurements, as discussed in the neutron moderation section, and density measurements by gamma ray attenuation. In civil construction projects, this is the preferred method of density measurement for monitoring soil compaction with respect to the design criteria.

In the direct transmission density method, a gamma ray source is lowered into a pre-driven hole just below the level of a compacted lift. Detectors are located at the soil surface in the base of the gauge (Figure 6). Emitted gamma rays are either absorbed or scattered by the soil particles. The number of gamma rays that are transmitted from the source to the detector without being scattered or absorbed is indicative of the soil density. It follows that the number of gamma rays passing through a soil decreases with increasing soil density, as there is more material available to attenuate the gamma radiation within the same sphere of influence. The number of gamma rays reaching the detector over time can be directly correlated to soil density.

The backscatter density method is typically only used when making a hole is inconvenient or undesirable, as in asphalt construction. Surface roughness can lead to considerable error in density measurements and so is not recommended in soils; as such, this method will not be further discussed in this paper.

Methods

<u>Direct Transmission Gamma-Ray Attenuation Materials</u>

- Nuclear moisture-density gauge (engineering)
- Footprint template
- Drop hammer
- Shovel or similar tool to create a smooth, flat surface for gauge placement
- Standard calibration block (gauge specific)

<u>Direct Transmission Gamma-Ray Attenuation Procedure</u>

1. Calibrate the gauge according to manufacturer's instructions.
2. Prepare a reasonably smooth, level footprint on the soil surface to accommodate the base of the gauge. Site preparation is not as critical for density measurements as for moisture measurements.
3. Drive a hole into the soil for the gamma-ray source using the template and drop hammer.
4. Insert source into hole about two inches below the lift thickness and ensure that no gap exists between the source and the soil wall.
5. Perform a density measurement following the manufacturer's instructions.

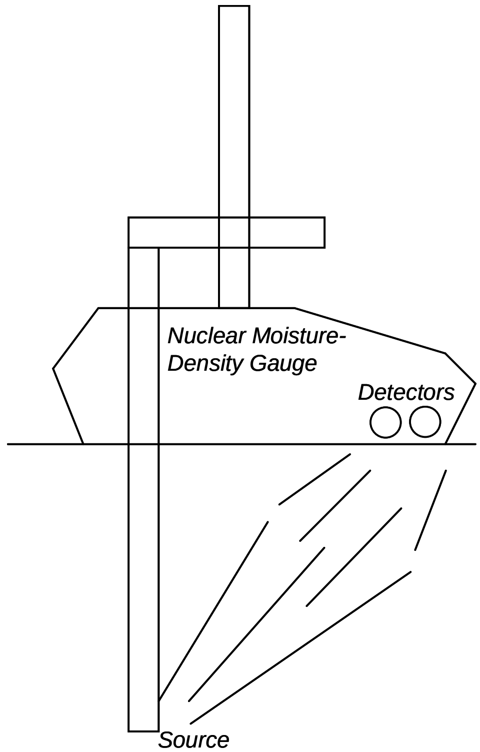

Figure 6. Nuclear moisture-density gauge in direct transmission mode. Gamma rays are emitted from the submerged source and measured by detectors in the base of the gauge.

Discussion

<u>Calibration</u>

A typical expression for the gamma ray attenuation response to soil density is the following:

$$r = A\,e^{-d*b} - C \tag{15}$$

where *r* is the ratio of counts reaching the detector through the soil to the count from a known reference material, *d* is density of the soil, *A* is coefficient of direct count over the background count at zero density, *b* is calibration coefficient accounting for material attenuation coefficient and the path length, and *C* is calibration coefficient representing the background count (count at infinite density).

A, b, and *C* are empirically determined for low, medium, and high density materials over a representative range of measurements. Humboldt Scientific, Inc., provides standard calibration blocks for this purpose, consisting of a low-density magnesium block at 110 lb/ft^3, a medium-density block of alternating Magnesium and Aluminum at 133 lb/ft^3, and a high-density block of Aluminum at 164 lb/ft^3. Calibration may be performed using soil material but is more difficult and inconvenient.

The gauge measures both moisture content, or moisture density, and wet soil density. Dry density is measured as the difference between gauge-measured wet density and moisture density.

Measurement volume

The soil volume of measurement is about $6.2x10^{-3}$ m^3 (0.22 ft^3), depending on the source depth.

Factors influencing density measurements

Table 6 provides a summary of factors that can affect the number of detected gamma rays by the gauge detectors and, subsequently, the wet density and dry density determination. Calculation of dry density is dependent upon moisture content, as discussed above, and influences dry density determinations. Factors affecting neutron counts and their subsequent effect upon moisture density determination are given in the neutron moderation moisture meter section. One of the easiest operator errors is to stand too close to the gauge reflecting both gamma rays and neutrons back to the detectors. The reflection of neutrons is especially significant as it produces errors in both moisture content and dry density measurements.

Table 6. Factors affecting the attenuation of gamma rays and the subsequent influence upon calculated soil density. Adapted from Humboldt (2004)

Factor	Change in Gamma Ray Count	Affect upon Calculated Density	Comments
Increased wet density	Decreases	Increases	Increased density increases gamma ray attenuation.
Increased dry density	Decreases	Increases	Increased density increases gamma ray attenuation.
Wrong calibration	unaffected	Varies with variability of factor	Results in large error from expected density.
Not in notch	Source too low: Decreases Source too high: Increases	Varies with variability of factor	An increase in source depth of 0.005″ results in error of +0.025lb/ft^3 at 6 inches.
Not against side of hole	Increases	Decreases	Can reduce calculated density by 0.5 lb/ft^3.
Poor seating	Increases	Decreases	Air gap of 0.25″ can reduce calculated density by 1.0 lb/ft^3 at 6 inches.
Improper standard count	Varies with variability of factor	Varies with variability of factor	The standard count decreases about 2.23% per year as the radioactive source decays.
Close proximity of objects.	Increases	Decreases	Both gamma rays and neutrons are reflected by above-surface objects decreasing the calculated densities.
Pin Compaction	Negligible	Negligible	Soil near the hole walls will be compacted when driving the pin.
Hole surface damage	Negligible	Negligible	Removing of pin may cause soil to break away around the hole.
Non-soil material in measurement path	Varies with variability of factor	Varies with variability of factor	A large air void or organic material will decrease the calculated density. A boulder or other debris can increase the calculated density.

Manufacturers

CPN International, Inc.
2830 Howe Road
Martinez, CA, 94553 USA
Email: cpn@cpan-intl.com
Internet: www.cpn-intl.com

Humboldt Manufacturing Company
7300 W. Agatite Avenue
Norridge, IL 60706-4704 USA
Email: hmc@ehumboldt.com
Internet: www.humboldtmfg.com

Troxler Electronics Laboratory, Inc.
3008 Cornwallis Road, Research Triangle Park, NC 27709 USA
Email: troxsale@troxerlabs.com
Internet: www.troxlerlabs.com

Advantages

- Large measurement volume reduces variance
- Nondestructive
- Insensitive to small-scale variability such as pin compaction and hole surface damage
- Most established nondestructive method of standard practice

Disadvantages

- Measurement volumes of moisture density and wet density are not the same; though, both are used to calculate a representative dry density
- Costly
- Surface preparation can be difficult and timely
- Involves cost of regulation and licensing of a radioactive source

Summary / Conclusions

Gamma ray attenuation is the most commonly used method of soil density determination in earthwork projects. The same nuclear moisture-density gauge used to measure gamma ray attenuation is also used for moisture determination, and this measurement is used to calculate both a dry density and gravimetric moisture content. This method is well established and has been used for many years in engineering practice. Unlike other methods of nondestructive soil moisture and density measurement, this device was designed exclusively for earthwork construction applications, not agricultural applications.

Nuclear Magnetic Resonance

Introduction

The information presented in this section is based upon Preston (2002). Nuclear magnetic resonance (NMR) detects nuclear species that have a magnetic moment or spin causing interaction with magnetic fields. When placed in a magnetic field, nuclei of different spin energies separate into distinct populations. These populations produce distinct NMR signals when transitions between energy levels are made.

Methods

Hydrogen has a nucleus spin of ½ and has the highest natural sensitivity of all NMR-active nuclei. Other soil components that produce an NMR response are ^{13}C, ^{15}N, ^{27}Al, ^{29}Si, and ^{31}P.

A sample is placed in a magnet within a wire coil that transmits radio frequency (RF) pulses and detects the response of the nuclei as a voltage induced in the coil. The ½ spin H nuclei can be thought of as bar magnets placed in a magnetic field. The magnet produces a constant magnetic field in which the magnetic moment of the nuclei rotates about the magnetic field. The coil is used to produce an oscillating magnetic field at a right angle to the static field produced by the magnet. A 90º RF pulse rotates the nuclei and causes a response signal that decays in time, called the free induction decay (FID). The size of the NMR response is affected by the number of H nuclei, the static magnetic field strength, and the characteristic relaxation of the nuclei.

Measurement of soil moisture content may be accomplished by sending a 90º RF pulse to the coil and measuring the maximum signal height of the FID. The sample moisture content may then be determined from a calibration curve prepared using the same soil over the moisture range of interest.

Discussion

NMR has been used in the study of soil water, though not extensively. Simple moisture measurements, as described above, have been used on other materials such as food and seed. Preston (2002) reports a study by Simeral and Krygsman (1999) using a bench-top low-resolution pulse NMR on zeolite, which gave favorable results comparable to those that would be expected in soils. A five point calibration from 0 to 20% gravimetric moisture content provided a standard deviation of 0.4% over the range of 12 to 20% water, and 1.9% at 4% water. A similar study by Nygren and Preston (1993), reported by Preston (2002), using seeds yielded an accuracy of 0.2% of gravimetric water content. It is probable that these values reflect the upper limits of accuracy for similar studies in soils.

Sample heterogeneity is probably the greatest source of uncertainty, which makes NMR impractical for field use. Iron will produce a significant bias and must be accounted for in the moisture calibration. Bound water populations respond at a different spin energy level than free water, and, at low moisture contents, the NMR measured moisture content decreases below the gravimetric moisture content. This is the case because, as the moisture content decreases, the soil water is increasingly adsorbed by the soil grains and the water nuclei become less mobile in response to the RF pulse.

Equipment

Bruker Minispec
Bruker Instruments, Karlsruhe, Germany
Internet: www.bruker.de

Advantages

- Rapid
- Nondestructive
- High accuracy and precision over uniform samples

Disadvantages

- Highly dependent upon sample calibration
- Not suitable for field use
- Costly
- Not well established or used in soil studies

Summary / Conclusions

NMR is a potentially useful bench-top instrument for measurement of soil water content. Due to the strong dependence on calibration and the small margin between spin energy levels, NMR is not a good candidate for field monitoring where heterogeneous soils are encountered. Studies on other particulate media show a high level of accuracy and precision; although, accuracy suffers at low-moisture contents due to decreased nuclei mobility of bound water.

Near Infrared Spectroscopy

Introduction

Near infrared reflectance spectroscopy (NIRS) is a promising method for real-time soil moisture sensing. Recent advances in instrumentation and computation have made NIRS a possibility for non-invasive, real-time applications, such as soil moisture sensing. While no commercially available instrument has been designed for soil applications, numerous studies have been made using custom-built instruments; however, most of these do use older technology. Commercial application of NIRS is seen in the food processing and agricultural industries for tasks such as quality control of baked goods and beer or the quantitative analysis of corn for moisture, protein, fiber, oil, etc. Applications in food processing involve the conveying of a product past a stationary sensor demonstrating real-time analysis capabilities.

Theory

The information summarized in this section is based on “Introduction to NIR technology” (Analytical Spectral Devices, Inc. 2003). For additional, in-depth, review of the theory and application of NIRS the reader is referred to Williams and Norris (2001) and Burns and Ciurczak (1992). NIR or near infrared refers to light in the 750–3000 nm wavelength region of the electromagnetic spectrum. In near infrared spectroscopy (NIRS), the amount of light of a particular wavelength absorbed by a sample is related to the concentration of particular molecular components within that sample. This principle is represented by Beer's law:

$$\log(transmittance_{\lambda}^{-1}) = \alpha_{\lambda}\, l\, c \tag{16}$$

where the left-hand term is the absorbance (a NIRS instrument actually measures transmittance) of photons of a particular wavelength λ, α_{λ} is the molar absorption coefficient at a particular wavelength, l is the path length, and c is the analyte (substance that is being tested for) concentration. In NIRS, absorbance follows Beer's law quite well and increases fairly linearly with analyte concentration.

Particular molecules display a characteristic frequency response according to their structure. The shape of a spectrum for a particular molecule is made up of its characteristic fundamentals and overtones. Near infrared reflectance (NIR) spectra consists primarily of overtones and combination bands of O-H, N-H, and C-H, and C=O bonds in the mid infrared and far infrared regions. Thus, the spectrum is inherently complex and requires rigorous statistical methods to correlate spectra with molecules. This can be accomplished with computers using commercially available chemometric software.

As an example, in the case of soil moisture sensing, the O-H bonds of water molecules will absorb photons of a characteristic range of wavelengths. The number of photons absorbed by the water molecules is then proportional to the amount of water in the soil. The moisture content of a particular soil may then be empirically correlated to particular NIR spectra.

Discussion

Calibration

An effective calibration model is very important in NIRS. In the case of soil moisture sensing, the calibration model must be able to discriminate changes in the spectra due only to changes in moisture content and irrespective of all other variables, such as color, particle size, particle arrangement, etc. (Siesler et al. 2002).

A relatively simple approach to moisture prediction calibration is based upon the change in reflectance at a particular wavelength with changes in moisture content. For a particular soil sample, the reflectance exponentially decreased as moisture content increases (Bowers and Hayden 1967; Skidmore et al. 1975; Lobell and Asner 2002). Lobell and Asner (2002) present a simple model relating dry soil reflectance as the sole input toward degree of saturation.

A more general calibration model is attainable using multivariate calibration techniques. A general approach to multivariate spectral analysis is given by Analytical Spectral Devices, Inc. (2003):

1. Data preprocessing: correct for baseline drift and/or slope effects.
2. Outlier detection: remove outliers from both training set and validation set.
3. Build calibration model: calculate regression equation based on spectra and known analyte information. Common linear methods include Multiple Linear Regression (MLR), Partial Least Squares Regression (PLR), and Principal Component Regression (PCR). Common nonlinear methods include Artificial Neural Networks (ANN), Locally Weighted Regression (LWR), and Multivariate Adaptive Regression Splines (MARS).
4. Validation: the calibration model is independently tested using a validation set from the same parent population as the calibration set but not included in the calibration model.
5. Prediction: the calibration model is applied to unknown samples.

This analysis may be accomplished using off-the-shelf software often packaged with the instrument hardware or available from the manufacturer of the instrument.

The calibration model referred to above is known as a chemometric model and is built to represent the material to be tested. Chemometric models are built up of many spectra from samples that represent maximum variability of a single property of interest and random variation for all other properties. For an in-depth discussion of calibration procedures the reader is referred to Chang (2000), Martens and Naes (1989) and Beebe et al. (1998). Due to the variety of possible calibration models, it is obvious that no single calibration technique will suit all possible applications and different models should be attempted to obtain the best accuracy (Chang 2000).

Instrumentation

There are no commercially available NIRS instruments designed specifically for soil moisture sensing. Commercially available instruments are typically on-line/semi-portable instruments designed for process control applications (e.g., Labspec® Pro, Spectra-Quad™) or stationary laboratory equipment (e.g., Foss NIRSystems 6500 Scanning Monochromator).

The following is a brief list of domestic manufacturers of NIRS systems. An extensive list of instrument types and their respective manufacturers can be found in Workman and Burns (1992).

Labspec® Pro
Analytical Spectral Devices, Inc
Boulder, CO, USA
Internet: www.asdi.com

Spectra-Quad™
Thermo Electron Corporation
Internet: www.thermo.com

Foss NIRSystems 6500 Scanning Monochromator
Foss NIRSystems
Laurel, MD, USA
Internet: www.foss.dk

In addition to the commercial offerings, several soil scientists have developed custom NIR units. Skidmore et al. (1975) developed a portable NIR reflectometer using an integrating sphere and manually interchangeable narrow band pass filters. Moisture determination was manually computed or read from a graph. Bowers and Hayden (1967) developed a portable NIR reflectometer similar to that of Skidmore et al. (1975). The unit was reported to be portable, rugged, and inexpensive, but the wavelength selection system (manually positioned narrow band pass filters) made laboratory grade accuracy impossible. Kano et al. (1985) developed a small (38.1 mm (1.5 in.) diameter, 381 mm (15 in.) long), hand-held, near infrared reflectance moisture meter. Spectra were measured at 1.80 and 1.94 μm using narrow band optical filters. Selection of these wavelengths was based upon visual inspection of the spectra and prior experience. Ryu et al. (1999) developed a portable NIRS soil analyzer using an MLR calibration that processes and analyzes a field sample. Sample preparation for NIR measurement takes 15 minutes after removal from the field. The first three instruments are truly portable, hand-held units, while the last instrument is about the size of a large cabinet. None of these sensors are capable of real-time soil monitoring applications, where relative movement occurs between the sensor and the target material.

Factors Influencing Moisture Measurements

Sources affecting accuracy due specifically to the instrument-sample system are the following (Kemeny 1992):

- Sample inhomogeneities, including concentration, grain size, and color.
- Optical variations.
- Variations in distance between the sensor and sample (e.g., rough sample surface, equipment vibrations, etc.); see Figure 7.
- Variation in the relative lateral movement between the sample and instrument. On-line applications will typically have a stationary sensor while the material is conveyed past the sensor. The instrument's capabilities limit how fast the material may be conveyed.

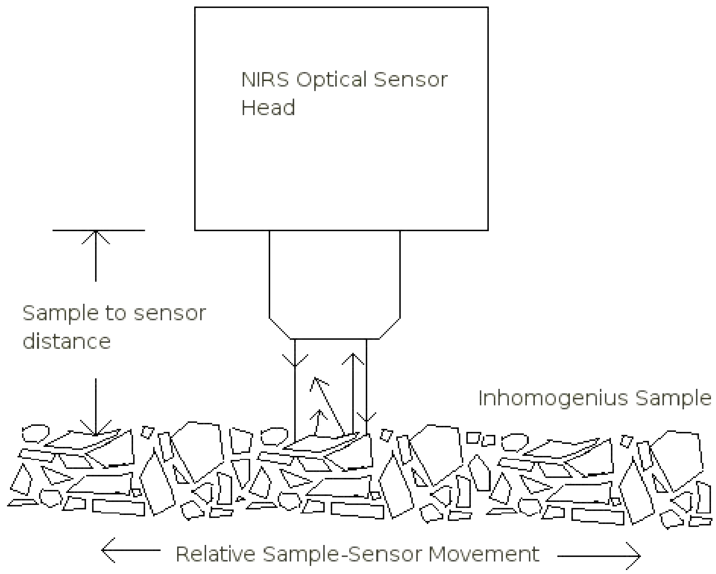

Figure 7. Depiction of a commercial type non-contact optical arrangement emphasizing sensor-sample noise sources. Adapted from Kemeny (1992)

Sources affecting accuracy due to factors outside the instrument-sample system are the following (Kemeny 1992):

- Ambient light
- Temperature variation of the sample
- Ambient temperature changes
- Mechanical vibrations
- Power line fluctuations
- Dust
- Corrosive vapors (steam, water vapor)

Factors of specific importance to soil sampling and sample presentation include the following (Williams 1992):

- Type of sample
- Size of sample

- Storage of sample
- Sample selection (calibration only)
- Texture
- Particle size
- Bulk density
- Static electricity
- Cell type, size, loading, and cleanup (instrument specific)

Additional soil-specific factors include the following:

- Ionic content: Sodium Chloride solution, a common ionic compound in soil applications shows high absorption near 1900 nm, indicating a reduction in hydrogen bonds due to the NaCl (Siesler et al. 2002).
- Particle size: reflectance tends to decrease exponentially as particle size increases (Bowers and Hanks 1965).
- Soil color: Skidmore et al. (1975) report that a light-colored Carr Sandy Loam reflected almost 80% of radiation passing a 1.95 µm filter, while a dark-colored Farnum Sandy Clay Loam reflected only about 43% of radiation passing a 1.95 µm filter.
- Moisture content: generally, reflectance decreases exponentially as moisture content increases (Bowers and Hanks 1965; Bowers and Hayden 1967).

Application / Literature Review

A review of NIRS fundamentals, instrumentation, and techniques is given by Siesler et al. (2002) and Williams and Norris (2001). NIRS has been applied to soil applications and used to predict C, N, cation exchange capacity (CEC), clay, and moisture content (Chang 2000).

Kano et al. (1985) designed a portable, hand-held NIR reflectance soil moisture meter to measure reflectance at both 1800 and 1940 nm wavelengths. They developed a single calibration model for clay and loam with a standard error of calibration = 1.9% over a moisture range of 5%–35%.

Slaughter et al. (2001) used a Model 6500 NIRSystems spectrophotometer and a partial least squares (PLS) technique to measure soil moisture. A correlation of $r^2 = 0.97$, standard error of prediction (SEP) = 1.3%, and bias = 0.2% between predicted and measured moisture content was achieved in the 1400–2400 nm range when the validation set contained the same soil type and particle sizes as the calibration set. When the validation set contained particles of different size, then the calibration set slope and bias errors were introduced and SEP increased to 2.2%, the bias to 4.0%, and the effect on the correlation coefficient was negligible. The increase in SEP and bias were considerably reduced using slope and bias correction. They concluded that a global calibration could be achieved as long as soils are similar in type and particle size distribution.

Ryu et al. (1999) achieved a correlation of R = 0.991, SEE = 1.648, and SEP = 2.040 using a semi-portable NIRS soil analyser. A total of 540 diverse soil samples collected from a wide region in Korea were used for both calibration and validation of the soil analyser. The analyser requires pre-processing of the samples, which takes about 15 minutes. They noted a strong dependence between particle orientation and reproducible NIR reflectance.

Chang et al. (2000) used a FOSS NIRSystems 6500 scanning monochromator and 802 soil samples collected from four major land resource areas (MLRAs). The PCR technique was used to calibrate over a spectral range from 1300 to 2500 nm. The coefficient of correlation between measured and predicted moisture content was $r^2 = 0.84$, and the standard deviation was 0.01 kg kg^{-1}.

Advantages

- Rapid
- Minimal to no sample pretreatment
- Nondestructive
- Simultaneously determines numerous constituents or parameters as calibrated

Disadvantages

- Requires complex calibration procedures with very large data sets
- Sensitive to soil type, particle size, and particle arrangement
- Sensitive to environmental factors in field applications
- Portion of unknown samples must be periodically analyzed by the reference method to validate the calibration
- Separate calibration needed for each analyte of interest

Summary / Conclusions

NIRS has the potential to be a solid solution for soil moisture sensing. Historically, the main encumbrances to its development have been technological. With recent advances in sensing technology and chemometrics, NIRS is now ready for soil applications. The principle issues that need to be overcome are calibration and sensor-soil noise sources, such as ambient light and machine vibration.

Calibration is a problem because of the vast variety of soil types and presentations available to NIRS analysis. In order for NIRS to work, it must be trained for all possible soil variations. To this end, it is possible to envision a very large database of different soils built up over a wide geological region and constantly updated with time. This database could be built from agricultural and civil applications and maintained by a central repository that is accessible to the public and can be added to by licensees.

Seismic Methods

Introduction

In this section, the principles of seismic wave propagation in unsaturated soil are discussed as an alternative means of soil moisture content measurement.

Theory

The information summarized in this section is based upon "Soils and Waves" (Santamarina et al. 2001) and "Exploration Seismology" (Sheriff and Geldart 1995). The theory of wave propagation in porous media was developed by Biot (Biot 1956a, 1956b). The basic equations describing elastic wave propagation assume an infinite, isotropic, linear, elastic, single-phase continuum; such a material allows two modes of propagation. The P-wave, or longitudinal wave, exhibits particle motion parallel to the direction of propagation. The S-wave, or shear wave, exhibits particle motion transverse to the direction of propagation.

Both wave parameters (frequency, wavelength, amplitude, and mode) and material parameters (skeleton stiffness, porosity, saturation, etc.) affect wave propagation. Both bulk and shear moduli are contingent upon interparticle forces (skeletal, local contact, capillary, and electrical) and fabric. Wave propagation is considered low loss (low attenuation) at small strains and may be described using viscoelastic models.

In unsaturated soil, the bulk modulus of the fluid is negligible and P-wave velocity is primarily a function of the skeleton stiffness and mass density:

$$V_p = \sqrt{\frac{M_{sk}}{\rho}} \qquad \text{low freq, } \omega \ll \omega_o \qquad (17)$$

where V_P is the phase velocity, M_{sk} is the constraint modulus (stiffness) of the soil skeleton, and ρ is the mass density; ω is the wave frequency and ω_o is the material specific relaxation frequency.

Attenuation for a P-wave is a function of frequency and at low frequencies may be approximated as the following:

$$\alpha \approx \frac{\omega^2}{2\omega_o V_P} \qquad \text{low freq, } \omega \ll \omega_o \qquad (18)$$

Similar results for α and V_P are found for S-waves.

Factors Affecting Wave Propagation

Anisotropic loading, as well as inherent fabric anisotropy, can cause significant velocity anisotropy. For unsaturated soils, the velocity of a P-wave in a principal direction is dependent upon the effective stress in the direction of propagation, while the velocity of an S-wave in a principal direction is dependent upon the effective stress in the polarization plane.

A summary of soil properties and factors affecting seismic velocity is given in Table 7. Representative soil velocities are provided in Table 8. Figure 8 and Figure 9 illustrate the effects of saturation and porosity on P-wave velocity.

Table 7. Summary of factors affecting seismic velocity

Property	Effect on Velocity	Comments
Soil type	Variable	-Soils that do not react with water show little velocity dependence with moisture content (e.g., sand).
Bulk Density	Increases density - Decreases velocity	See equation (17)
Stiffness	Increases stiffness - Decreases velocity	See equation (17)
Saturation	Variable (see Figure 8)	-A small amount of gas in the pore spaces significantly decreases soil stiffness (Saturation < 100%). -Increasing saturation increases the bulk density
Porosity	Increases porosity - Decreases velocity (see Figure 9)	-Porosity is the most significant factor affecting velocity because it affects both stiffness and density
Adsorption of Water	Variable	-Encourages formation of grain bonding leading to increased stiffness -Can decreases stiffness by breaking chemical bonds between soil grains -Decreases porosity
Remolding	Variable	-Remolded soil properties may be very different from in situ soil properties
Stress	Increases stress - Increases velocity	-Increases cohesion between grains -Decreases porosity -Breaks cementation between grains, decreasing pre-stress velocity
Time After Remolding	Increases time - Increases velocity	-Cementation between grains increases with time leading to increased stiffness -Cementation decreases porosity
Temperature	Negligible effect above freezing	-Freezing of soil significantly increases stiffness

Table 8. Typical P-wave velocities in m/s. Adapted from Burger (1992)

Material	Velocity (m/s)	Material	Velocity (m/s)
Soil	250–600	Glacial till-saturated	1,700
Clay	1,100–2,500	Glacial till-compacted	1,200–2,100
Sand-unsaturated	20–1,000	Water	1,400–1,600
Sand-saturated	500–1,500	Air	331.5
Glacial till-unsaturated	400–1,000		

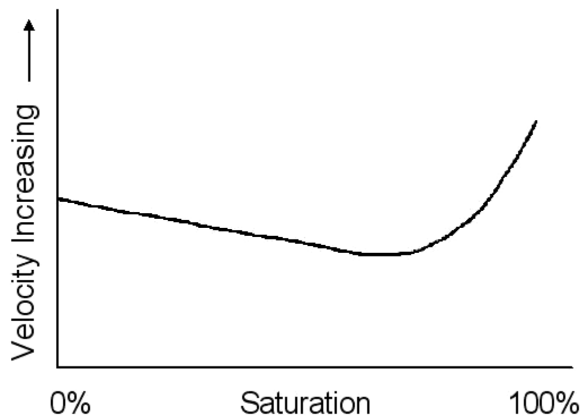

Figure 8. Effect of saturation on P-wave velocity. Adapted from Sheriff and Geldart (1995)

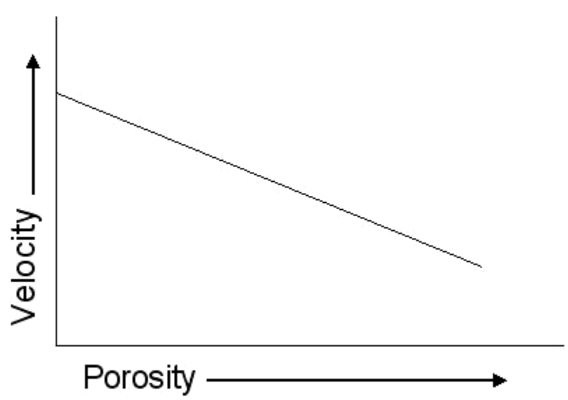

Figure 9. Effect of increasing porosity on P-wave velocity. Adapted from Sheriff and Geldart (1995)

Literature Review

The degree of saturation generally affects the speed and attenuation of P and S waves (Velea et al. 2000; Santamarina et al. 2001) and significant correlations between attenuation vs. water-filled porosity and attenuation vs. volumetric water content in unsaturated soils have been found by Oelze et al. (2002). However, the type of material/soil has a significant effect upon wave propagation. Shields et al. (2000) show that water can sometimes react with grain surfaces to form a layer of water with higher viscosity than free water, causing an increase in contact stiffness by increasing the area of contact. Shields et al. (2000) state that moisture content has little effect on wave velocities, unless the moisture reacts with particle surfaces to form a viscous liquid or solid. In soils that do not react with the saturant, such as water and Ottawa sand, there is little to no correlation between moisture and density and acoustic properties (Oelze et al. 2002; Velea et al. 2000).

Hogan (1967) utilized a seismic refraction technique in an attempt to correlate dry density and water content in extracted and in situ soils from wave velocity. It was found that maximum velocity was generally obtained at 1.6% less than optimum moisture content. The most important variables found to affect velocity were moisture, dry-density, remolding or compaction method, and the elapsed time after compaction until velocity measurement. However, these variables are interdependent and this study does not reveal the nature of their dependencies. It was recommended that field and laboratory tests be made within a short time after compaction. Also, air drying of the field surface could be a problem for field measurements. In laboratory experiments on a Kansan age glacial till, the specimen with highest velocity at the time of compaction showed a decrease in velocity over time, while the specimen compacted at highest moisture content exhibited increased velocity over time. In general, about seven days after compaction, tested soils showed little velocity change, with variation in either moisture content or dry density. This phenomenon was attributed to pore water redistribution and subsequent variation in fluid damping.

Santamarina et al. (2001) stresses that freshly remolded samples do not take into account diagenetic processes that can affect wave velocity. Cementation, the precipitation, and formation of salts and other minerals in soils causes stiffening of the soil over time, resulting in increased wave velocities (i.e., two specimens at different confinements will tend to approach the same stiffness over time due to cementation). Likewise, decementation occurs when the material is strained, either due to applied stress or stress relaxation. This causes a decrease in velocity and hysteretic affects upon reloading.

Increased stress usually leads to an increase in wave propagation speed and a decrease in attenuation due to increased cohesion between particles (Oelze et al. 2002; Santamarina et al. 2001). Lu et al. (2004) used a modified triaxial cell to measure the effects of compaction upon the acoustic properties of soil. It was found that acoustic velocity and the deviator stress increased linearly initially and then nonlinearly at intermediate compaction levels. Also, water content was shown to significantly reduce the maximum obtainable acoustic velocity.

Fam and Santamarina (1997) performed a study of the effect of consolidation on seismic wave velocity. It was observed that the change in velocity closely followed the transfer of load from the pore pressure to skeletal stresses and corresponding increase in stiffness during consolidation.

There is no commercially available acoustic sensor for soil applications. Hamilton et al. (1956) demonstrate an in situ probe consisting of two transducers on the ends of vertical rods plunged into sea floor sediment. The instrument and procedure were considered to have a standard deviation of about 100 ft/sec. Lu et al. (2004) state that an in situ probe has been developed at the National Center for Physical Acoustics at the University of Mississippi to be used for in situ compaction monitoring.

Laboratory methods of measuring acoustic properties in soil are given by Santamarina et al. (2001) and include explanations of peripheral electronics and transducers. The device used by Hogan (1967) utilized a Model 217 Micro-Seismic Timer by Dynametric, Inc., Pasadena, Ca.; a transducer consisting of a crystal phonograph needle; and a tack hammer coupled to the soil with a 5/8 inch steel ball acting as the impact device. Lu et al. (2004) modified a Bishop and Wesley triaxial cell to incorporate piezoelectric transducers for P-wave generation and sensing in conjunction with controlled soil loading.

Seismic waves are typically in the infrasound (frequency less than 20 Hz) range, with geophysical testing in the field typically conducted at values greater than 0.1 Hz and less than 10 kHz in the laboratory (Santamarina et al. 2001). In laboratory tests performed by Oelze et al. (2002), seismic data was deemed unreliable outside frequencies of 2 – 6 kHz for several soils.

Discussion

The application of seismic methods to moisture sensing seems plausible with the exception that soil stiffness and the variation of effective stress throughout a soil volume are likely to have a higher significance than the moisture content upon seismic wave propagation. As such, it would be very difficult to calibrate a seismic instrument to measure moisture content that accounted for variability in soil stiffness and density. It is even less plausible that any calibration could result in absolute measurements of soil water content, but only the relative change in moisture content over time (Santamarina et al. 2001).

The use of seismic wave to measure changes in density and stiffness seems a more reasonable application of seismic technology. The use of seismic techniques to monitor settlement and the gain in shear strength as a function of increased bulk density and stiffness (i.e., as a function of increased soil velocity) over time seems to be a more practical application.

Advantages

- Sensitive to changes in stiffness and density

Disadvantages

- Affect of moisture content uncertain, too many other factors influencing velocity
- No commercial apparatus available for soil applications

Summary / Conclusions

Seismic methods will probably not find application in soil moisture sensing but may be a useful tool in measuring the change in strength of soils over time, whether due to consolidation or diagenetic processes.

Electromagnetic Induction Methods

Introduction

The information summarized in this section is based upon Kachanoski et al. (2002). Electromagnetic induction (EMI) produces a primary electromagnetic (EM) field using a primary coil excited by an alternating current. The primary field induces secondary fields within the soil that are measured by a secondary coil at a fixed distance from the primary coil. The relative strength of the secondary field(s) to the primary field is determined by the bulk soil electrical conductivity.

Bulk soil electrical conductivity is primarily influenced by soil moisture, the concentration of dissolved electrolytes in the soil water, soil texture (e.g., clay content), and temperature (approximately 2% for each degree Celsius). Because electrical conductivity varies nonlinearly over a vertical soil profile and soil temperature varies nonlinearly with depth and time, it is extremely difficult to construct a general calibration curve relating measured soil conductivity and soil moisture.

Methods

The Geonics EM-38 (Geonics Limited, Ontario, Canada) is the most popular instrument for EMI measurements. The instrument may be mounted on a nonmetallic wheeled frame or carried by a person. Readings may be taken continuously and automatically logged or manually logged for individual readings. Individual readings should take less than five seconds when operated by a single person. Continuous measurements may be taken instantaneously, facilitating mounting the instrument to equipment. Unfortunately, the presence of metallic objects, electrical lines, and the orientation of the instrument relative to the ground surface influence the measurements. The depth of measurement is approximately 0.75 m or 1.5 m depending on the instrument orientation.

Discussion / Field Studies

In a 1.8 ha field with clay content of 2.5 to 44%, apparent electrical conductivity (EC) explained 90% of the spatial variation of water content (Kachanoski et al. 2002). Brevik and Fenton (2002) conducted an experiment using an EM-38 in which 79% of the variation in soil electrical conductivity was explained by soil water and temperature. Brevik et al. (2003) used TDR to find the relative influence of soil water content, calcite content, and temperature on the bulk soil conductivity. From 20 soil water and calcite combinations in an Iowa Loess soil, it was determined that soil water explained 70%-78% of the variation in EC over constant calcite content. For a calcite range of 0%–30% and temperature range of 10°C–40°C, soil water content explained 70% of the EC variations. Using multiple linear regression, it was found that the regression coefficient for soil water content on EC is at least two orders of magnitude greater than for either temperature or calcite content. In a study evaluating how many calibration points were needed along a 1950 m transect, Sheets and Hendrickx (1995) found that a calibration point every 200 to 400 m was sufficient for a reliable calibration curve. These point calibrations were performed using neutron moisture meters installed in access tubes but may have been determined using other methods, such as TDR.

Advantages

- Non-invasive, nondestructive
- Rapid
- Avoid soil-electrode contact issues
- Highly integrable with complimentary technologies such as GPS, data loggers, etc.
- Soil moisture is the primary variable influencing bulk soil electrical conductivity

Disadvantages

- Null setting on EMI instruments can drift
- Affected by temperature which varies nonlinearly with time
- Metallic objects and power lines can significantly influence measurements
- Depth of influence of commercial instrument (EM-38) is too great for typical soil lift thickness in earthwork construction

Summary / Conclusions

EMI is a rapid method of soil water content measurement but is prone to error from nonlinear variables such as the variance of conductivity and temperature with depth, making a general calibration nearly impossible. Also, the influence of metallic objects and electrical fields makes mounting to machinery difficult. The most potential for the EMI method is extrapolation of water content measurements from spot measurements by methods such as TDR and neutron moderation.

Thermal Property Methods

Introduction

The following is based upon Bristow (2002). Heat flow in soil takes place as conduction, convection, radiation, and transfer of latent heat. Conduction occurs mainly through the contiguous solid fraction, while convection is principally due to movement of water liquid and vapor across soil pores. Soil thermal conductivity (λ) is a measure of the soils ability to transmit heat. It is defined as the quantity of heat that flows through a unit area in a unit time under a unit temperature gradient and is described by Fourier's law of heat conduction:

$$\lambda = \frac{-G}{\nabla T} \tag{19}$$

where λ is the thermal conductivity (W m^{-1} K^{-1}), G is the heat flux density (W m^{-2}), and ∇T is the temperature gradient (K m^{-1}).

Soil thermal conductivity is influenced by soil composition, particle shape, mutual configuration of the various soil components, bulk density, and water content.

Soil composition influences the thermal conductivity with quartz, having the highest thermal conductivity of common soil solids. Table 9 provides a summary of the thermal conductivities of some common soil materials.

Table 9. Thermal properties of soil materials (Bristow 2002)

Material	Thermal Conductivity (W m^{-1} K^{-1})
Basalt	2.2
Granite	2
Quartz	8.8
Clay minerals	2.9
Organic matter	0.25
Water	$0.552 + 2.34 * 10^{-3}\,T - 1.10 * 10^{-5}\,T^2$
Air	0.0237 + 0.000064 T
Ice (0°C)	2.18

T = temperature (K).

The influence of water content upon soil thermal conductivity is of principle interest in this report as it provides a nondestructive means of soil moisture sensing. At low moisture contents, the air volume fraction dominates the thermal conductivity and most air dry soils have similar thermal conductivities. At low moisture contents, there is a rapid increase in thermal conductivity due to improved interparticle contact from the thickening water film. Beyond this point, increased moisture content simply fills the pores and thermal conductivity is dominated by the solid fraction, and the increase in thermal conductivity slows with increasing moisture content.

Methods

There are two principal methods for measuring soil thermal conductivity: the steady state method and the transient heat pulse method.

Steady State Method

The steady state method may use a guarded hot plate apparatus (Figure 10) in which two identical soil samples are placed between a main heater and two auxiliary heaters. The temperature drop across the sample is then measured until the system reaches a steady state temperature. The final hot plate temperature depends on the electrical power input, soil thermal conductivity, and the temperature of the cold plates. The average thermal conductivity may then be calculated as (Bristow 2002):

$$\lambda = \frac{E}{A}\left[\frac{1}{(dT/z)_1 + (dT/z)_2}\right] \tag{20}$$

where E is the electrical power consumed by the main heater (W), A is the main heater surface area (m^2), dT is the temperature difference across the sample (K), and z is the sample thickness (m). Subscripts 1 and 2 correspond to the two soil samples.

The guarded hot plate method is simple but labor intensive and timely. A major drawback of the steady state method is that the constant temperature gradient causes moisture redistribution in the soil sample, altering the thermal properties of the soil. This method requires soil sampling leading to sample disturbance and alteration of the soil thermal properties. Finally, perfect, repeatable thermal contact at the soil-heater interface is clearly unattainable and can lead to considerable error because of the very low thermal conductivity of air ($\lambda = 0.024$ W m^{-1} K^{-1}) acting as an insulator between the heater and the soil. Because of these limitations, the steady state method is seldom used in soil thermal conductivity measurements.

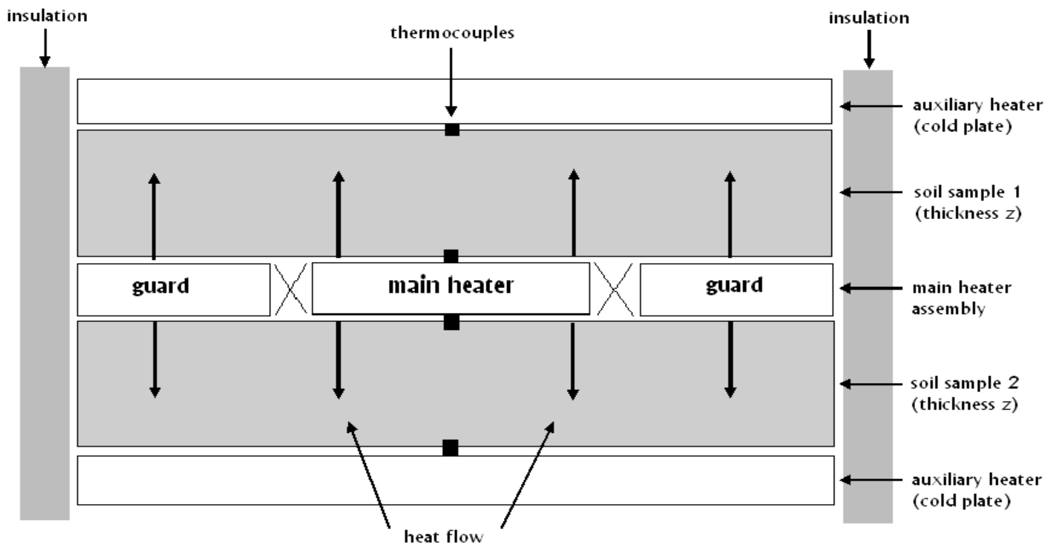

Figure 10. Illustration of steady state method using a guarded hot plate apparatus. Adapted from Bristow (2002)

<u>Transient Heat Pulse Method</u>

The transient heat pulse method measures the rate at which applied heat is transmitted away from a heat source embedded in the soil. There are two types of apparatus used in the transient method: single-probe and dual-probe. Single-probe devices combine both a heater and temperature sensor into a single small-diameter tube, while the dual-probe method contains the heat source in one tube and a temperature sensor in another. The apparatus applies a heat pulse and measures the power consumed by the heater and the temperature change over a period of time. The change in temperature vs. time data are then used to calculate the thermal conductivity and thermal diffusivity. If a dual-probe heat pulse sensor is used, the heat capacity may also be directly measured. Otherwise, the heat capacity may be calculated from the thermal conductivity and thermal diffusivity.

The transient heat pulse method is based on several assumptions (Ochsner et al. 2003):

- Heat transfer around and through the sensor is the same as the heat transfer around an infinite line source.
- The finite duration heat pulse approximates an instantaneous heat pulse.
- Heat transfer is done only by conduction.
- No contact resistance exists between the sensor and the soil particles.
- The material being tested is homogeneous and isotropic.

While these assumptions cannot be met by any apparatus, they are deemed adequate for accurate thermal properties measurements (Decagon Devices, Inc. 2004).

Discussion

A summary of factors influencing soil bulk thermal conductivity is given in Table 10.

Table 10. Summary of factors influencing soil bulk thermal conductivity

Factor	Affect on Soil Bulk Thermal Conductivity
Moisture content increases	Thermal conductivity increases
Bulk density increases	Thermal conductivity increases
Salt content increases	Thermal conductivity decreases
Sand dominant texture	Thermal conductivity increases
Clay dominant texture	Thermal conductivity decreases
Organic matter increases	Thermal conductivity decreases
Temperature decreases	Thermal conductivity increases

The theory behind soil thermal conductivity measurements assumes a homogeneous, isotropic, and rigid material. Because soil does not meet these criteria, it is essential that the soil conditions at the time of measurement and the experimental procedures employed to make the measurement are fully understood (Bristow 2002).

When installing probes, it is important that good soil-probe contact is made, or the measurement results will not represent the soil being measured. The same is true for coarse soils with high porosity. In this case, the measurement volume may be too small to capture the bulk soil thermal conductivity. Thermal grease may be used to improve contact between the probe and soil particles in drier soils (Decagon Devices, Inc. 2004).

The speed of measurement is a major downfall of this method, compared to other nondestructive methods. The KD2 Thermal Properties Analyzer (Decagon Devices, Inc.) is a single probe transient heat pulse type sensor used to measure soil thermal conductivity. The instrument requires 90 seconds to equilibrate to the soil temperature and 30 seconds to make a heating and measurement cycle. The total measurement time is two minutes, not including probe installation.

A concern with all of the factors affecting soil thermal conductivity is their variation in time. For example, if a thermal conductivity sensor were to be used to monitor soil moisture during a compaction process, it would require that the changing density be accounted for in the calibration. It is easy to see that all of the factors listed in Table 10 are subject to variation with time.

Application to Soil Moisture Sensing

Abu-Hamdeh and Reeder (2000) studied the effects of texture, soil density, moisture, salt concentration, and organic matter on soil thermal conductivity. Using a single probe heat pulse method, it was observed that clayey soils generally had a lower thermal conductivity than sandy soils. Increased bulk density at a particular moisture content increased thermal conductivity, while increased moisture content at a particular bulk density increased thermal conductivity. Increased salt content for a particular water content decreased thermal conductivity. Increased organic matter generally decreases thermal conductivity.

Ochsner et al. (2001) used a 3-probe thermo-TDR with a heater and thermocouple mounted in each probe. Using this instrument they were able to measure heat capacity, thermal diffusivity, and thermal conductivity of 59 samples of four soils. It was found that thermal properties primarily depend on the volume fractions of air (n_a), water content (θ_v), and solids (v_s). The relationship between thermal conductivity and the volume fraction of air ($r^2 = 0.93$) was found to be more significant than that of water ($r^2 = 0.63$), while the relationship between volumetric heat capacity and water content ($r^2 = 0.88$) was similar to that between volumetric heat capacity and the volume fraction of air ($r^2 = 0.86$). The volume fraction of solids showed the least correlation for thermal conductivity ($r^2 = 0.64$) and volumetric heat capacity ($r^2 = 0.31$). In this study, it was concluded that thermal conductivity was best described as a linear decreasing function of the air-filled porosity. The thermal conductivity of the soil samples used in this study was modeled after De Vries (1963).

Ren et al. (2003) used a thermo-TDR probe to measure the absolute water content of three soils, given the specific heat of soil solids (c_s). If c_s were assumed a common value of 0.725 kJ kg^{-3} K^{-1}, the water content was overestimated on average by 0.052 m^3 m^{-3}. When the heat-pulse method was used to calculate c_s from oven dried samples, the water content could be measured to -0.006 m^3 m^{-3} average error. The average RMSE for the soils tested was 0.061 using the common value of c_s and 0.039 m^3 m^{-3} using the heat-pulse determined c_s.

Manufacturers

The following is a list of U.S. companies supplying thermal conductivity measurement equipment suitable for soil applications:

Anter Corporation
1700 Universal Rd.
Pittsburgh, PA 15235-3998
Internet: www.anter.com
email: sails@anter.com
phone: 412-795-8225

Decagon Devices, Inc.
P.O. Box 835
950 NE Nelson Court
Pullman, WA 99163
Internet: www.decagon.com
email: sales@decagon.com
phone: 509-332-2756

Thermal Logic
805 NW State Street
Pullman, WA 99163
Internet: www.thermallogic.com
email: sales@thermallogic.com
phone: 509-334-3016

Advantages

- Minimal intrusion/soil disturbance (small probe geometry)

Disadvantages

- Relatively expensive
- Small measurement volume
- Long measurement time (>2 min)

Summary / Conclusions

Correlating moisture content to soil thermal conductivity can provide accurate results (Ren et al. 2003) but is subject to the weaknesses of measuring soil thermal conductivity. The major disadvantages of this method are its sensitivity to many soil attributes and the long measurement time. The authors were unable to find any field studies using this method. The majority of work has been conducted in the laboratory under highly controlled conditions.

EVALUATION OF SELECTED TECHNOLOGIES

The selection of which technologies should be evaluated was based upon the availability of particular technologies and the opportunity for field evaluation. In this study, TDR was the only technology to be evaluated in the field. All other evaluations were conducted in the laboratory. An attempt was made to provide unique and interesting data, such as the use of a commercially available TDR unit for spot-checking during a compaction operation and the adaptation of the Duff Moisture Meter (Campbell Scientific, Logan, Utah) towards compacted mineral soils.

The technologies selected for evaluation are TDR, ultrasound, capacitance, and thermal property methods.

Time Domain Reflectometry

Methodology

Site Preparation and Compaction Operations

Four test strips, identified as A through D, were constructed and tested. Construction operations consisted of the following steps: (1) aerate/till existing soil with a CAT RR350, (2) moisture condition soil with water truck, (3) remix with one to two additional passes of the CAT RR350, (4) blade to level surface, and (5) compact with 6 to 10 passes of a CAT CP-533E roller. The test strips varied in loose lift thickness and water content. Tables 11–14 summarize the loose lift thickness (12 to 16 inches) and water content measurements (~8%–19% on dry mass basis) at each test point.

The soil type was relatively uniform and of glacial origin and was classified as a sandy silty clay.

Compaction was achieved with 6 roller passes—all conducted in the forward direction. Loose lift thicknesses for these test strips were approximately 12 inches for A strip and 16 inches for strips B through D. Based on nuclear tests, the average moisture content increased from A to D: 9.5%, 12.2%, 15.4%, and 17.3%, respectively. A standard Proctor test indicates that optimum water content is around 12 to 13%.

TDR Water Content Measurements

The TDR instrument used was an IMKO TRIME®-EZ probe with coated rods 16 cm long and 6 mm in diameter. Readings were taken using the TRIME Data Pilot and manually recorded for each test location. Figure 11 shows the probe inserted into the soil. Output is a volumetric moisture content, θ_{std}, based upon the manufacturer's standard calibration equation.

Figure 11. IMKO TRIME-EZ shown inserted into soil

TDR readings were taken at all test points in test strips A through D. A probe template was used to create pilot holes for the TDR probe as close as possible to the site marker (stake). If the initial attempt at penetration was unsuccessful due to rocky or extremely stiff soil, a new site was selected near the previously attempted site. After the pilot holes were made, the probe was inserted into the pilot holes and a reading was taken. θ_{std} was manually recorded on a data sheet.

θ_{std} values were then plotted with respect to gravimetric oven dried moisture content and nuclear density gauge moisture values (θ_{nuc}). Both actual and nuclear moisture contents were converted to volumetric moisture content using oven dried and nuclear density gauge dry densities, respectively.

Results

The calibrated TDR moisture content (θ_{cal}) is found using the calibration equations from Figure 12. The calibration equation based on the nuclear density gauge volumetric moisture content is the following:

$$\theta_{cal} = (-0.0187)\theta_{std}^2 + (1.8986)\theta_{std} - 18.231 \quad (23)$$

with $R^2 = 0.8277$. The calibration equation based on the oven dried moisture measurements is the following:

$$\theta_{cal} = (-0.0432)\theta_{std}^2 + (3.2456)\theta_{std} - 35.305 \quad (24)$$

with $R^2 = 0.72$.
Using these calibration equations, θ_{cal} is plotted versus the nuclear density gauge moisture content (Figure 12) and the direct measurement of the moisture content (Figure 13). Figure 14

shows a plot of nuclear density gauge moisture content versus the direct moisture content on a volumetric basis and is useful for comparing data scatter with the TDR plots. Results for test strips A, B, C, and D are shown in Tables 11, 12, 13, and 14, respectively.

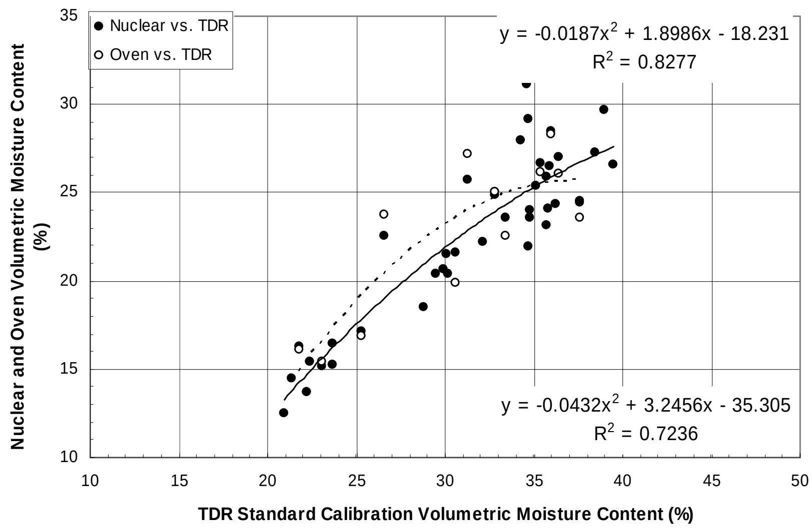

Figure 12. TDR calibration curves based on nuclear density gauge moisture content and oven-dry moisture content

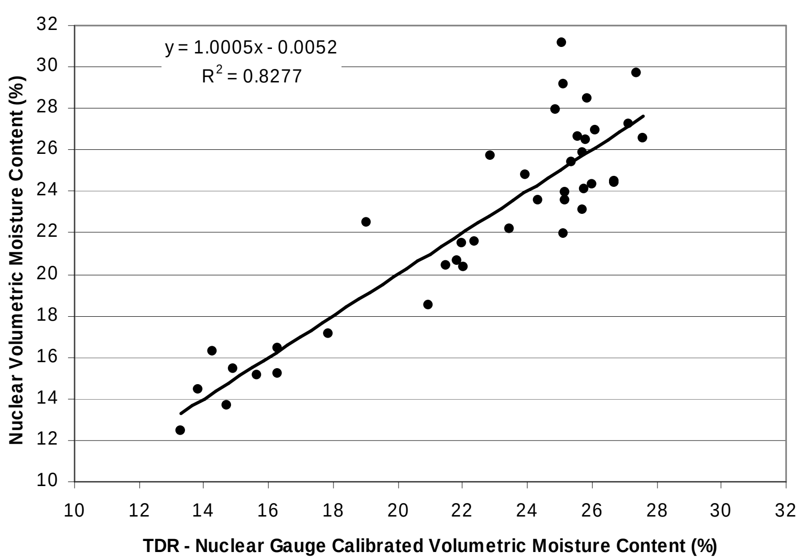

Figure 13. TDR nuclear gauge calibration volumetric moisture content vs. nuclear gauge volumetric moisture content

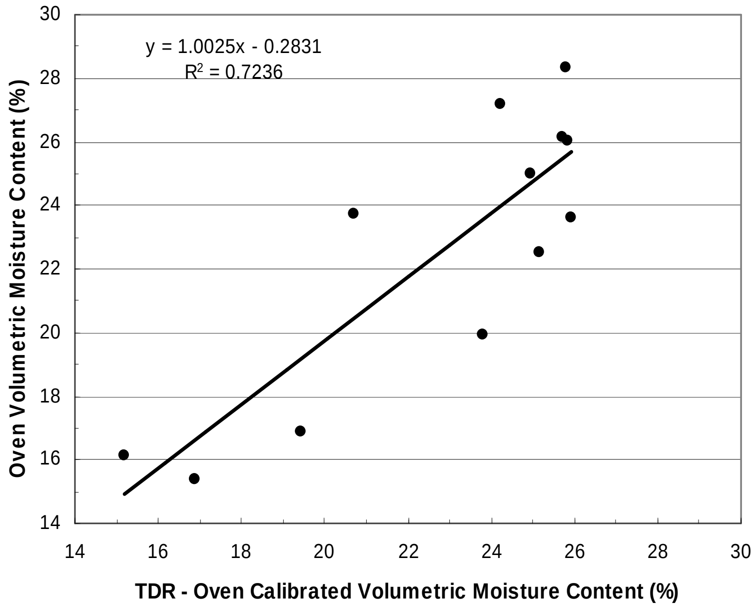

Figure 14. Oven calibrated TDR volumetric moisture content vs. oven dried volumetric moisture content

Table 11. Summary of test results for test strip A

Test Point	Nuclear		Field Samples		Loose lift (in)	Number of Roller Passes	TDR Measurements		
	Water content (%)	Dry Unit Weight (pcf)	Water content (%)	Dry Unit Weight (pcf)			Theta-v std	cal. Theta-v	Theta V
1A	9.0	105.4	8.3	115.7	12	6	23.1	15.12	15.39
2A	8.0	106.7	8.5	—	12	6	22.2	13.67	0.00
3A	12.9	99.8	8.2	—	12	6	29.9	20.62	0.00
4A	10.8	98.8	9.3	113.1	12	6	25.3	17.10	16.86
5A	9.7	106.2	8.5	—	12	6	23.7	16.42	0.00
6A	9.4	102.4	9.1	—	12	6	22.4	15.42	0.00
7A	9.5	100.0	8.6	—	12	6	23.7	15.22	0.00
8A	10.0	101.8	9.3	108.2	12	6	21.8	16.31	16.13
9A	7.2	108.1	7.8	—	12	6	20.9	12.47	0.00
10A	8.9	102.0	8.5	—	12	6	21.4	14.46	0.00

Table 12. Summary of test results for test strip B

Test Point	Nuclear		Field Samples		Loose lift (in)	Number of Roller Passes	TDR Measurements		
	Water content (%)	Dry Unit Weight (pcf)	Water content (%)	Dry Unit Weight (pcf)			Theta-v std	cal. Theta-v	Theta V
1B	14.3	103.2	12.9	—	16	6	34.8	23.57	0.00
2B	13.8	101.8	13.2	112.2	16	6	26.6	22.51	23.73
3B	13.4	100.1	12.7	—	16	6	30.1	21.50	0.00
4B	14.5	101.7	12.4	113.1	16	6	33.4	23.55	22.54
5B	13.6	101.2	12.5	—	16	6	34.7	21.96	0.00
6B	13.5	102.7	12.7	—	16	6	32.1	22.22	0.00
7B	15.3	104.0	12.8	—	16	6	35.1	25.40	0.00
8B	12.6	101.0	12.1	—	16	6	29.5	20.39	0.00
9B	13.5	99.7	12.2	101.8	16	6	30.6	21.56	19.90
10B	11.4	101.7	11.4	—	16	6	28.8	18.49	0.00

Table 13. Summary of test results for test strip C

Test Point	Nuclear		Field Samples		Loose lift (in)	Number of Roller Passes	TDR Measurements		
	Water content (%)	Dry Unit Weight (pcf)	Water content (%)	Dry Unit Weight (pcf)			Theta-v std	cal. Theta-v	Theta V
1C	13.8	110.5	14.0	—	16	6	37.6	24.43	0.00
2C	17.2	103.4	15.7	112.5	16	6	36	28.49	28.33
3C	19.2	101.5	15.5	—	16	6	34.6	31.13	0.00
4C	14.6	104.5	14.1	—	16	6	36.2	24.35	0.00
5C	16.1	103.0	14.7	—	16	6	39.5	26.58	0.00
6C	16.7	109.2	14.0	—	16	6	34.7	29.14	0.00
7C	15.3	110.0	14.1	115.7	16	6	36.4	26.97	26.05
8C	14.3	104.7	14.3	—	16	6	34.8	23.98	0.00
9C	14.9	104.0	14.4	108.4	16	6	32.8	24.83	25.02
10C	12.3	103.4	12.9	—	16	6	30.2	20.38	0.00

Table 14. Summary of test results for test strip D

Test Point	Nuclear		Field Samples		Loose lift (in)	Number of Roller Passes	TDR Measurements		
	Water content (%)	Dry Unit Weight (pcf)	Water content (%)	Dry Unit Weight (pcf)			Theta-v std	cal. Theta-v	Theta V
1D	13.2	109.5	14.1	—	16	6	35.7	23.10	0.00
2D	15.6	109.4	14.8	—	16	6	38.5	27.26	0.00
3D	16.1	103.3	15.0	108.8	16	6	35.4	26.65	26.15
4D	15.4	98.0	13.8	—	16	6	35.8	24.11	0.00
5D	17.4	100.2	14.7	—	16	6	34.3	27.94	0.00
6D	14.7	104.0	13.8	106.7	16	6	37.6	24.49	23.60
7D	15.9	103.8	14.7	—	16	6	35.9	26.50	0.00
8D	16.6	112.0	15.3	—	16	6	39	29.69	0.00
9D	15.9	101.0	14.8	114.5	16	6	31.3	25.72	27.16
10D	16.1	100.6	14.1	—	16	6	35.7	25.88	0.00

Discussion

The TDR probe correlates well with both nuclear and oven determined moisture contents once material specific calibration of the TDR probe has been applied. Because the TDR probe measures volumetric water content, knowledge of the soil bulk density is needed if gravimetric water content is desired.

Because it is difficult to insert the probe into dry, dense soil, a template should be used to avoid damaging the instrument. The template is also useful for ensuring parallel rods insertion into the soil. Soil disturbance can occur in dry, crumbly soils and will affect the TDR measurement; if excessive soil disturbance occurs the measurement site should be rejected.

The main disadvantage between the TDR probe and nuclear density gauge is the timeliness of TDR calibration, which requires oven drying soil samples over the range of expected field moisture contents.

Summary / Conclusions

The main problem with TDR technology is calibration. Ideally, a field calibration would be performed so that in situ densities are used. However, it would then be difficult to take moisture readings over the full range of moisture values expected. Also, oven drying the samples takes a very long time (~24 hours). It is clear that TDR calibrations based on nuclear moisture-density gauge readings are favorable but are hardly practical as the purpose of using TDR would be to replace the nuclear moisture-density gauge.

Ultrasound

Introduction

Measuring soil moisture and density are timely and labor-intensive undertakings using the traditional methods of proctor tests and nuclear density gauge. In the case of the nuclear density gauge, there is the added inconvenience of federal regulation. Thus, an alternative means of monitoring soil compaction is highly desirable. Because soil compactability is mainly dependent upon moisture content, this should be the principle focus of any soil compaction monitoring technique. This study was conducted to evaluate the effects of aging, moisture content, and consolidation upon seismic wave propagation in soils.

Experimental Methods

Three experiments were performed to illustrate the possibilities and limitations of seismic waves in moisture content measurements and settlement. The first experiment looks at the effects of time upon remolded soil samples. The second experiment illustrates the effects of moisture content upon seismic velocity. The third experiment reveals the effect of consolidation upon seismic velocity.

In these experiments, the first arrival time is used in lieu of velocity. This is the case because the characteristic time lag due to instrumentation delay was unknown and so could not be compensated for in velocity measurements. Likewise, due to the wide range of velocities in geomaterials, absolute velocities have marginal significance (Sheriff and Geldart 1995).

Increase in Seismic Velocity with Aging

Four samples of oxidized glacial till soil were prepared at a range of moisture contents from 8.8% to 12.7% and dry densities from 18.7 to 19.3 kN/m^3 (Figure 15). Measurements of the first arrival times of 100 kHz and 250 kHz longitudinal waves (P-waves) were taken over a period of 8 days. Each sample was placed between two ultrasonic transducers and a constant pressure of 53 kN was applied to each sample. The experimental apparatus is illustrated in Figure 16 and Figure 17.

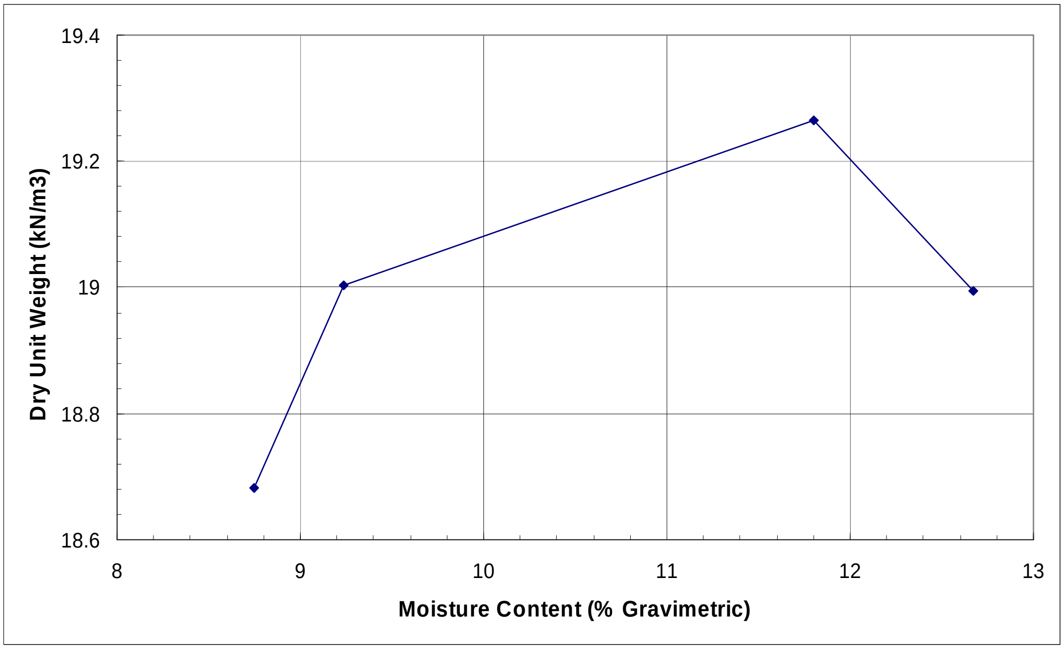

Figure 15. Moisture-density curve for oxidized glacial till soil

Variation of Seismic Velocity with Moisture Content

Oxidized glacial till soil was sieved through a 1.18 mm sieve and compacted to standard proctor energy in a single lift. Thirteen samples were prepared with moisture contents ranging from 8.3 to 12.9% gravimetric. The sample was placed between two ultrasonic transducers and a constant pressure of 53 kN was applied to each sample. A gel coupling fluid was applied to the sample surfaces prior to testing. The experimental apparatus is illustrated in Figure 16 and Figure 17.

Figure 16. Experimental setup for measuring arrival times through soil sample

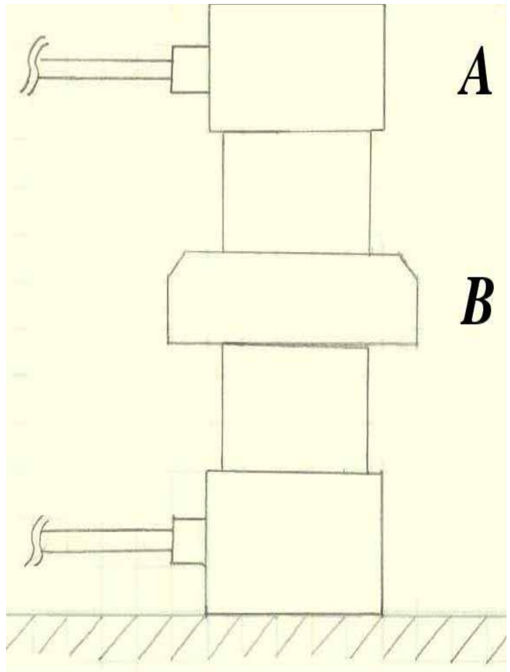

Figure 17. Experimental setup for measuring arrival times through soil sample: (A) ultrasonic transducer and (B) soil sample contained within soil cutter

Effect of Consolidation on Seismic Velocity

The effects of consolidation on seismic wave velocity were investigated over a single consolidation loading. A sample of Oxidized Glacial Till was prepared at 12.2% moisture content and compacted to standard proctor energy. A soil cutter was used to laterally confine the sample. The sample was placed between two ultrasonic transducers and loaded to approximately 45.88 kN/m^2. A dial gage was used to monitor settlement simultaneously with seismic wave arrival times. The experimental apparatus is illustrated in Figure 18 and Figure 19. Settlement and arrival time data were collected over a period of 79 hours.

Figure 18. Apparatus for measurement of arrival time and settlement

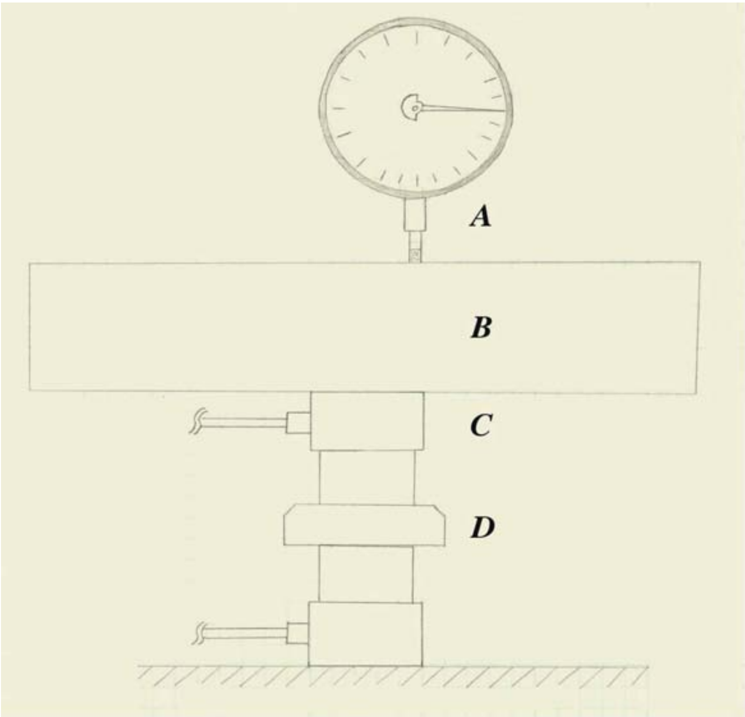

Figure 19. Consolidation and measurement apparatus: (A) dial gauge, (B) load, (C) Transducer, and (D) soil sample contained in soil cutter

Results

Increase in Seismic Velocity with Aging

Figure 20 and Figure 21 show an overall decrease in arrival times over the eight-day period. Figure 22 and Figure 23 illustrate the decrease in velocity change over time. It is observed that the change in arrival times decreases over the duration of the experiment. Although it was intended that the samples be kept at constant moisture content over the duration of the experiment, there was variation, as shown in Table 15. This change in moisture content is attributed to absorption of the gel coupling fluid applied to the soil sample during testing.

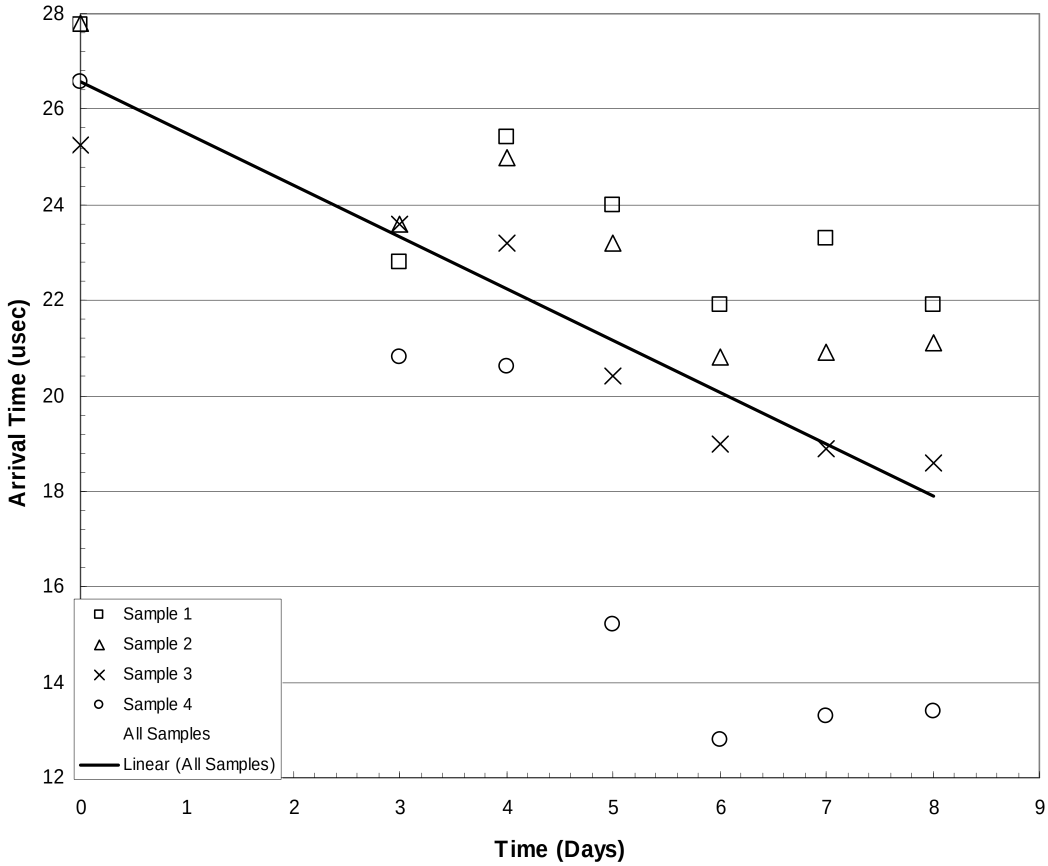

Figure 20. Decrease in 250 kHz arrival times over a duration of 8 days

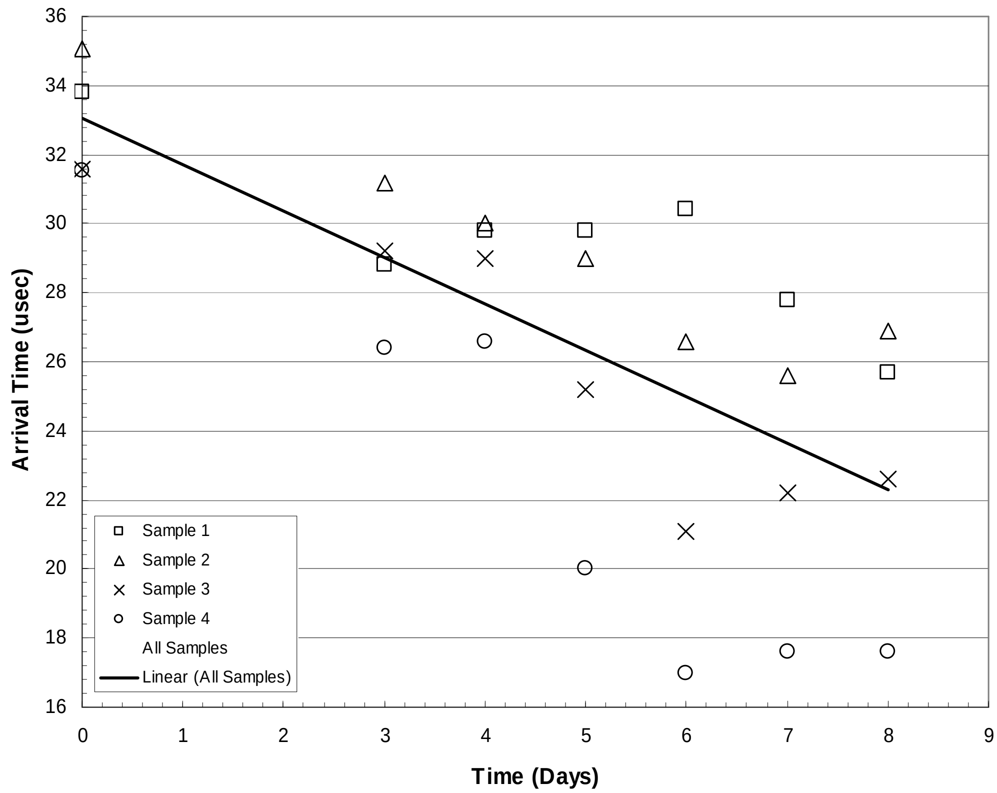

Figure 21. Decrease in 100 kHz arrival times over a duration of 8 days

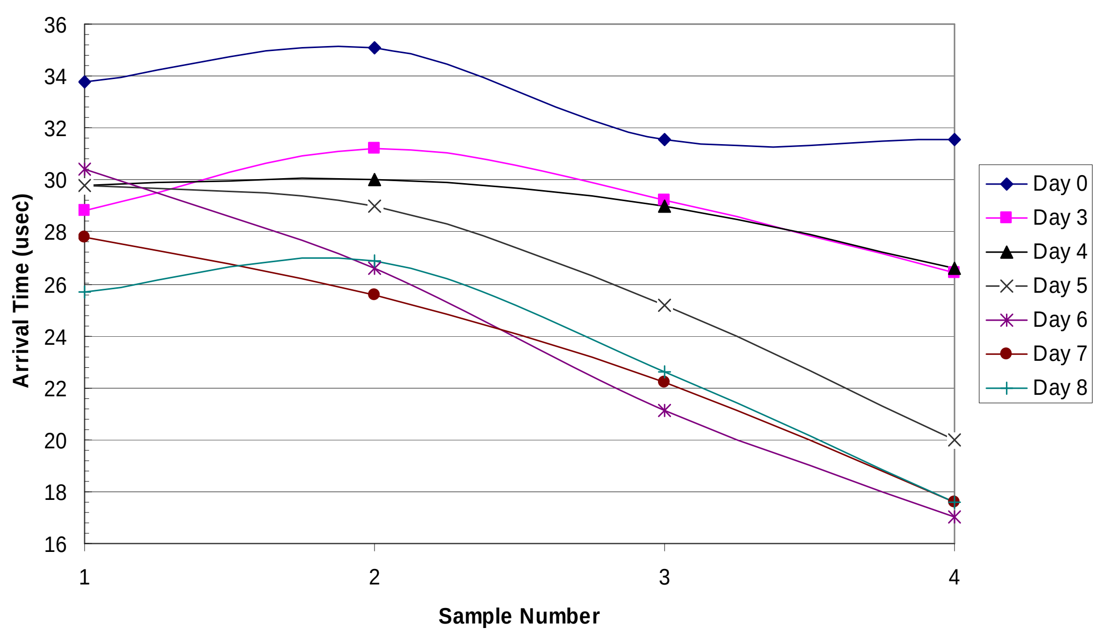

Figure 22. Decrease in 250 kHz arrival times over a duration of 8 days by sample number

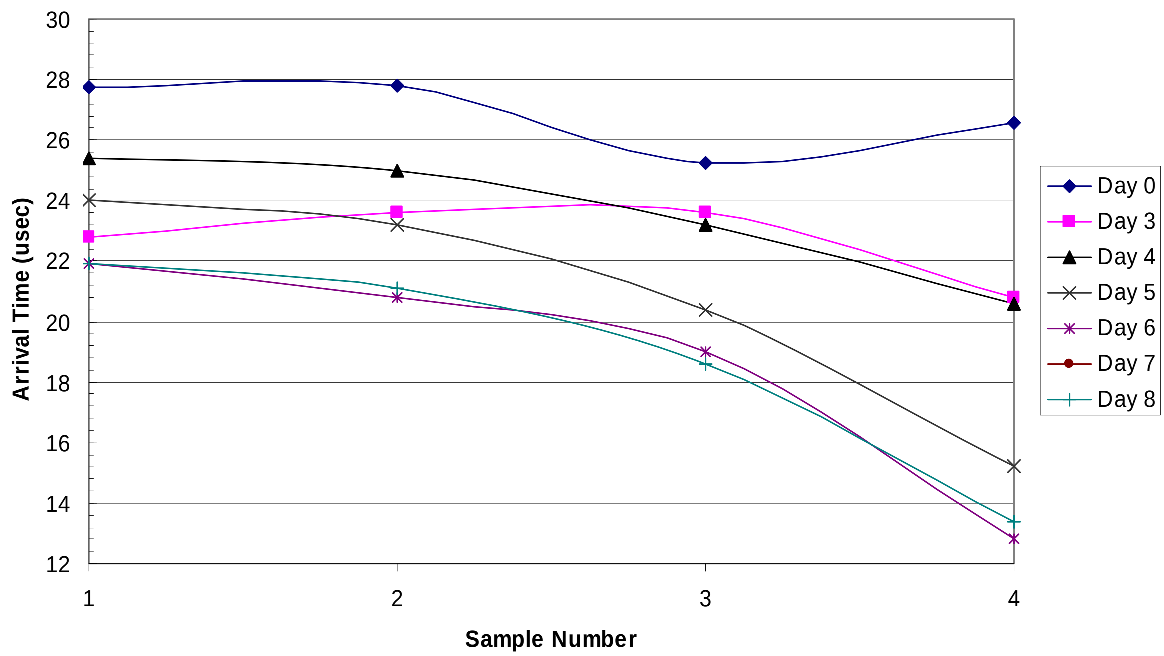

Figure 23. Decrease in 100 kHz arrival times over a duration of 8 days by sample number

Table 15. Change in moisture content over test period

Sample	1	2	3	4
0 Days	8.8%	9.2%	11.8%	12.7%
8 Days	11.1%	9.6%	10.9%	10.8%

Variation of Seismic Velocity with Moisture Content

Arrival times were recorded and plotted as a function of moisture content, as shown in Figure 24. The overall trend reveals a decrease in velocity (increase in arrival time) with increased moisture content. Initially, the arrival times decrease with moisture content, reach an optimum, and then begin to increase. Figure 25 shows the overall increase in arrival time with increasing moist unit weight of the samples.

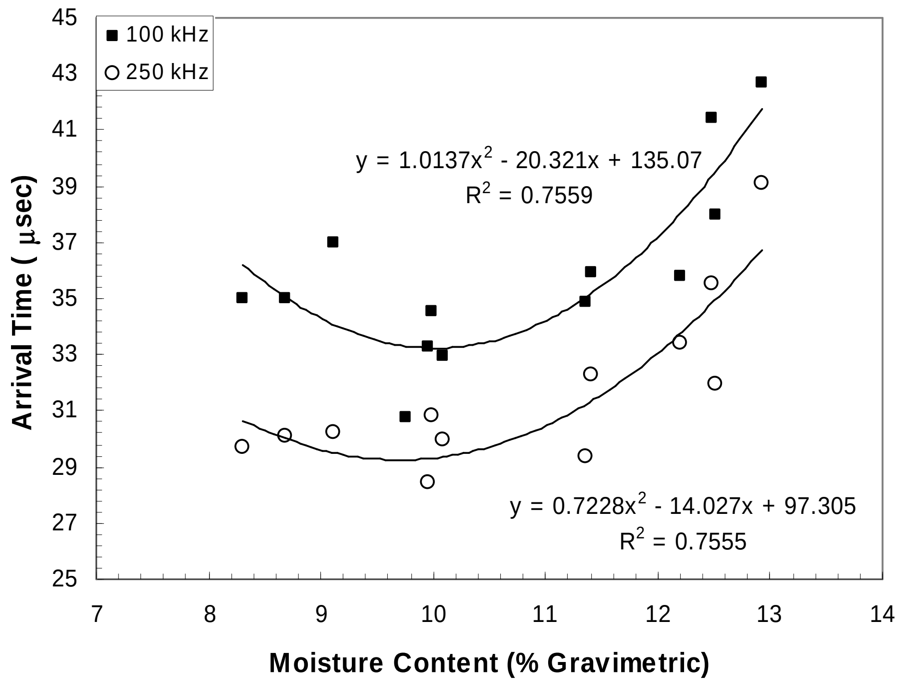

Figure 24. Arrival time vs. moisture content for 100 kHz and 250 kHz

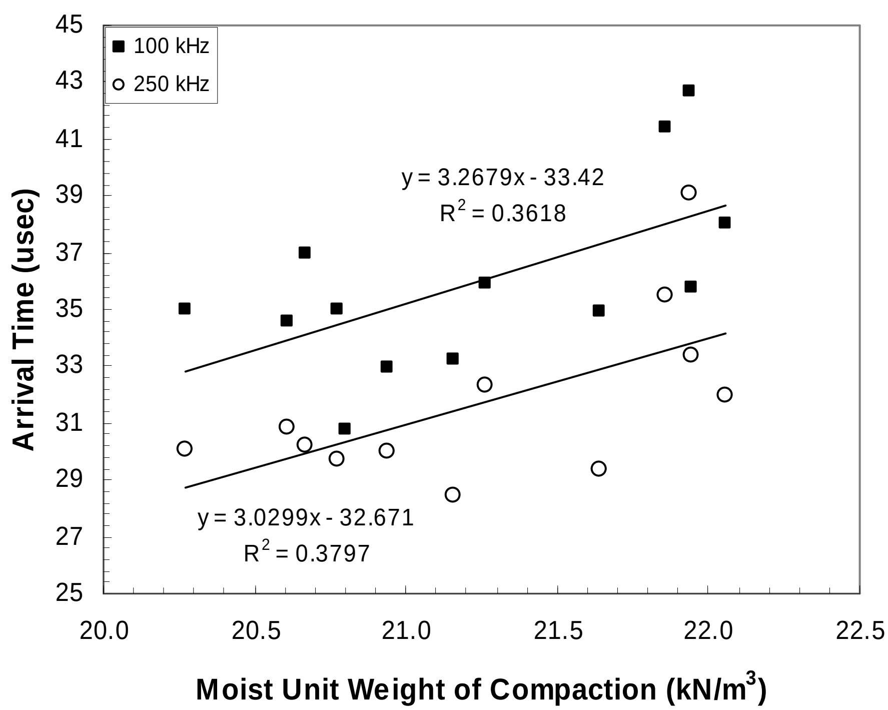

Figure 25. Sample moist unit weight vs. arrival time for 100 kHz and 250 kHz

Effect of Consolidation on Seismic Velocity

The void ratio and corresponding arrival times are plotted against time in Figure 26. The change in arrival time corresponds very closely to the change in void ratio of the soil sample over the consolidation period.

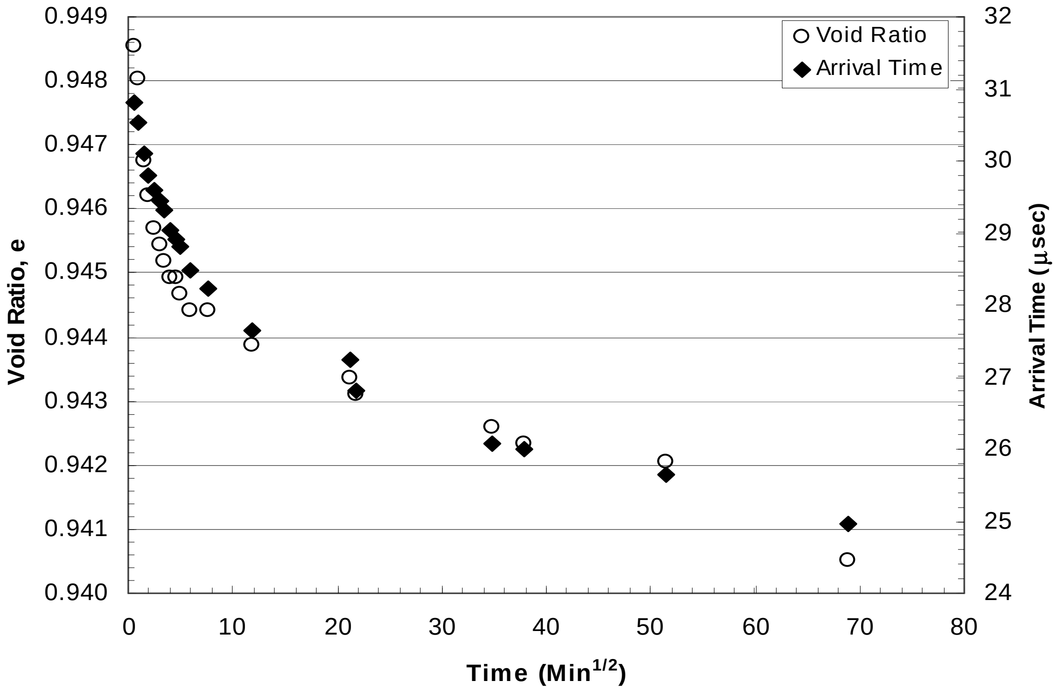

Figure 26. Consolidation of soil sample reflecting transfer of load from pore pressure to soil matrix. Arrival times closely track the void ratio.

Discussion

Increase in Seismic Velocity with Aging

All four samples show an overall increase in velocity. Samples 1 and 2 had an increase in moisture content of 2.3% and 0.4%, respectively. Samples 3 and 4 showed a decrease in moisture content of 0.9% and 1.9%, respectively. The effect of increasing moisture content should be a decrease in velocity; thus, it is probable that aging has a more significant effect upon soil velocity than moisture content. The change in moisture content was likely due to exposure to the air and the coupling gel applied to the soil surface prior to testing.

The practical relevance of this experiment is not the quantitative results but recognition that aging does have an effect upon soil velocity and should be considered in any experimental results, particularly in time-based experiments and for field samples that have sat around for a few days.

Variation of Seismic Velocity with Moisture Content

The expected effect of increased moisture content is a decrease in P-wave velocity due to an overall increase in density and wave damping caused by wave-pore water interaction. In this application, P-waves are more suitable than S-waves because fluids do not support the propagation of S-waves and so are not affected by fluid damping but only by increased density.

The overall trend was a decrease in velocity with moisture content, as shown in Figure 24. It is notable that at low moisture contents of about 9%-10%, the velocity actually increases prior to decreasing after about 10% moisture content. The reason for this phenomenon is unclear, and more careful experimentation is necessary to verify these results and determine the exact nature of its cause.

Figure 25 illustrates the overall decrease in velocity with increasing total density of the samples. Comparison of Figure 24 and Figure 25 shows a much better coefficient of determination (R^2 = 0.76 vs. R^2 = 0.38) for the arrival time vs. moisture content than the arrival time vs. moist unit weight. This may be the case because the effect of pore water damping is more significant than the change in density. The small volume of the samples makes density as a function of compaction energy more uncertain than for larger sample volumes, e.g., 4-inch proctor mold. This is illustrated in Figure 25 by lack of a clearly defined optimum moisture content.

Effect of Consolidation on Seismic Velocity

The correspondence between void ratio, *e,* and arrival time was very distinct, as shown in Figure 26. The increase in velocity can be attributed to a decrease in porosity and a corresponding increase in density and stiffness (Table 7). It is assumed that the cementation that occurs with aging is negligible over the loading period of 79 hours and that the settlement would discourage any formation of grain bonding due to cementation. In addition to stiffening, cementation would reduce the porosity, leading to an increase in velocity not attributable to settlement. The moisture content of the soil sample decreased only 0.3% over the duration of the experiment and is considered to have a negligible effect. It is also noted that the decrease in sample height during settlement reduces the distance of propagation and, subsequently, the arrival time. The effect of reduced sample height on arrival time was not accounted for in this study. An alternative test could be run under saturated conditions to more closely model the traditional consolidation test. In this case, shear waves may reflect more closely the skeletal changes as fluids do not support shear wave propagation. Fam and Santamarina (1997) studied consolidation using mechanical shear waves with similar results in kaolinite.

Summary / Conclusions

The effects of aging, moisture content, and consolidation upon seismic P-wave velocity were studied. Aging and consolidation increased wave velocity, whereas moisture content decreased wave velocity. The most precise results were obtained from the consolidation experiment with the P-wave arrival time closely following the change in void ratio. This suggests the possibility of an in situ device to monitor settlement in the field. However, the use of any in situ device must also be affected by changing moisture content and aging effects, such as stiffening and porosity reduction due to cementation.

The use of seismic studies in soils shows more promise in monitoring changes in soil properties rather than attempting to make absolute measurements of a particular soil property.

Capacitance

Introduction

Traditional field measurements of moisture content and dry unit weight of compaction are performed using a nuclear density gauge. Federal regulations, costs, maintenance, calibration, and safety make an alternative in situ method of compaction monitoring highly desirable.

This study evaluated the DMM600 Duff Moisture Meter, a capacitance based dielectric moisture sensor. The DMM600 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. Duff is highly organic, typically containing detritus, vegetation, etc. Moisture measurement consists of placing duff loosely into the sample chamber and then compressing the material to a preset pressure against a sensor plate containing the waveguides used to measure the dielectric constant of the material.

Figure 28. DMM600

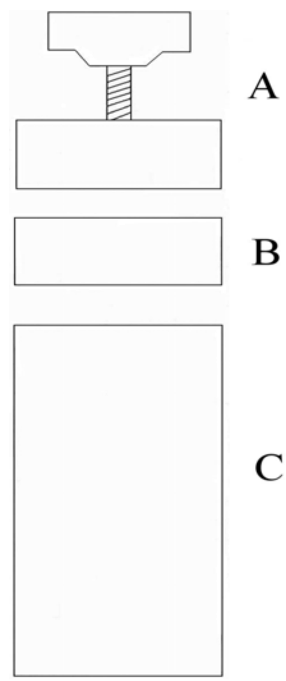

Figure 27. Major components of the DMM600: (A) sample chamber lid and compression knob, (B) sample chamber, and (C) electronics housing

Figure 29. DMM600 components: (A) sensor plate / waveguides, (B) electronics housing, (C) sample chamber, and (D) sample chamber cap including compression knob (right) and compression plate

In this research, it is proposed that the DMM600 may also be useful in mineral soil applications such as earthwork compaction monitoring. This study evaluates the performance of the DMM600 and develops a procedure for measuring the moisture and density of mineral soils.

Experimental Methods

Two experiments were performed for evaluation of the DMM600. The first one was an evaluation of soil calibration and instrument accuracy. The second experiment evaluates an alternative method in which a soil cutter containing the intact soil sample is placed into the DMM600 chamber.

Calibration of the DMM600 directly relates raw frequency output to the gravimetric moisture content of the soil. This method was chosen because it is the simplest and is easily incorporated into the standard procedure of proctor curve calculation. Furthermore, due to the self-contained instrument construction and flat waveguide geometry, measurement of dielectric solutions for alternative calibrations would be very difficult.

Evaluation of Soil Calibration and Instrument Accuracy

Two soil types, Oxidized Glacial Till and Western Iowa Loess, were used in this evaluation. The general laboratory procedure is as follows:

1. Screen air dried soil through a 2.360 mm sieve and thoroughly mix.

2. Choose a moisture range and prepare at least four water contents for instrument calibration (Paltineanu and Starr 2002).
3. Perform a standard proctor test for each water content.
4. Use a soil cutter to take a sample from the compacted proctor soil sample. This may be done using a soil extruder (Figure 30).

Figure 30. Use of a soil extruder and soil cutter to extract a sample for moisture measurement

5. Trim excess soil from the cutter (Figure 31).

Figure 31. Soil after extrusion ready to be trimmed

6. Weigh the cutter and soil and subtract the mass of the cutter to determine the moist unit weight. This can be used to determine a dry density for construction of a moisture density curve.
7. Extract the soil from the cutter and place in DMM600 sample chamber while maintaining integrity of the soil sample. Introduction of air gaps into the sample can lead to significant error. (Figure 32).

Figure 32. Soil placed in sample chamber

8. Turn out compression knob for adequate sample clearance and replace the sample chamber cap.
9. Turn on the DMM600 and turn the compression knob clockwise until the beep indicates that a measurement has been made. Raw frequency and moisture content are read from the display on the bottom of the electronics housing (Figure 33).

Figure 33. Frequency and calibration moisture content are displayed on the base of the electronics housing

10. Record the DMM600 frequency.

11. Turn the compression knob counter-clockwise until the sample chamber cap can be easily removed. Remove the sample chamber.
12. Extract soil sample from the DMM600 chamber and measure the gravimetric moisture content using a thermogravimetric method such as oven drying.
13. Perform calibration by fitting a second order polynomial to the calibration set of frequency—moisture content points. The resulting equation will be of the following form:

$$Gravimetric\ Moisture\ Content = b_0 + b_1 * frequency + b_2 * frequency^2 \quad (25)$$

    where b_x is soil dependent (Campbell Scientific, Inc. 2002).
14. Enter the calibration into the DMM600 or spreadsheet program. Note that the DMM600 will only output moisture content to 1% resolution.

Loess soil was screened through a 2.000 mm sieve, and calibration was performed using eleven points over a moisture range of 9.5%–20.8%. Eight points from 5.4% to 21.5% gravimetric moisture content were used for evaluation.

Oxidized glacial till was screened through a 2.360 mm sieve and proctor tests performed. The calibration consisted of five points over a range of 6.0%–14.4% gravimetric moisture content. Seven moisture contents over a range of 6.8%–13.1% were used for evaluation. The dry unit weight values determined from the soil cutter were compared to those found using the 100 mm (4-inch) proctor mold.

Evaluation of Alternative Method Utilizing a Soil Cutter

To increase the efficiency of soil testing using the DMM600, an alternative means of sample preparation was evaluated. The procedure is the same as that outlined above, with exception that the cutter containing the trimmed soil sample is placed into the DMM600 sample chamber (Figure 34). This eliminates the need to extrude the sample from the cutter. The proposed advantages of this method are time savings and minimized sample disturbance.

Oxidized glacial till was screened through a 2.360 mm sieve, and twelve soil samples were prepared at a range of moisture contents from 5.6% to 13.9% gravimetric moisture content. Five of the samples were used for calibration and the remaining seven were used to evaluate the overall accuracy. The cutter used in this experiment was machined to an outer diameter of 73.66 mm (2.900 inch) and a height of 19.05 mm (0.750 inch) to fit into the sample chamber and allow sufficient clearance for the sample compression plate such that binding does not occur during compression.

Figure 34. Intact soil sample and soil cutter placed upon sensor plate for moisture measurement

Results

Evaluation of Soil Calibration and Instrument Accuracy

Western Iowa Loess Soil Results

The resulting calibration for western Iowa loess soil is shown in Figure 35.

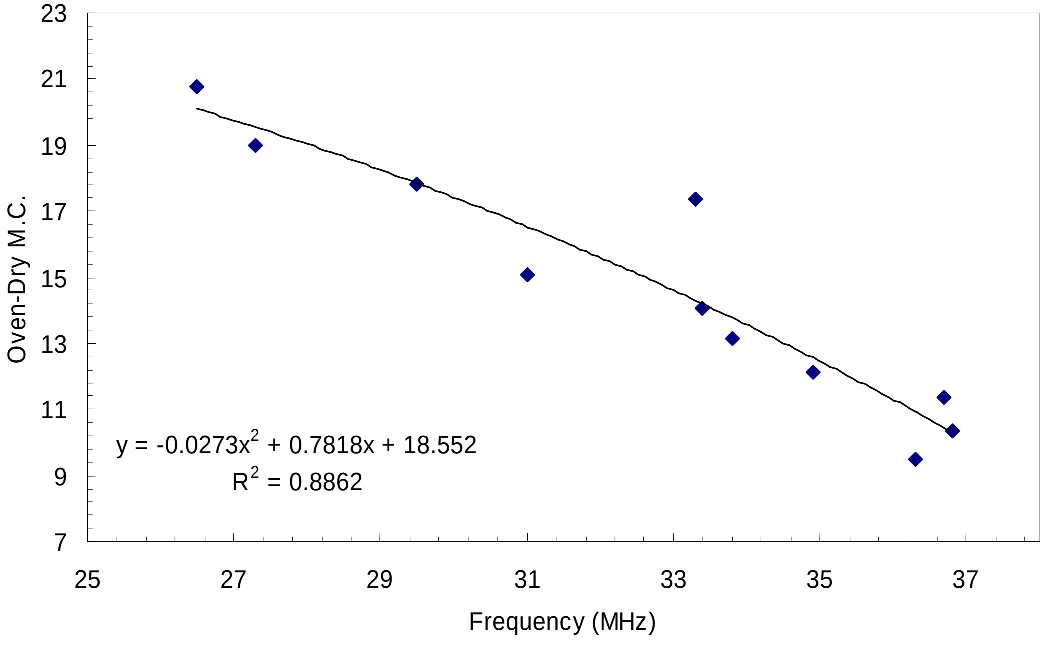

Figure 35. DMM600 Western Iowa Loess calibration curve relating oven-dry gravimetric moisture content to DMM600 frequency output

The displayed moisture content resolution of the DMM600 is 1%. In the case of duff material, the uncertainty is certainly high enough that 1% resolution is adequate. However, 0.1% resolution can be achieved by simply calculating the moisture content manually based upon the calibration curve and DMM600 frequency output. The DMM600 rounds moisture content values down to the nearest whole percent. The loss of resolution due to this round down is illustrated in Figure 36. To evaluate the significance of this rounding error, correlations are calculated for both the rounded-down and approximated moisture contents. In this report, rounded-down moisture contents refer to moisture contents given in 1% resolution, while approximated moisture contents refer to moisture contents given in 0.1% resolution.

The results are shown in Figure 37 and Figure 38. Good correlation is shown between oven-dry moisture content and DMM600 calculated moisture content. The coefficients of determination are $R^2 = 0.855$ at 1% resolution and $R^2 = 0.811$ at 0.1% resolution. The standard errors are 1.842 and 2.041, respectively.

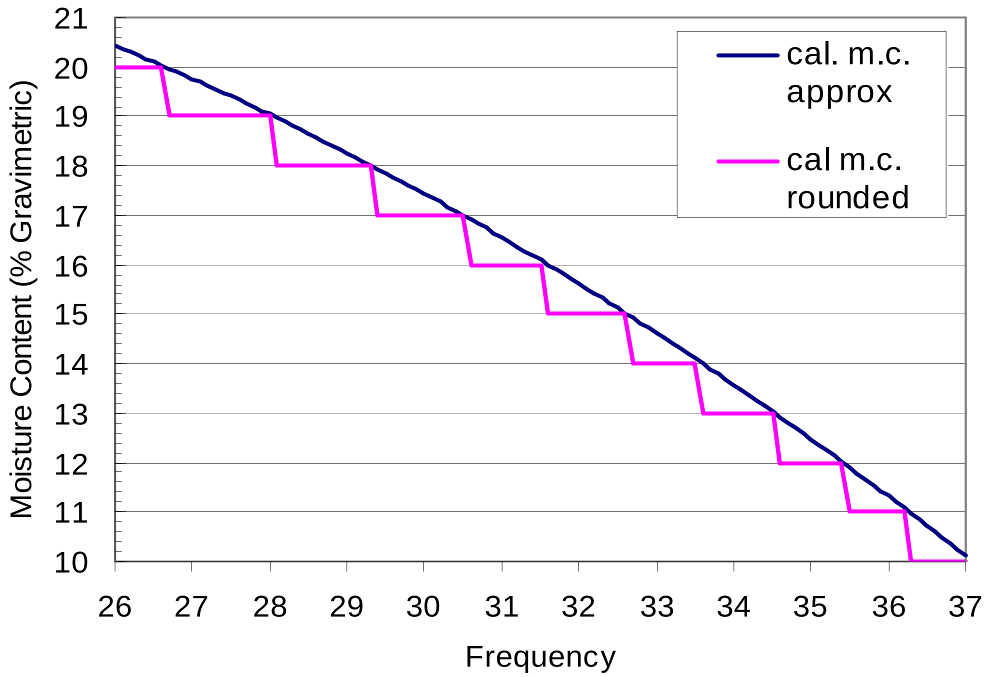

Figure 36. DMM600 displays moisture content to 1% resolution, rounding down to the nearest whole number. This is illustrated by the "cal m.c. rounded down" line.

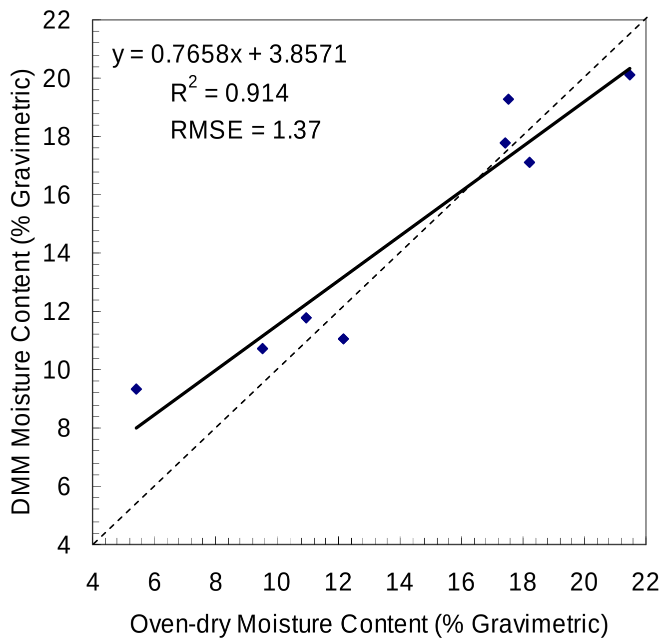

Figure 37. Linear regression of Approximated DMM600 moisture content to oven-dry moisture content for Western Iowa Loess. Approximate DMM600 moisture values calculated independently.

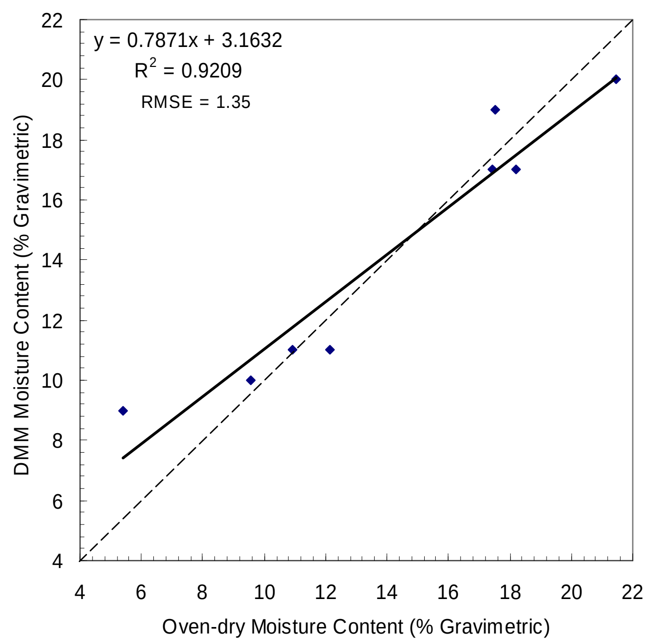

Figure 38. Linear regression of Western Iowa Loess rounded-down DMM600 moisture contents to oven-dry gravimetric moisture contents. Rounded-down DMM600 moisture values represent instrument display resolution.

Oxidized Glacial Till Soil Results

The calibration curve for Oxidized Glacial Till is given in Figure 39. The corresponding linear regressions are provided in Figure 40 and Figure 41. In this evaluation, five calibration points were used. The coefficients of determination are $R^2 = 0.882$ at 0.1% resolution and $R^2 = 0.854$ at 1% resolution. The standard errors are 1.283 and 1.633, respectively.

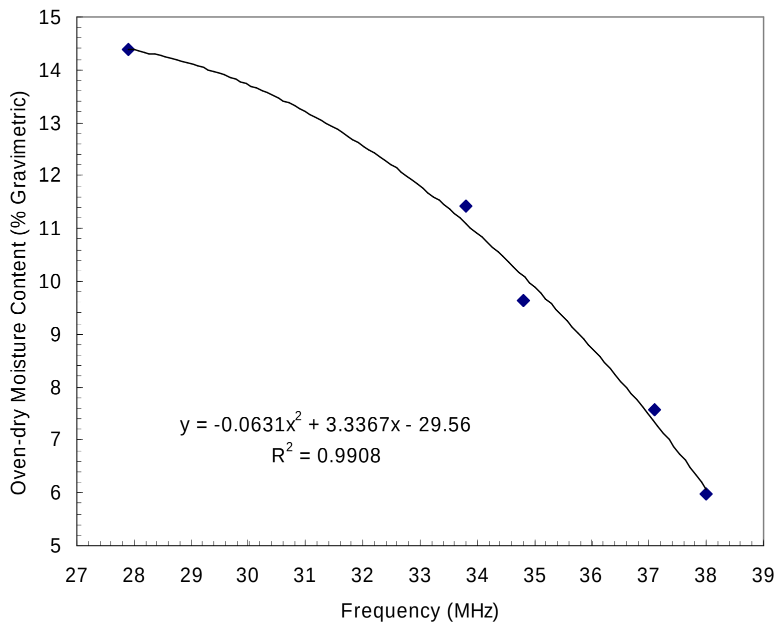

Figure 39. DMM600 calibration curve for Oxidized Glacial Till relating DMM600 raw frequency output to oven-dry gravimetric moisture content

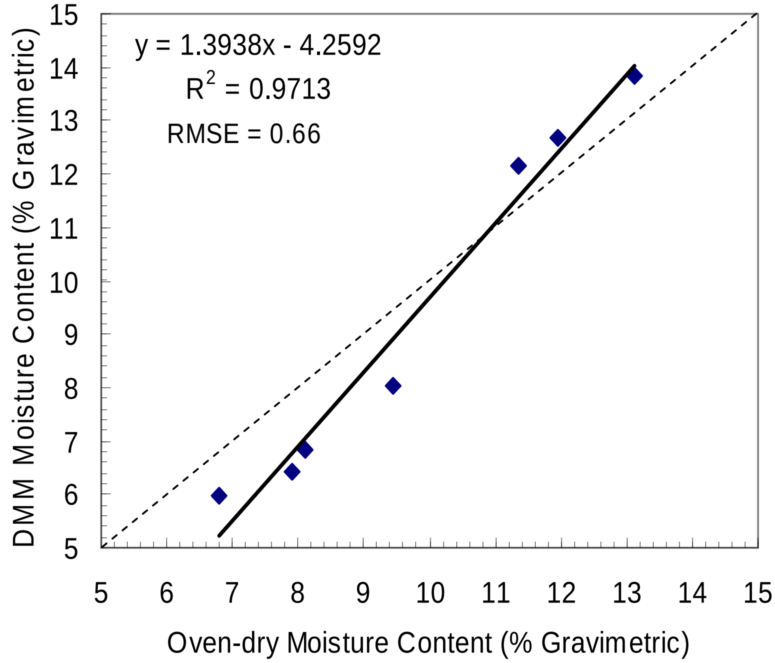

Figure 40. Oxidized Glacial Till linear regression of Approximated DMM600 moisture content to oven-dry moisture content. Approximate DMM600 moisture values calculated independently.

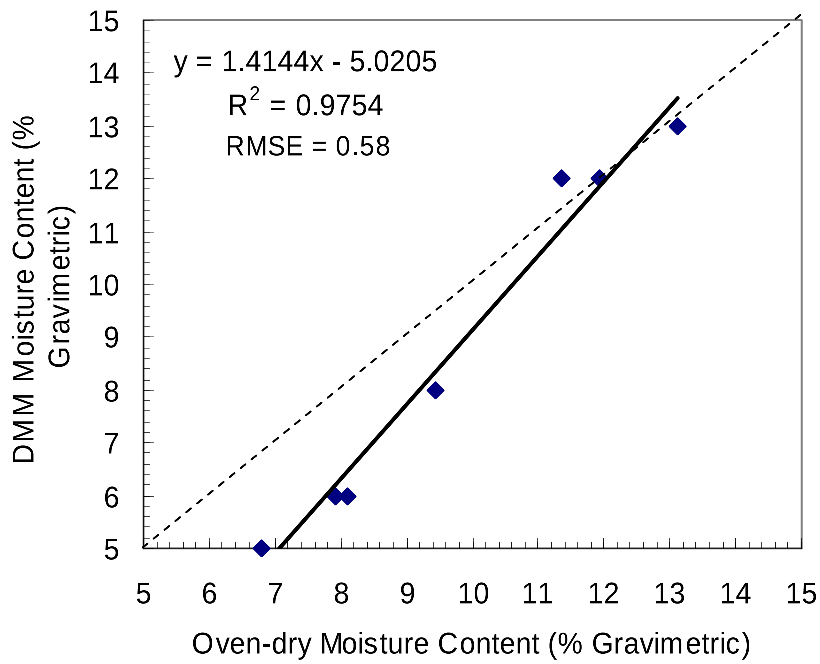

Figure 41. Oxidized Glacial Till linear regression of DMM600 moisture content to oven-dry moisture content. Rounded-down DMM600 moisture values represent instrument display resolution.

The comparison between dry unit weight values determined using cutter samples extracted from proctor molds and dry unit weight values determined from proctor molds is given in Figure 42. The coefficient of determination is $R^2 = 0.542$, and the standard error of prediction is 0.449.

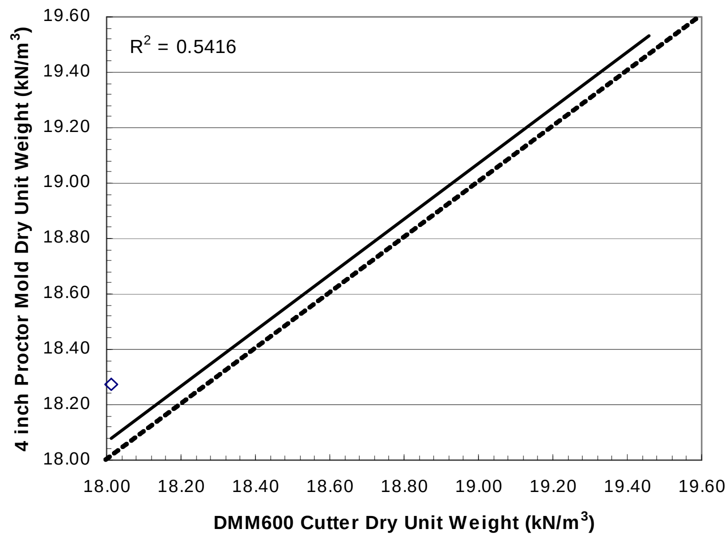

Figure 42. Comparison of dry unit weight determined by soil cutter and 4-inch proctor mold for Oxidized Glacial Till

<u>Evaluation of Alternative Method Utilizing a Soil Cutter</u>

In this experiment, the soil was not extruded from the soil cutter. The soil was trimmed flush to the top and bottom of the cutter and then inserted into the DMM600 sample chamber. Using this method, the trimmed side of the sample is rougher (pitted) than the other side which corresponds to the untrimmed end of the proctor mold. Both rough and smooth sides of the soil samples were tested in the DMM600 to evaluate the influence of surface texture.

The soil used in this experiment is oxidized glacial till prepared as above. Figure 43 shows the calibration curve for the rough side of the soil sample, while Figure 44 shows the calibration curve for the smooth side of the soil sample. Figure 45 and Figure 46 show the results from the rough-side samples for both approximated and rounded-down values. Figure 47 and Figure 48 show the results from the smooth-side samples for both approximated and rounded-down values. Table 16 provides a summary of the experimental data and results.

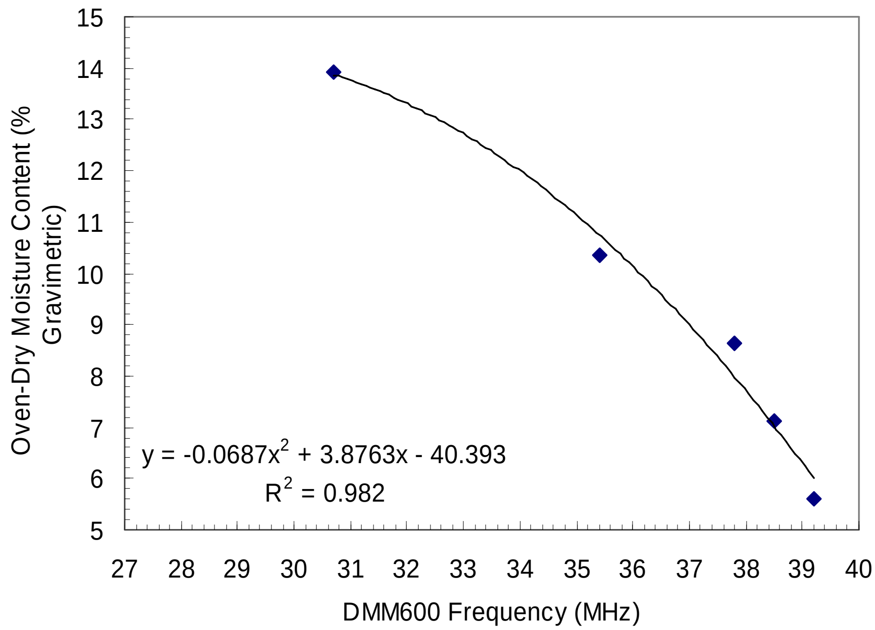

Figure 43. DMM600 calibration curve of Oxidized Glacial Till. The rough side of the soil sample is placed in contact with waveguides.

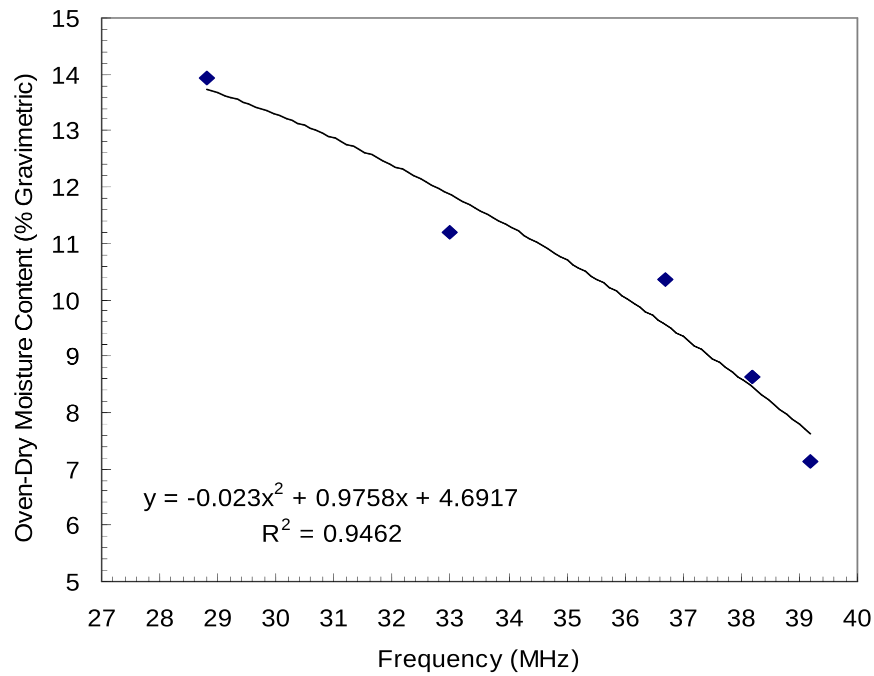

Figure 44. DMM600 calibration curve of Oxidized Glacial Till. The smooth side of the soil sample is placed in contact with waveguides.

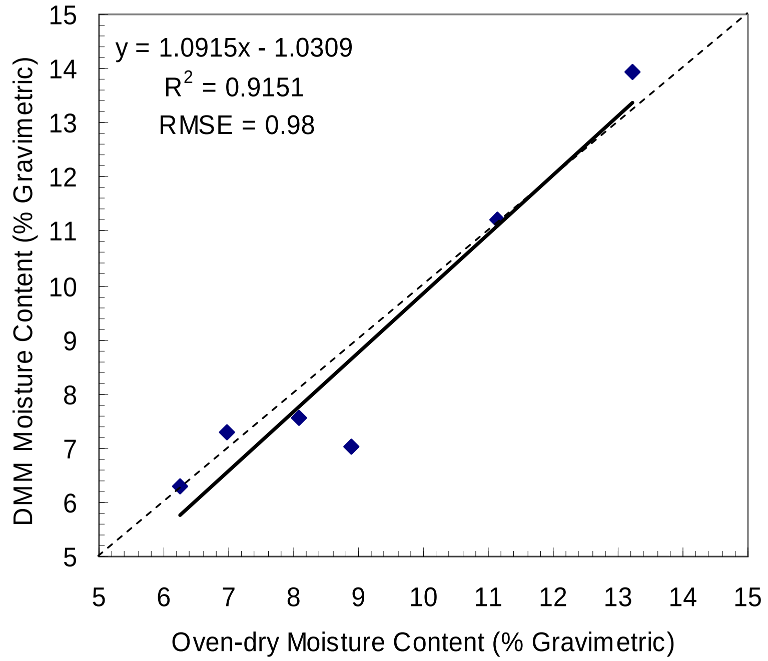

Figure 45. Linear regression of DMM600 moisture content to oven-dry moisture content. DMM600 moisture values approximated. Rough side of soil sample.

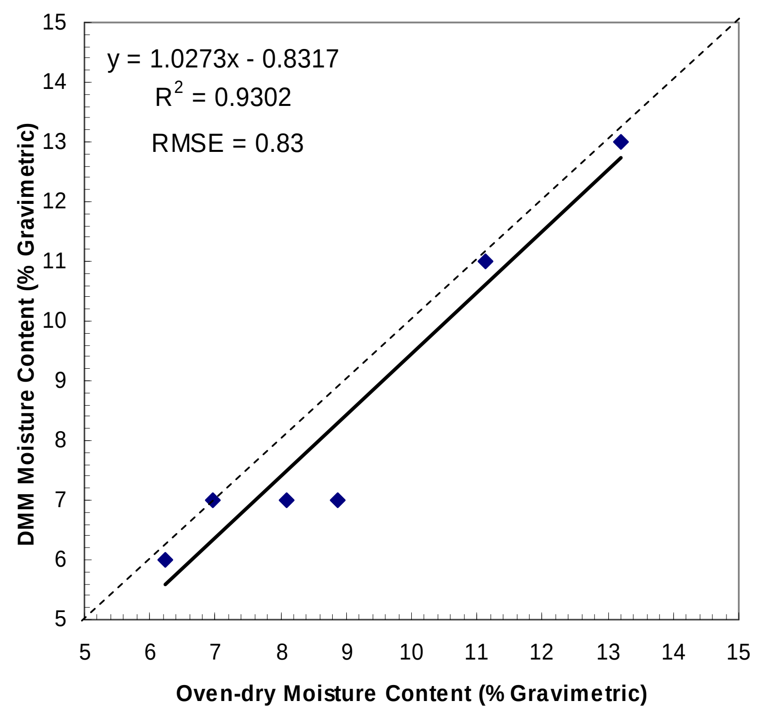

Figure 46. Linear regression of DMM600 moisture content to oven-dry moisture content. DMM600 moisture values rounded down. Rough side of soil sample.

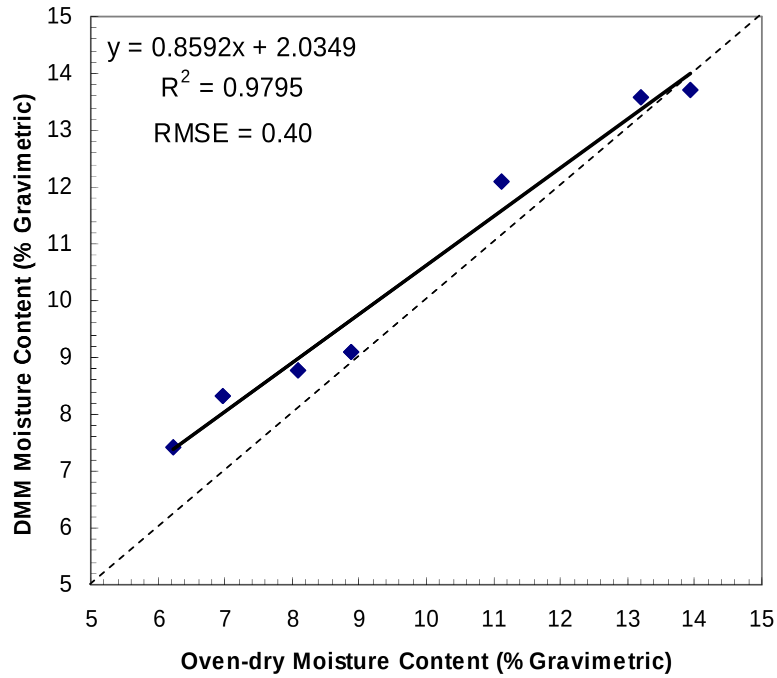

Figure 47. Linear regression of DMM600 moisture content to oven-dry moisture content. DMM600 moisture values approximated. Smooth side of soil sample.

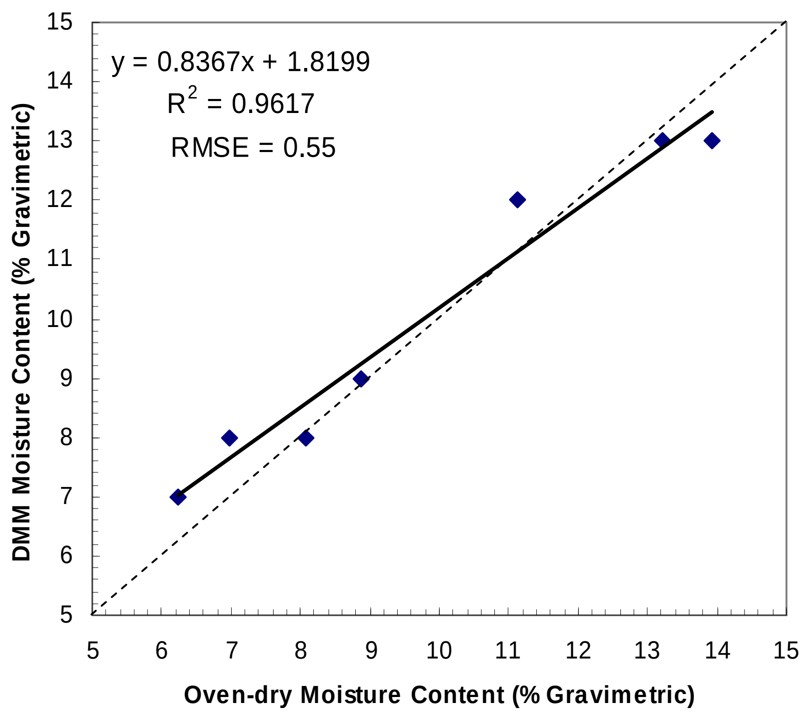

Figure 48. Linear regression of DMM600 moisture content to oven-dry moisture content. DMM600 moisture values rounded down. Smooth side of soil sample

Table 16. Data source, calibration equations, coefficient of determination (R2), standard error of the estimate (S_{est}), and the number of evaluation observations (N)

Calibration		Validation						
		Approximated			Rounded Down			
Data Source	**Equation**	R^2	S_{est}	RMSE	R^2	S_{est}	RMSE	N
W. Iowa Loess	$\theta_g = -0.0273f^2 + 0.7818f + 18.552$	0.91	2.0	1.37	0.92	1.8	1.35	8
Oxidized Glacial Till	$\theta_g = -0.0631f^2 + 3.3367f - 29.56$	0.97	1.3	0.66	0.98	1.7	0.58	7
Till & Cutter: Rough Side	$\theta_g = -0.0687f^2 + 3.8763f - 40.393$	0.92	0.9	0.98	0.83	1.0	0.83	7
Till & Cutter: Smooth Side	$\theta_g = -0.023f^2 + 0.9758f + 4.6917$	0.98	1.0	0.40	0.96	0.7	0.55	7

Discussion

Significance of Soil Type

Comparison of the Western Iowa Loess and Oxidized Glacial Till data sources in Table 16 shows overall improvement in the coefficient of determination and standard error for the till soil over the loess soil. The standard error of the loess soil is 37% greater than the till soil using the approximated moisture contents and 10% greater using the rounded-down moisture contents.

Significance of Calculating Moisture Contents to 0.1% compared to 1%

The difference between results using 0.1% resolution and 1% resolution was not that significant. Nor was there consistent improvement in standard error using 0.1% resolution over 1% resolution. Calculating the moisture content to 0.1% resulted in a 10% increase in standard error for the Western Iowa Loess, a 23% decrease for the Oxidized Glacial Till, a 5% decrease for the Till & Cutter: Rough Side, and a 31% increase for the Till & Cutter: Rough Side. From this study, it cannot be concluded that calculating the moisture content to 0.1% resolution improves the accuracy of the method.

Significance of Alternative Method Utilizing a Soil Cutter

The lowest standard errors and highest coefficients of determination were obtained using this method. The Till & Cutter: Rough Side data set is more relevant than the Till & Cutter: Smooth Side data set because all field samples will necessarily be tested using a rough, trimmed face of the sample. The Till & Cutter: Rough Side data set standard errors were 27% lower for the approximated moisture contents and 41% lower for the rounded-down moisture contents than the Oxidized Glacial Till data set. This is a significant improvement in both cases.

The ease of testing was significantly improved using this method; although, the sample size was necessarily decreased to facilitate a smaller cutter that would fit into the DMM600 sample chamber. It is probable that the DMM600 zone of influence is very small, such that the smaller sample size is of little significance for moisture measurements. However, if bulk density measurements are to be based upon the volume of the soil cutter, then a reduced volume will likely require more samples to achieve the desired accuracy.

Significance of Using the Cutter Volume to Estimate the Dry Density

This experiment was performed using the Oxidized Glacial Till data set. The results are shown in Figure 42. The coefficient of determination was 0.542 and the standard error was 0.449. Only one sample was taken from each proctor mold, and this likely contributed to the most significant error as each of the three layers will have a different density. It may be necessary to take up to three cutter samples from each proctor mold during calibration to achieve better accuracy. Furthermore, the DMM600 measures volumetric moisture content. This means that the moisture content and bulk density are dependent. Thus, significant error in measurement of bulk density necessarily leads to significant error in moisture content.

General Comments

If there is a significant difference in the bulk density of field samples compared to the samples used for calibration, the measured moisture content may err significantly from the actual moisture content.

The accuracy of measuring bulk density in the field may be compromised by the relatively small sampling volume provided by the soil cutters. In the case of the 0.750-inch-high by 2.900 inch in diameter cutter, the sampling volume is only 2.87 E -3 ft^3. For comparison, the sample volume of a standard proctor mold is 3.33 E -2 ft^3, over an order of magnitude smaller. This small sampling volume may not be able to account for the global variability in the soil population, and many samples may need to be taken to achieve sufficient accuracy. A field evaluation should be performed to evaluate the significance of this problem.

Summary / Conclusions

The DMM600 Duff Moisture Meter used according to the methods described in this report reveals a promising alternative for soil compaction monitoring. In this study, a DMM600 was used to measure the moisture content of soil samples extracted from compacted proctor samples. Calibration curves relating DMM600 frequency to gravimetric moisture content were constructed and evaluated on additional soil samples with good results. A method in which a soil cutter containing the intact soil sample is placed directly into the DMM600 sample chamber was evaluated with good results. The significance of this method is that it does not require extraction of the soil from the cutter, reducing measurement time and improving sample integrity. It is stressed that a field evaluation is needed to evaluate this method.

Thermal Property Methods

Introduction

The purpose of this portion of the study was to evaluate the effects of moisture content and dry density upon thermal measurements for two different soils. A single-probe transient heat pulse type instrument was used to make measurements of thermal conductivity and thermal diffusivity. From these values, the volumetric heat capacity was calculated. Dry density and moisture content were then plotted versus the measured thermal properties.

Experimental Methods

The measurement method used in this study was the single-probe transient method. Alternative methods include the steady-state method and dual-probe transient method. The steady-state method is not recommended for soil thermal analysis as it requires removal of the soil from the in situ state and can cause water redistribution from the constant temperature gradient (Bristow 2002). In all of the literature reviewed for this study, the dual-probe transient method has been used. However, at the time of this study, a single-probe unit was recently put on the market that incorporated a probe and hand-held reader and provided relatively fast measurement times compared to the other instruments reviewed. To the authors' knowledge, there has been no previous independent study using this particular instrument.

A Decagon Devices, Inc. (Pullman, WA) KD2 Thermal Properties Analyzer was used to make the thermal measurements. The soils used were Oxidized Glacial Till and Western Iowa loess. The first study investigated the change in thermal properties with bulk density (dry density) and the second investigated the changes in thermal properties with moisture content.

Materials

- Decagon Devices, Inc. KD2 Thermal Properties Analyzer (Figure 49)
- Volumetric cylinder
- Tamping device

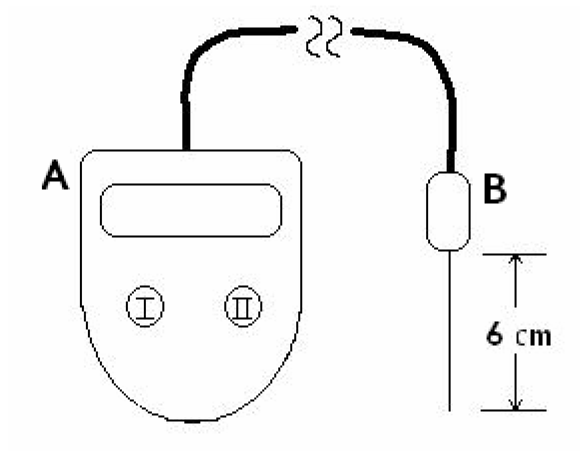

Figure 49. Thermal properties meter: (A) hand-held reader and (B) needle probe sensor (6 cm in length by 1.28 mm in diameter)

Figure 50. Decagon Devices KD2 Thermal Properties Analyzer

<u>Instrument Procedure</u>

The KD2 measures thermal conductivity, resistivity, and diffusivity in a single measurement and requires no calibration. Operation of the KD2 is covered in detail in the KD2 User's Manual (Decagon Devices, Inc. 2004). Readings are taken by inserting the needle into the soil and starting the measurement cycle. After about two minutes, the results are displayed on the display screen. If desired, heat capacity may be calculated using these readings.

<u>Varied Bulk Density Sample Preparation</u>

Till soil was passed through a 4.750 mm sieve, and distilled water was added to achieve a gravimetric moisture content of 11%. The loess soil was passed through a 2.000 mm sieve and distilled water was added to achieve a gravimetric moisture content of 14%. Both soils were allowed to equilibrate for 24 hours in a 22°C environment. The soils were then packed into a volumetric cylinder from which the volume could easily be determined. The probe needle was inserted into the soil and three readings were taken with at least five minutes in between measurements to allow for heat dissipation, according to the manufacturer's recommendation. The probe was not removed from the soil in between measurements. The same soil was then compacted further and additional measurements were taken. Twelve measurements were taken for each soil, at four different bulk densities with three replications per density. The till was compacted at bulk densities of 1.14 to 1.58 gm cm^{-3} and the loess was compacted from 1.04 to 1.27 gm cm^{-3}.

Varied moisture content sample preparation

Till soil was passed through a 4.750 mm sieve and distilled water was added to achieve volumetric moisture contents from 7.1% to 20.5%. Loess was passed through a 2.000 mm sieve and distilled water was added to achieve volumetric moisture contents from 5.9% to 28.6%. Both soils were packed into cylinders at constant bulk density. Care was taken to achieve uniform density throughout the soil column. The till was compacted to 1.3 gm cm^{-3}, while the loess was compacted to 1.2 gm cm^{-3}. Five different moisture contents were prepared for each soil, and thermal property measurements were taken as described above. Fifteen measurements were taken for each soil at five different moisture contents, with three replications per moisture content.

Results

Variation of thermal properties with bulk density is presented in Figure 51 and Figure 52 for the Till and Loess soils respectively. The overall trend is an increase in thermal conductivity and diffusivity with uncertain results for volumetric heat capacity. These trends are to be expected as the increased bulk density increases the particle-particle contact area, allowing more heat flow through the solid fraction of the sample.

Variation of thermal properties with volumetric moisture content is presented in Figure 53 and Figure 54. The overall trends reveal an increase in thermal conductivity, diffusivity, and volumetric heat capacity. The trend for volumetric heat capacity is more defined for the loess than the till. This may be due to increased needle-particle contact in the finer grained loess compared to the till.

Summary / Conclusions

The expected trend is an increase in soil thermal property values with increased bulk density and moisture content (Abu-Hamdeh and Reeder 2000; Bristow 2002; Ochsner et al. 2003). While the data sets presented here are small, the trends are evident. The KD2 is a relatively new sensor on the market and, to the authors' knowledge, there are no published studies using this instrument. While previous studies have presented theoretical equations for determining absolute moisture content, these are modeled after dual-probe heat-pulse instruments, while the KD2 is a single probe type instrument. This does suggest the potential for absolute moisture content measurements. The major downfall of this technique however is the relatively long time (>2 min) needed per measurement, compared to other techniques such as TDR and capacitance methods.

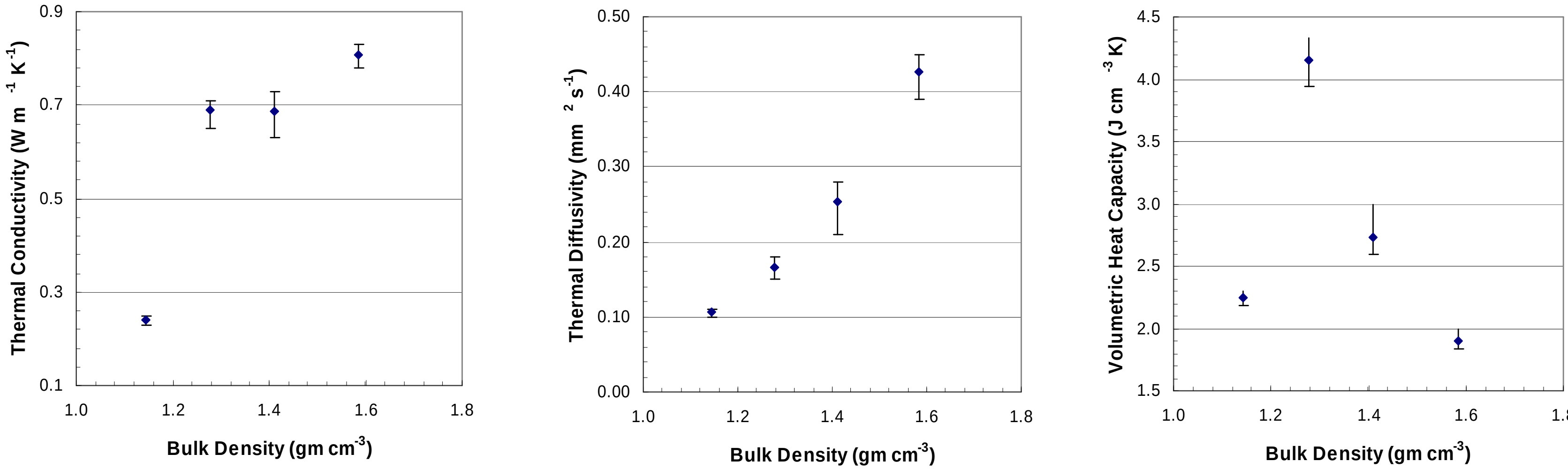

Figure 51. Till soil thermal properties vs. bulk density at a gravimetric moisture content of 10.7%

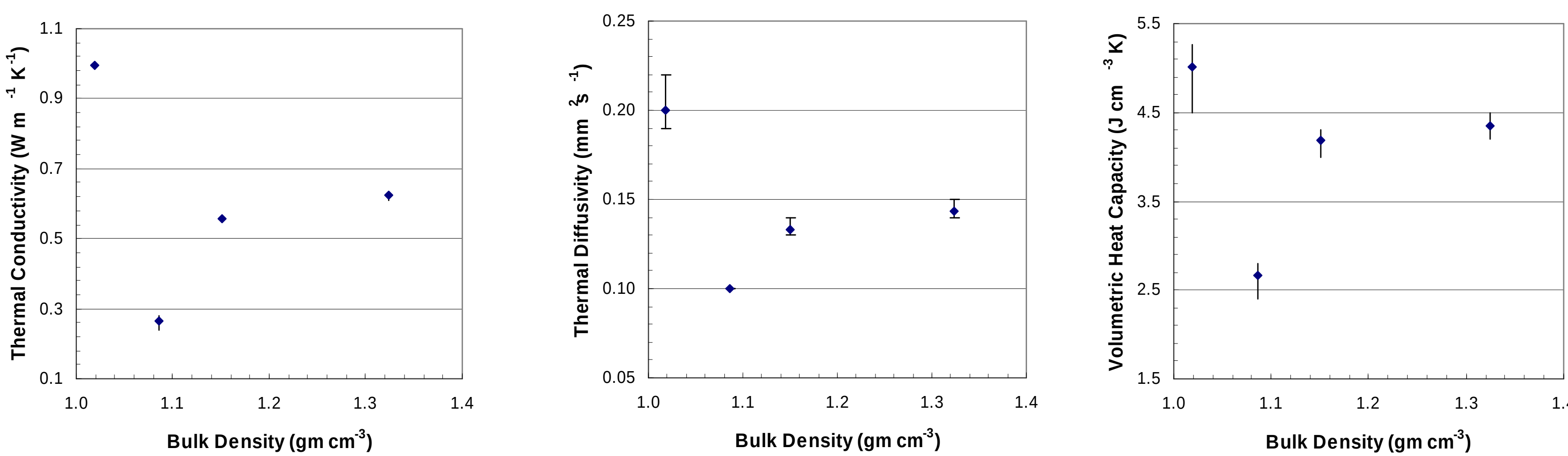

Figure 52. Loess soil thermal properties vs. bulk density at a gravimetric moisture content of 13.8%

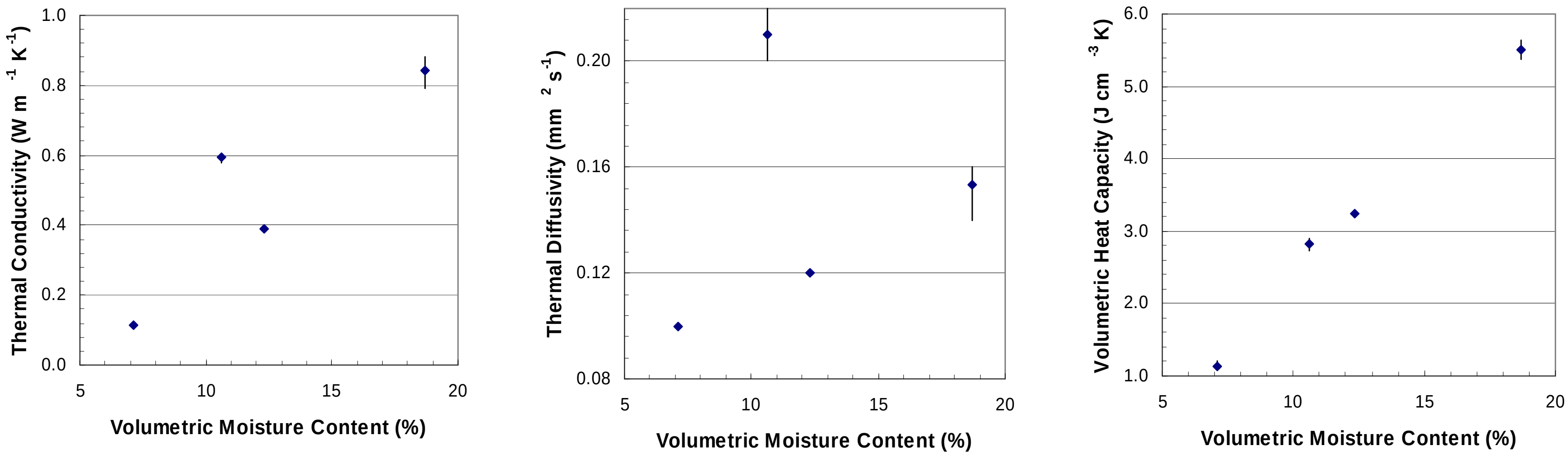

Figure 53. Till soil thermal as volumetric moisture content at a bulk density of 1.30 gm cm^{-3}

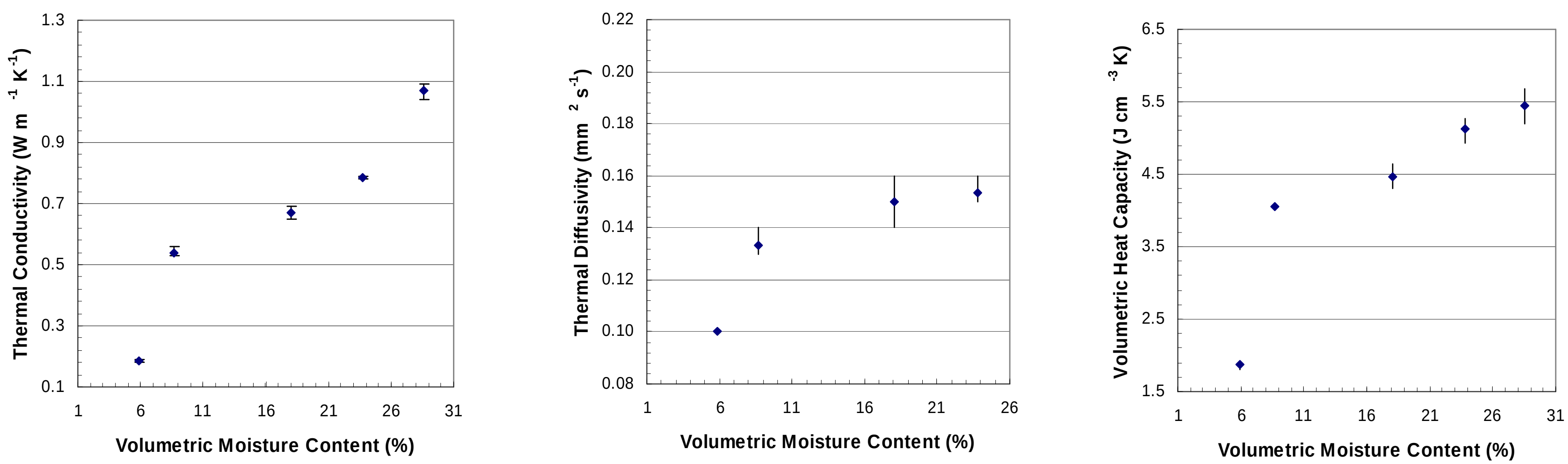

Figure 54. Loess soil thermal as volumetric moisture content at a bulk density of 1.17 gm cm^{-3}

DISCUSSION

General Discussion

The goal of this research was to review and selectively evaluate current nondestructive techniques that could potentially improve field quality control operations by (1) increasing the coverage area in lieu of spot tests, (2) providing engineering parameter values that provide better estimates of "quality," and (3) speeding up the inspection process and providing real time results in computer format.

Current practice relies primarily upon method specifications (e.g., sheepsfoot walkout) or field spot testing (e.g. nuclear density gauge, gravimetric sampling). The disadvantages of these methods are a lack of quantitative data in the case of method specifications and very small coverage area in the case of spot testing.

In this study, several technologies have been evaluated in an attempt to learn which hold the greatest potential for overcoming the shortcomings of current practice. The following is a list of technologies investigated in this study:

- Nuclear methods
- Seismic methods
- Dielectric methods
- Magnetic methods
- Thermal methods
- Spectroscopy

The criterion for their potential is based upon how well they meet, or potentially meet, the three objectives stated above. Quantitative and qualitative measures by which these criteria may be met are the following:

1. Increasing the coverage area in lieu of spot tests
2. Providing engineering parameter values that provide better estimates of "quality"
3. Speeding up the inspection process and providing real time results in digital format

To provide a basis for evaluating each technology, the following value-based selection method has been adapted from Cape (1997). Cape (1997) developed a table of soil moisture sensor attributes deemed most important by potential users. Weights and ranks from the responses were then assigned to each attribute identified. Basic questions concerning a potential sensor are asked and a score of 1 or 0 is assigned to an answer of Yes or No. These scores are multiplied by a weighting factor for each attribute, resulting in the "relative importance" of the attribute. The relative importance scores are then tallied and a comparison between sensors can be made.

This method has been adapted so that a potential user can evaluate the technologies listed above according to the quantitative and qualitative measures of how well they meet the three measures stated above. To do this, each objective is assigned a series of questions relating to sensor attributes that can be answered in a yes/no manner. Additional attributes that fall outside the three objectives are also included. Many of the attributes are taken from Cape (1997) and are assigned the original weights as given by him. Additional weighting factors must be assigned for the attributes added by us according to relative importance, that a potential user feels is most important; likewise, the weights already assigned may be changed to reflect the user's application.

The following procedure is given by Cape (1997):

1. For each Yes or No answer, score a one (1) or zero (0) in column B.
2. For each attribute, multiply the point in column B with the weight in column A to obtain column C, the relative importance.
3. Total all the values in column C to obtain the total relative importance, T.
4. Calculate COST, the total estimated life cost of the sensor, by estimating capital, installation (if applicable), running, and maintenance costs for the expected life of the sensor.
5. Divide COST by LIFE, the expected life of a sensor in years, to determine A, the annual cost of the sensor.
6. A = COST/LIFE
7. Divide the total relative importance, T, by the annual cost of the sensor to obtain the value, V, of the sensors.
8. V = T/A
9. The sensor with the highest value, V, may be the best choice to suit both your needs and provides the best value for cost.

See Table 17.

Table 17. Value-based technology/sensor evaluation table

Attributes	Weight (A)	Device 1		Device 2	
		Point (B)	Score (C)	Point (B)	Score (C)
1. Increasing coverage area in lieu of spot tests.					
Is this sensor only capable of spot tests? (Yes = 1; No = 0)					
Is the measurement volume acceptable? (Yes = 1; No = 0)					
Is the level of invasiveness acceptable? (Yes = 1; No = 0)					
Does this sensor have real-time measurement potential? (Yes = 1; No = 0)					
2. Providing engineering parameters that provide a better estimate of quality.					
Is the range of moisture measurement acceptable? (Yes = 1; No = 0)	**8**				
Is the accuracy acceptable? (Yes = 1; No = 0)	**14**				
Is accuracy affected by soil type? (Yes = 0; No = 1)	**11**				
Does the sensor provide more than one parameter per measurement? (Yes = 1; No = 0)					
3. Speeding up the inspection process and providing real time real-time results in digital format.					
Is the speed of measurement acceptable? (Yes = 1; No = 0)	**8**				
Is data handling and interpretation easy? (Yes = 1; No = 0)	**8**				
Does the sensor provide data logging, download capabilities, friendly software for analysis and interpretation? (Yes = 1; No = 0)	**10**				
4. Operation and Maintenance.					
Is the sensor easy to use? (Yes = 1; No = 0)	**2**				
Is the calibration universal? (Yes = 1; No = 0)	**2**				
Does the sensor have long life (> 5 years)? (Yes = 1; No = 0)	**2**				
Is the sensor maintenance free? (Yes = 1; No = 0)	**2**				
Is the sensor easy to install (if applicable)? (Yes = 1; No = 0)	**2**				
5. Miscellaneous.					
If you have evidence of the sensor's reliability is the failure rate acceptable? (Yes = 1; No = 0)	**13**				
Does the sensor pose an acceptable safety risk? (Yes = 0; No = 1)	**8**				
Total (T) of score column (C)	**X**				

Discussion of Preliminary Evaluations

Preliminary evaluations for permittivity (TDR and capacitance methods), seismic, and thermal technologies were conducted and presented in the Evaluation of Selected Technologies section of this report. The soil permittivity technologies showed the greatest promise for an alternative soil moisture sensing technology in civil engineering. This is due in part to the rapid commercial development of these sensors for use in the agricultural markets. The major downfall of all the technologies evaluated was their inability to measure soil bulk density, and, consequently, the fallibility of their respective soil moisture calibrations. Furthermore, if soil specific calibrations are necessary to achieve desired accuracy, what is the best method of calibration? There is no industry standard for calibration procedure or standard method of reporting sensor accuracy.

Field calibration is difficult as the desired range of moisture contents may not be available and would require knowledge of the soil moisture either a priori or after field measurement. Because the standard method of determining soil moisture content is by oven-drying for 24 hours, this is not acceptable for efficiency reasons and because the moisture and/or density of the field plot used for calibration probably have changed by the time the calibration is finished. Alternatively, the microwave method of drying soil or a portable stove could be used.

Laboratory calibration using soil taken from the field is an option but still requires drying the soil for moisture determination. Furthermore, the discrepancy between in situ soils and disturbed laboratory samples will be unknown.

A solution to the problem of calibration would be to use an empirical correlation, such as Topp's equation, and simply accept the uncertainty. Given the typical designation of +/- 2% of optimum moisture content in earthwork construction, this may be an acceptable alternative; although, the accuracy of the calibration must still be verified.

The use of a DMM600 Duff Moisture Meter (Campbell Scientific, Logan, Utah) to measure soil moisture was a new application of this instrument, as it was designed for soft organic materials. A novel technique was used in which a soil cutter containing a soil sample was placed directly into the DMM600 sample chamber to find both the moisture content and density of the soil. Using a portable scale, this method could be used in the field to measure both volumetric and gravimetric moisture content and dry density. One problem with this method is that the scale must be robust enough to handle large changes in temperature, very low and very high temperatures, and wind. As with TDR, calibration is another problem that must be dealt with for this method to work efficiently and accurately.

Seismic technology is an interesting tool but is too sensitive to soil stiffness and density changes to be a reliable guide to soil moisture content. It may be a useful technique for in situ monitoring of settlement and stiffening due to diagenetic affects over time.

Thermal properties measurement does show promise in the long-term monitoring of soil moisture changes. However, the measurement time is at present too long (>2min) to be of practical use for construction applications.

Soil thermal properties are subject to changes in both soil moisture content and bulk density; therefore, soil moisture calibrations would require knowledge of changes in soil bulk density to obtain accurate results.

Statistical Methods for Soil Moisture Measurements

This section is based upon "How Many Soil Water Content Measurements are Enough?" (Campbell Scientific, Inc. 2001).

Large variations in soil texture, structure, and moisture content are possible within a relatively small volume of soil. Given the small measurement volume and high sensitivity of most moisture sensors, it is therefore necessary to take more than one measurement to get a true picture of the soil moisture content.

The confidence interval is the sum of values that lie below and above the population mean and is described by the following formula:

$$\mu - k\frac{\sigma}{\sqrt{(n)}} < \bar{x} < \mu + k\frac{\sigma}{\sqrt{(n)}} \qquad (26)$$

where μ is the population mean, k is the confidence coefficient that specifies a probability value, σ is the population standard deviation, and n is the number of samples. This equation results in a range within which a measured mean will fall for a specified probability.

An alternative form of the previous equation is one which describes the probability that a given interval includes the actual population mean. This equation assumes that the population mean and population standard deviation are known in advance:

$$\bar{x} - k\frac{\sigma}{\sqrt{(n)}} < \mu < \bar{x} + k\frac{\sigma}{\sqrt{(n)}} \qquad (27)$$

Because the population standard deviation and population mean cannot be known in advance, they must be estimated. This is accomplished by estimating a population standard deviation from a sample standard deviation and applying student's t-distribution:

$$\bar{x} - t\frac{s}{\sqrt{(n)}} < \mu < \bar{x} + t\frac{s}{\sqrt{(n)}} \qquad (28)$$

where t is the student's t-value corresponding to a specified confidence interval and s is the estimated sample standard deviation. The value s must be estimated from trial measurements, previous data, or experience. The value t is obtained from published tables of student's t-values where the degrees of freedom are *n-1* and a desired confidence interval is known.

The minimum number of samples necessary to achieve a desired level of confidence is often the chief desire of the experimenter. If the sample mean and sample standard deviation are known and a confidence interval is chosen, the minimum number of samples is given by the following formula:

$$N = \frac{4 t^2 s^2}{L^2} \qquad (29)$$

where N is the minimum number of measurements and L is the acceptable range of measurements specified by the experimenter. The values t and s are found as described above.

SUMMARY AND CONCLUSIONS

A review of commercially available technologies for moisture measurement was undertaken. Seven principal techniques were identified and evaluated: (1) gravimetric, (2) dielectric, (3) nuclear, (4) spectroscopic (5) ultrasonic, (6) electromagnetic induction, and (7) thermal methods. The primary disadvantage of all the methods is the small sample volume measured. Additionally, all the methods possessed some sensitivity to non-moisture factors that affected the accuracy of the results. As the measurement volume increases, local variances are averaged out providing better accuracy. Most dielectric methods with the exception of ground penetrating radar have a very small measurement volume and are highly sensitive to variations in density, porosity, etc. Nuclear methods tend to have a large measurement volume and are less sensitive to variations in density (neutron thermalization), resulting in low variability. Near infrared method is capable of measuring a large surface area very quickly but cannot be expected to measure at depths more than several millimeters.

The state of the art in soil moisture sensing technologies today is dielectric methods, the most popular techniques of which are TDR and capacitance type sensors. While much progress has been made in the development of these technologies, they are still lacking with respect to the timeliness and difficulty of calibration and the ability to measure only one soil parameter—moisture content (TDR can also measure electrical conductivity but that is of minor importance with respect to soil moisture), while the traditional technique using a nuclear moisture density gauge can measure two soil parameters—moisture and density. Also, calibration of the nuclear moisture density gauge is relatively quick and easy; for these reasons, and because it has been the standard technique for so long, it will not be easy to supplant the nuclear moisture density gauge.

Four techniques were subject to further evaluation: (1) time domain reflectometry (TDR), (2) capacitance, (3) seismic, and (4) thermal properties. The TDR method was easily employed in the field except in very stiff, dry soils; although, it was highly variable relative to the nuclear moisture-density gauge. The capacitance sensor was evaluated using soil samples contained in confining rings. Laboratory results were favorable, but no field evaluation was performed. Seismic testing showed promise in monitoring the change in void ratio due to compression and consolidation. Moisture content did have an influence, but there are no general calibrations for seismic methods. Thermal properties measurement showed trends for both changes in moisture content and bulk density but no general calibration was used or formulated.

Due to the limitations of the current technologies in measuring moisture, a brief review of statistical methods for soil moisture measurement was undertaken. It is anticipated that a combination of measurement technologies in tandem may allow for an improved accuracy of water measurement over the use of single technologies.

The review of technologies conducted has identified some potential technologies for research for fuller development of technologies studied. Technical goals for additional research include identification and development of a technique(s) (e.g., x-ray/nuclear, ultrasound, capacitance, magnetic, thermal, optical, microwave, sound, infrared, and spectroscopy) or hybrid system(s) (i.e., combinations of techniques) that will enable moisture content determination in situ from construction equipment and/or portable testing devices.

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