Scholars' Mine

Fall 2008

Laboratory analysis of small strain moduli in compacted silts

David M. Weidinger

LABORATORY ANALYSIS OF SMALL STRAIN MODULI

IN COMPACTED SILTS

by

DAVID M. WEIDINGER

A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN CIVIL ENGINEERING

2008

Approved by

Louis Ge, Advisor
Richard W. Stephenson
David J. Hoffman

PUBLICATION THESIS OPTION

This thesis consists of the following two articles that have been submitted for publication as follows:

Pages 3-32 are intended for submission to the MATERIALS IN CIVIL ENGINEERING.

Pages 33-64 are intended for submission in the JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING.

ABSTRACT

Soil compaction quality control accounts for a significant portion of geotechnical practice. Often the performance of a roadway can be directly linked to the quality of the compacted subgrade. A poor subgrade can result in weak areas in the road causing excessive deflections at the surface, ultimately leading to a pot hole or uneven surface and an unpleasant ride for the travelers. Vehicles passing over a section of highway causes small strains in the founding soil. These strains accumulate over time. A better understanding of how the compacted soil responds at small strains could shed light on improving the quality of the soil in turn improving the quality of the roadway.

In this study, the small strain moduli of compacted low plastic silt was investigated under varying moisture contents and dry densities. An ultrasonic pulse velocity testing system was used to determine the dynamic elastic moduli of the soil specimen. Detailed procedures on how to filter the ultrasonic pulse velocity results and determine wave arrival times were established. Trends in the dynamic elastic moduli versus dry density and moisture content were studied.

A Briaud Compaction Device (BCD) was also used to determine the BCD Low-Strain Modulus. The BCD is a non-destructive test that can be used in both the laboratory and field as a means of quickly determining a modulus. The use of the BCD as a compaction quality control tool was investigated. BCD repeatability and the established trends suggest that the BCD could be benefit for compaction quality control. The BCD modulus was also compared to the dynamic elastic moduli producing trends with good correlation.

ACKNOWLEDGMENTS

I would like to thank my parents, Mark and Joyce Weidinger, for their never ending support and encouragement throughout this project and in previous endeavors. I would like to thank my adamant advisor, Dr. Louis Ge, for keeping me on the right track, helping me through the numerous disappointments often associated with research, and investing the time and effort required for me to complete this project. I would also like to thank the other members of my committee, Dr. Richard W. Stephenson and Mr. David Hoffman for taking their time to answer my many questions and help troubleshoot test data. I would like to thank the University and all of its contributing alumni that made my research possible with top notch lab settings and ample scholarship opportunities. The financial support for this research work was by the Senator Bond Fund in Transportation Research through Missouri Transportation Institute and is gratefully acknowledged. Finally, many thanks to my friends, family, and dog, for keeping me level, on task, and sane when times in the lab were rough.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

.

INTRODUCTION

Soil compaction quality control is paramount in the construction of most civil engineering projects. When a soil is compacted to its optimum state, the soil will perform at its maximum shear strength, produce the least amount of settlement, have a low hydraulic conductivity and be less susceptible to erosion. All of these properties are important to the long term performance of the founded structures. Current quality control methods for soil compaction are based on dry density and moisture content. Dry density is a measure of how many soil particles reside in a given volume of a soil. At maximum dry density, the compressibility of the compacted soil as well as the hydraulic conductivity will and have the lowest but other factors such as soil suction, moisture content, clay content and cementation often have more affect on strength than dry density. A soil can have a high dry density and have low shear strength or visa versa. Modulus is a measure of the amount of strain associated with a given shearing stress. Compaction quality control based on soil modulus rather than dry density is advantageous because it directly measures a soil's response to an applied load rather than measuring dry density, which is only loosely related to soil modulus performance. In applications such as subgrade compaction for highways, a soil with a high modulus is more important than a soil with a high dry density. A better understanding of small strain moduli in compacted soils could lead to better subgrade quality control leading to longer lasting, smoother highways. Such is the motive of this research.

An alternative method to dry density quality control is to use a device to measure modulus in the field to determine if the soil has reached its optimum state, or if more compactive effort is required. Several devices exist that are capable of determining a modulus in the field. These include the Falling Weight Deflectometer (FWD), the Lightweight Falling Weight Deflectometer (LFWD), the Geogage, the Cleg Impact Hammer and the Plate Load Test (PLT), to name a few. These tests are adequate for determining a field modulus but due to their size and boundary effects cannot easily be conducted in a laboratory setting. This drawback limits their usefulness. Without a laboratory value to compare to, only correlations to other lab tests can be used to specify a target field modulus. The Briaud Compaction Device (BCD) was invented to address

these issues. Using the BCD the operator can conduct a laboratory test to produce a BCD modulus compaction curve (similar to the proctor compaction curve) then compare BCD modulus values obtained from the field directly to BCD modulus values from the lab test. This is an attractive alternative to soil compaction control based on dry density because it does not require the use of cumbersome and potentially hazardous dry density measuring tests such as the Sand Cone or the Nuclear Density Gage. The use of the BCD on compacted silts as a compaction quality control test was investigated in this study.

Ultrasonic pulse velocity measurement is a nondestructive testing technique which provides compression and shear wave velocity information that can be used in calculating important soil properties based on the Theory of Elastic Homogeneous Isotropic Materials. Soil testing under small strain is often referred to as dynamic testing and the results can be used to determine the dynamic properties including Young's modulus and shear modulus. These moduli can be used in seismic and foundation design. Understanding how the BCD correlates with the dynamic elastic moduli could expand the BCD's usefulness as a testing tool. In addition to establishing correlations between the BCD and the dynamic elastic moduli, the ultrasonic pulse velocity instrument was used to examine soil properties variation with increasing moisture content and dry density.

PAPER

I. ULTRASONIC PULSE VELOCITY TESTING ON COMPACTED SILTS

David Weidinger[1], Louis Ge[2], and Richard W. Stephenson[3]

ABSTRACT

Ultrasonic pulse velocity measurement is a nondestructive testing technique which provides compression and shear wave velocity measurements that can be used in calculating dynamic elastic properties including Young's and shear moduli. This paper presents the results of a series of ultrasonic pulse velocity tests on compacted silt. Measured P-wave and S-wave signals were processed by a 4th-order Butterworth digital filter so arrival times could be properly determined. Analysis of the ultrasonic pulse velocity results versus bulk density instead of dry density produced more meaningful relationships. The elastic moduli versus bulk density and moisture content can be described by bi-linear tends.

Keywords: Nondestructive testing; Ultrasonic pulse velocity; Compacted silt

[1] Staff Geotechnical Engineer, Vector Engineering Inc., Grass Valley, CA 95945, USA. Formerly Graduate Student, Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO 65409. E-mail: dmwbnd@mst.edu

[2] Assistant Professor, Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO 65409. E-mail: geyun@mst.edu

[3] Professor, Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO 65409. E-mail: stephens@mst.edu

1. INTRODUCTION

Soil stiffness is strain dependent and at small strains, soil behaves elastically (Viggiani and Atkinson, 1993). Soil testing under small strain is often referred to as dynamic testing. The results can be used to determine the dynamic elastic properties such as the Poisson's ratio, and the shear, Young's, and bulk moduli. These moduli can be used in seismic design and machine foundation design. Resonant column and pulse transmission tests are laboratory tests often used for dynamic property testing. Resonant column tests are capable of determining shear modulus and damping ratio at a shear strain levels ranging from 10^{-4} to 10^{-2}%. Wave velocities are computed from the measured resonant frequency of the test specimen. Pulse transmission tests, on the other hand, directly measure the transmission velocities of waves through the specimen.

Ultrasonic pulse velocity testing is a type of pulse transmission test that propagates high frequency sound waves ranging in frequency from 20 kHz to 1 GHz through a soil specimen to produce strains on the order of 10^{-4}% (Leong et al., 2004). Ultrasonic pulse velocity testing is a nondestructive testing technique that can be used to determine the dynamic properties of materials capable of transmitting waves. Elastic bodies can transmit three different types of waves: longitudinal or compression waves also known as primary waves (P-waves), shear or transverse waves also known as secondary waves (S-waves), and Rayleigh waves. Rayleigh waves are surface waves that travel on the outside surface (free surface) of a medium. Compression waves move in the same direction as the direction of particle displacement. Shear waves move orthogonal to the direction of particle displacement, and are typically about half the speed of compression and Rayleigh waves. The velocities at which the P-waves and S-waves

travel through a specimen are a function of the dry density and elastic constants of the specimen. By measuring the velocity of the P and S waves through a soil sample, the shear modulus (G), Young's modulus (E), and Poisson's ratio (ν) can be determined for the strain level of 10^{-4} %.

The recent developments of improved testing equipment and measurement techniques combined with the simplicity of the test have attracted several researchers to investigate ultrasonic pulse velocities in soils. Many attempts have been made to establish correlations between dynamic elastic properties and static properties such as shear strength, density, degree of saturation, moisture content, and Atterberg Limits (e.g., Aracne-Ruddle et al., 1999; Inci et al., 2003; Loeng et al., 2004; Fener et al., 2005). Trends between pulse velocity results and standard geotechnical soil properties for both sands and clays have been investigated. However, studies on silty soils have remained limited. The purpose of this research is to establish sound testing and analysis procedures for compacted silt specimens, and investigate the dynamic properties determined by ultrasonic pulse velocity testing.

2. EXPERIMENTAL SETUP

2.1. Material

The material used in this study was selected based upon its availability, past experience, and its typical textbook silt-like properties. The soil is a modified loessial, low plastic silt that comes from the Mississippi River Valley near Collinsville, Illinois. The silt has a liquid limit of about 30, a plastic limit close to 24, and natural clay content

of 17.0% or so. The material is classified by the Unified Soil Classification System as an

ML soil (Izadi, 2006).

The soil was first mechanically pulverized then passed through a #40 sieve (425

mm). The soil was moistened to a predetermined moisture content then allowed to cure

for 24 hours. It was then compacted into a 152 mm (6-inch) split proctor mold in three

equal height lifts under standard proctor compaction energy (ASTM Standard D 698).

An automated compaction device was used for a tighter control on the compaction effort.

Fig. 1 shows the standard proctor compaction curve for this particular soil. The soil has a

standard proctor optimum moisture content of 15% and a maximum dry density of 17.1

kN/m^3. After compaction, the soil was gently extruded from the split mold, wrapped in

plastic wrap, placed inside a sealed bag, and allowed to further cure in a moist cure room.

Three 152.4-mm (6-inch) diameter proctor specimens were trimmed at each moisture

content, so that three independent tests could be conducted.

2.2. Ultrasonic Pulse Velocity Measurement System

All pulse velocity measurements determined in this study utilized a GCTS ULT-

100 Ultrasonic Velocity Test System. The device consists of sender and receiver

transducers housed in the top and bottom platens of a standard triaxial cell. The two, 70-

mm diameter test platens are wired to a data acquisition and processing unit. The

piezoelectric crystals are arranged for the transmission and reception of P and S-waves.

Piezoelectric crystals are small ceramic elements that change shape when a voltage is

applied, or produce a voltage when they change shape. These properties transform an

electrical wave into a mechanical wave or vice versa. The strain level produced by these

piezoelectric crystals has been found by Loeng et al. (2004) to be around 10^{-4} %. By

arranging the piezoelectric crystals differently within the test platens, the test can either be conducted to produce and measure P-waves only, ignoring the S-waves, or in S-wave mode, ignoring, for the most part, the P-waves.

The GCTS pulse velocity device operates in a through-transmission mode of testing, that is, a signal is produced at one end of the specimen and received at the other (GCTS, 2004). The time required for the wave to propagate through the specimen can be determined by analyzing arrival times of the received signal. The wave velocity is the travel distance (specimen height) divided by the arrival time of the wave. Because the piezoelectric crystals are protected by a metal face, there will always be some degree of delay in the received signal. This slight delay can be determined and accounted for by simply placing the top and bottom platens directly together and testing. The delay in the arrival time is considered to be the face-to-face delay time and must be subtracted from the measured arrival time. The face-to-face delay times for the ultrasonic device used are 14.1 microseconds for the P-wave test mode and 16.5 microseconds for the S-wave mode.

Along with the unique face-to-face delay times, pulse velocity devices also transmit unique frequencies. The GCTS ULT-100 is designed to produce wave frequencies between 1 and 100 kHz. Depending on the manufacturing, each device can have different operating frequencies. The Fast Fourier Transform (FFT) of the received signal is analyzed to determine the operating frequency. A good signal will have a high amplitude at the frequency of the transmitted wave. Fig. 2 shows the FFT plots from the face-to-face delay test for both the P and S-waves. The P and S-wave FFT plots have large amplitudes at the operating frequencies of 46 kHz and 39 kHz respectively.

Irregularities on the surface of the specimen face can create air pockets between the soil and the test platens that do not transmit wave energy, reducing the signal clarity (Eckelkamp, 1974). An acoustic couplant is often used to fill in the irregularities, and increase the quality of the received data. A number of materials can be used as acoustic couplants. The only requirement is that they easily transmit longitudinal and shear waves, and that the impedance matches that of the system (Eckelkamp, 1974). Several types of acoustic couplants were tested for this study, and the results can be observed in Fig. 3. The greater the amplitude of the dominant frequency, the better acoustic couplant. For the setup used in this study, natural honey and Fiber Glass Resin Jelly were decent couplants, but the use of no complant produced the greatest amplitude of dominant frequency. It was found that the surface of the soil sample absorbed the acoustic couplant rapidly and yielded unreliable data. Plastic and latex membranes between the couplant and soil were investigated as a way to stop absorption of the couplant with minimal success. Higher viscous acoustic couplants were also of little use. Wave attenuation in the specimens accounted for more signal loss than poor contact between the soil and platen. For these reasons, tests were conducted free of an acoustic couplant between the soil specimen and the test platens (additionally, the specimen were carefully finished smooth to insure minimal surface irregularities).

The ultrasonic velocity testing platens were mounted in a triaxal cell so that the normal load applied to the specimen in each test could be closely monitored. All tests were conducted without the exterior acrylic cylinder to the triaxal cell. This was to ensure no cell pressure developed and the test was conducted completely unconfined. Fig. 4 shows a typical test setup. A small, computer-controlled load frame was used to apply a

low normal load of 50 N to improve the interface between the soil and platen, and to simulate a slight overburden.

2.3. Testing Procedure

This study was conducted on air-dried, lossial silt that was first mechanically pulverized and then sieved through a #40 (425 mm) sieve. Water was then added to the proper moisture content, and the soil was thoroughly mixed and allowed to cure. The soil was compacted at standard compaction efforts (600 kN-m/m^3) with an automatic compaction hammer in a 152.4-mm (6-in) split proctor mold. The samples were extruded and weighed. The ultrasonic testing setup used could not accommodate 152.4-mm diameter specimens, so a sample trimmer was used, and the samples were carefully trimmed to a diameter of 71 mm (2.8 inch). The tops and bottoms of the samples were trimmed parallel and finished smooth to avoid the use of acoustic couplants.

Once the sample faces were trimmed, the samples were mounted in the modified trixial cell for ultrasonic pulse velocity testing, as shown in Fig. 4. A normal load of 50.0±5.0 N (11.3±1.2 lbf) and no confinement pressure were applied to the samples. Initial tests revealed that regardless of the acoustic couplant used, at full specimen height of approximately 114 mm (4.5 in), attenuation through the silt specimens was too great and no conclusive arrival time data could be observed. Therefore, the specimens were sliced into thirds (about 30 mm in height) and finished smooth. Tests conducted on the sample thirds resulted in clean data with a high amplitude of frequencies matching the predetermined original wave frequencies (46 kHz for P-waves and 39 kHz for S-waves).

The average sample height used for ultrasonic testing was approximately 25 mm (1 in.). Although specifications for rock sample dimensions are presented in ASTM D

2845, no soil specific specifications are available at this time. The ASTM D 2845

standard recommends the ratio of specimen length to diameter (L/D) should not exceed

five, but has no minimum length dimension. Loeng et al. (2004) investigated the effect of

the length to diameter (L/D) ratio, and the length to wavelength (L/λ) ratio, and found

there were few issues when L/D > 2 and L/λ > 2. Wavelength can be related to frequency

by the following expression:

$$\lambda = \frac{1}{f} \times v_{p,s}$$

where λ is the wavelength in meters, f is the frequency in hertz and $v_{p,s}$ is the P or S-wave

velocity in meters per second. Therefore, based on average wave velocities, the P and S-

wave wavelengths are approximately 7.6 x 10^{-3} mm and 3.8 x 10^{-3} mm respectively.

Consequently, L/λ values are much larger than 2. With the silt selected for this study, a

specimen length (L) greater than the diameter (D) resulted in far too much attenuation

yielding unusable data. ASTM D 2845 states that the sample diameter should not exceed

5 times the wavelength (D≤5λ). Again, due to the very short wavelength, this was not an

issue for these tests. Following the pulse velocity tests, the sample height, diameter,

weight, and moisture contents were measured so that density and wave travel length

(specimen height) could be determined.

Often, noise in the system makes determining the arrival times difficult. Signal

processing and filtering is often implemented to help refine the signal so that arrival times

can accurately be determined. Numerical filtering was conducted using the computer

program MatLab (version 7) by applying a bandpass 4th-order Butterworth filter. The raw

P and S-wave signals for each test were analyzed both unfiltered and filtered so that the affects of filtering could be investigated.

3. ANALYSIS

3.1. Arrival Times

Determination of the correct arrival time is paramount in ultrasonic pulse velocity testing. Inaccurate arrival time determinations will result in erroneous wave velocities which will affect the calculated elastic constants. Several methods for determining arrival times are currently available. For simplicity, this study determined all pulse velocity arrival times using the First Peak Time method. This method defines the arrival time as simply the time when the peak, or maximum amplitude of the first wave arrives. Other reported methods include the absolute threshold, relative threshold, and tangent of first peak (GCTS, 2004). To determine the range of results that can occur from the various arrival time methods, the Absolute Threshold method was compared with the First Peak method. The Absolute Threshold method determines the time value of the first point in the signal that passes the "Absolute Threshold." The Absolute Threshold is a normalized value that represents the signal amplitude when no wave is being received (GCTS, 2006). Of all the arrival time methods, the Absolute Threshold method calculates the earliest arrival time and the First Peak method determines the latest arrival time. From this study, the First Peak method determined S-wave arrival times that differed about 4% and P-wave arrival times differed approximately 10%. Determining arrival times based on the First Peak Method results in dynamic properties the varied by 10 % when compared to the Absolute Threshold method.

3.2. Longitudinal Waves

Determining the arrival times for the longitudinal (P) waves was quite trivial. P-waves are the fastest of the dynamic waves that propagate through solid bodies; therefore, when analyzing the P-wave data, the first signal received is generally the P-wave arrival time. If there is a great deal of noise in the data, filtering of the noise must be conducted before arrival times can be determined.

In the majority of tests, the P-wave arrival time could be determined without the use of filtering. Every test resulted in data with a large initial spike at the beginning of the test followed by a hump in the signal where the P-wave is believed to have arrived. This spike can be observed in Fig. 5 and is likely to come from internal interference within the ultrasonic pulse velocity testing system and could not be eliminated. Internal interference can be any electrical noise emitted by electronics as current passes through them. For example, a typical U.S. light bulb emits a noise at a frequency of 60 Hz due to the current that passes through it. Typical P-wave data is presented in Fig. 5.

The arrival time of the longitudinal waves is used to calculate the P-wave velocity from the following equation:

$$V_p = \frac{H}{(T_p - D_p)} \times 10^6$$

where V_p is the P-wave velocity in m/s, H is the specimen height in meters, T_p is the P-wave arrival time in microseconds, and D_p is the P-wave face to face delay time in microseconds. The P-wave velocity is used in calculating the elastic constants of the soil.

3.3. Filtering

Though most of the P-wave signals were easily interpreted without the use of filtering, some P-wave data required filtering to remove some of the subjectivity

embedded in arrival time determination. Signal filtering was accomplished with MatLab via a 4th-order bandpass Butterworth filter centered on the predetermined wave transmission frequencies of 46 kHz for P-waves and 39 kHz for S-waves (Leong et al., 2004). Several other filtering techniques are available, but the Butterworth filter did well at filtering this particular data so no other filters were investigated. Usually some variation of windowing of the data is applied along with the filter. Windowing amplifies data of interest while reducing or ignoring data outside the zone of interest. Windowing was unnecessary in this study and was not applied.

Often filtering can cause a non-linear phase shift in the data (Leong et al., 2004) which could lead to inaccurate arrival times. To avoid this, zero-phase digital filtering was implemented which processes the input data both in the forward and reverse directions. The filter first processes the signal in the forward direction then reverses the filtered sequence and runs it back through the filter, resulting in precisely zero-phase distortion and double the filter order (the 4th-order Butterworth filter become an 8th-order). Fig. 5 shows typical matching filtered and unfiltered signals with zero phase distortion.

3.4. Shear Waves

The shear (S) wave data was first filtered to improve arrival time determination. The same filter for the P-wave was used for the S-wave data. The piezoelectric crystals used for S-wave testing are arranged in the platens so that primarily S-waves are sent and received. Whenever dynamic energy is input to a medium, all dynamic wave forms are produced. The arrangement of the piezoelectric crystals within the GCTS platens may reduce the amount of non-shear waves received, but some P-wave signal is picked up

even though testing is being conducted in S-wave mode. This makes S-wave arrival time

determination difficult, and the initial increase in the received signal could be the arrival

of the faster P-wave and not the S-wave arrival time. Take for example the ASTM

Graded Ottawa Sand pulse velocity test shown in Fig. 6. The P-wave arrival appears as

well as the S-wave arrival in the S-wave data. The ASTM-Graded Sand transmits S-

waves well, and a strong increase in signal amplitude compared to the P-wave occurs

when the S-wave arrives. With the silt, attenuation makes the received S-wave much

weaker and a strong increase in signal amplitude where the S-wave arrives does not

occur. This makes it difficult to accurately determine the S-wave arrival time. Typical

filtered ultrasonic pulse velocity data is shown in Fig. 7. The P-wave arrival time is easily

identified using the P-wave signal data; however, the S-wave is less discrete. There are

several maximums in the signal that could be either the S-wave arrival time or part of the

P-waves appearing in the S-wave data.

To help determine the correct S-wave arrival time, all possible arrival times were

investigated. Based on assumptions of what the Poisson's ratio and shear wave velocity

should be for the soil, the most probable arrival time was determined. Table 1 shows how

the possible arrival times were analyzed.

For each test, four possible arrival times for the S-wave were chosen. Using the

arrival times, the shear wave velocity was determined by:

$$V_s = \frac{H}{(T_s - D_s)} \times 10^6$$

where V_s = the shear wave velocity in m/s, H is the specimen height in meters, T_s is the

presumed arrival time of the S-wave in microseconds, and D_s is the face-to-face delay

time for the shear wave in microseconds. The Poisson's ratio was then calculated using

the theory of elasticity for homogenous, isotropic solids:

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}$$

where ν is the Poisson's ratio and V_p is the longitudinal wave velocity in m/s.

The calculated Poisson's ratio was compared to an assumed range of values. The

actual Poisson's ratio of the silt is unknown, but an appropriate range can be assumed.

Typically, Poisson's ratios for sands range from 0.2 for loose sands to 0.4 for dense

sands. Poisson's ratios for clays range from 0.4 to 0.5 for saturated clays (Holtz and

Kovacs, 1981). The soil used for these tests is a densely compacted low plastic slit with

17% clay content. This places the Poisson's ratio in the range of 0.35 to 0.40, depending

on the moisture content.

The expected shear wave velocities were obtained from a combination of

geophysical field tests located in the vicinity of the soil barrow site and from pulse

velocity tests conducted on silt of similar moisture contents and densities. The field shear

wave velocities were cited from a study by Karadeniz (2007) that generalized shear wave

velocities for an area that encompasses the borrow site. The shear wave velocities

reported by Karadeniz were the average velocities measured from the ground surface to a

depth of approximately 30 meters. On average, the shear wave velocities within the area

of interest were between 200 and 250 m/s. The geophysical shear wave velocities

measured were from saturated soils under large confinements, and can be expected to be

greater than those determined from pulse velocity testing of unsaturated soils under zero

confinement. Natural soil under large confinements is likely to have higher densities as

well as soil cementation which will increase the ability for the soil to transport a signal, increasing the shear wave velocities. Therefore, velocities obtained in this laboratory study should be less than those in the field.

4. RESULTS AND DISCUSION

The results from the ultrasonic pulse velocity tests are presented in Table 2. Two additional soil pucks were compacted at each moisture content (12 additional pucks). The additional pucks were ultrasonic pulse velocity tested produced similar results to those presented in Table 2. The Poisson's ratio ranged from 0.41 in the stiff, low moisture content samples to 0.34 for the softer samples at higher moisture contents and lower dry density. The average Poisson's ratio for all tests was 0.38 with a standard deviation of 0.02 which confirmed the assumed range of the Poisson's Ratio was between 0.35 and 0.40. Shear wave velocities obtained from ultrasonic pulse velocity measurements were ranging from 164m/s to 117m/s with an average of 148m/s and a standard of deviation of 128m/s while the field shear wave velocities were believed to be around 200-250m/s at a depth of 10 meters. The maximum shear wave velocities occurred in the soil samples prepared dry of the optimum moisture content and decreased with increasing moisture content and saturation. Published Shear wave data for silt are limited but other researchers have found low plastic clay to have shear wave velocities ranging 500 to 1000 m/s, decreasing as saturation increases (Inci et al. 2003). Clean Ottawa Sand at low confinements was found to be between 150 and 200 m/s (Aracne-Ruddle et al. 1999). Kimura (2006) reported shear wave velocities on marine sediments range between 50 m/s

and 75 m/s. The low plastic silt used in this study shows a shear wave velocity somewhere between that of a low plastic clay and a sand.

Fig. 8 shows the variation of the dynamic elastic properties with both the dry density and bulk density. Dry density describes number of dry solid particles in a specific volume whereas wet density or bulk density refers to all materials (solid particles and water) within a volume. Bulk density accounts for all three materials present in the compacted soil, that is air, water, and solids. Dry density is a measure of only air and solids. Wave velocity is a function of both the elastic properties and internal properties of the soil. Bulk density becomes a better independent variable than dry density for the pulse velocity data because it better describes the internal properties of the soil. Fig. 8 shows how dry density fails to describe any sort of trend and the data is more scattered whereas bulk density develops a trend with the pulse velocity results. Both elastic moduli (E and G) exhibit bi-linear trends where the moduli is relatively constant at bulk densities up to 2000 kg/m^3 then drops rapidly with increasing bulk density (Fig. 8). This can be expected, as the bulk density increases the moisture content and saturation increases. Particles become "heavier" with the additional water and sluggish to energy (waves) which slows the wave velocity. Fig. 9 shows the variation of the moduli versus moisture content. As the compacted samples approach 100% saturation (high moisture content), the moduli greatly reduces. Strong bi-linear trends can be established from the data as shown in Fig. 9. The moduli is relatively constant at moisture contents at or below the optimum moisture content (omc) for maximum dry density (14.5%) then decreases at moisture contents wet of omc.

The calculated shear moduli ranged from 26 MPa for the higher moisture content samples (lower dry density) to 58 MPa for the stiffer, lower moisture content samples (higher dry density). The calculated shear moduli corresponds to a very small strain level of 10^{-4} to 10^{-6} (Loeng et al., 2004). At such strain levels the soil behaves elastically, the shear modulus (G) is the maximum shear modulus (G_{max}) for the soil. Shahbaz (1993) investigated the dynamic properties of a similar soil using the resonant column and cyclic torsional tests, and found G_{max} values around 75 MPa. Dynamic property studies on some clays have found dynamic shear moduli as low as 23 MPa. The silt tested in this study was a low plastic silt with 17% clay, making it reasonable to assume that the dynamic shear modulus lies somewhere between that of a silt and a clay. The obtained results fall within this range.

5. CONCLUSIONS

Ultrasonic pulse velocity testing is a relatively quick and simple, nondestructive test that has its place in the geotechnical community. The current sophistication level of the available equipment is a vast improvement over the original, often home-made, pulse velocity devices. The onset of the new equipment results in straightforward testing procedures and better determination of wave arrival times. The wave velocities associated with various soils are a measure of the elastic properties, and can yield a great deal of information about a soil under dynamic loading.

For the silt samples investigated in this study, sample height and wave attenuation were the largest testing concerns. Sample height had to be limited in order to receive a measurable signal for processing. An acoustic couplant was not used for the majority of

the tests, but the testing faces of the sample were carefully finished flat and smooth. Arrival time determination is often subjective therefore filtering was applied to help determine the arrival times. Several techniques exist to eliminate some of the guess work involved, but can still yield sporadic results. Determining arrival times based on the First Peak Method made analyzing the wave less subjective but resulted in dynamic elastic moduli 10% less than those determined with the Absolute Threshold Method.

Several trends were investigated. Ultrasonic pulse velocity results are best view against the bulk density (wet density) as the independent variable instead of dry density. Bi-linear trends in the wave velocities and elastic properties are observed with increasing bulk density (Fig. 8), and moisture content (Fig. 9). The elastic properties of the compacted silt remain relatively constant with increasing moisture content and bulk density up to a point then decrease rapidly as moisture content increases wet of omc and bulk density increases from around 2000 kg/m^3. The investigation of how shear wave velocities and moduli vary with density, moisture content, and saturation could provide another tool for assessing soil characteristics. Based on the trends observed in this study, ultrasonic pulse velocity testing could provide insight on the stability of partially saturated compacted soils.

6. ACKNOWLEDGEMENTS

from Dr. Eng-Choon Leong at Nanyang Technology University in Singapore are also
greatly appreciated.

7. REFERENCES

Aracne-Ruddle, C.M., Bonner, B.P., Trombino, C.N., Hardy, E.D., Berge, P.A., Bora,
C.O., Wildenschild, D., Rowe, C.D., and Hart, D.J. (1999). Ultrasonic Velocities
in Uncnsolidated Sand/Clay Mixtures at Low Pressures, Technical Report, No.
UCRL-JC-135621, Lawrence Livermore National Laboratory.

ASTM, Standard D698-07, "Standard test method for laboratory compaction
characteristics of soil using standard effort (12,400 ft-lb/ft^3 (600 kN-m/m^3)),"
Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.
2007.

Eklecamp, R. M. (1974). Laboratory Evaluation of Dynamic Soil Properties by
Ultrasonic Testing Methods. Department of Civil Engineering, University of
Missouri-Rolla. M.S.

Fener, M., Kahraman, S., Bay, Y., and Gunaydin, O. (2005). "Correlations between P-
wave velocity and Atterberg limits of cohesive soils." *Canadian Geotechnical
Journal*, Vol. 42, No. 2, pp. 673-677.

GCTS (2004). Data Acquisition and Ultrasonic Velocity Software User's Guide.

Holtz, R. D. a. K., W.D. (1981). An Introduction to Geotechnical Engineering, Prentice-
Hall.

Inci, G., Yesiller, N., and Kagawa, T. (2003). "Experimental investigation of dynamic response of compacted clayey soils." *Geotechnical Testing Journal*, Vol. 26, No. 2, pp. 1-17.

Izadi, A. (2006). Behavior of Undrained Monotonically Loaded Low Plasticity Silt Under Triaxial Compression. Department of Civil, Architectural, and Environmental Engineering, University of Missouri-Rolla. M.S.

Karadeniz, D. (2007). Pilot Seismic Hazard Assessment of the Granite City, Monks Mound, and Columbia Bottom Quadrangles, St. Louis Metropolitan Area. Department of Geological Sciences and Engineering, University of Missouri-Rolla. Ph.D.

Kimura, M. (2006). "Shear wave velocity in marine sediment." *Japanese Journal of Applied Physics*, Vol. 45, No. 5B, pp. 4824-4828.

Leong, E.-C., Yeo, S.-H., and Rahardjo, H. (2004). "Measurement of wave velocities and attenuation using an ultrasonic test system." *Canadian Geotechnical Journal*,Vol. 41, pp. 844-860.

MathWorks, T. (2005). Matlab 7.1 User Guides.

Eklecamp, R. M. (1974). Effect of saturation and plasticity on dynamic properties of silt. Department of Civil Engineering, University of Missouri-Rolla. M.S.

Stephenson, R. W. (1977). "Ultrasonic testing for determining dynamic soil moduli." Dynamic Geotechnical Testing, ASTM Special Technical Publication 654, pp. 179-195.

Viggiani, G., and Atkinson, J.H. (1993). "Stiffness of fine-grained soil at very small strains." *Géotechnique*, Vol. 45, No. 2, pp. 249-265.

Table 1 – Analysis of S-wave arrival times

Case	Arrival Time (µs)	Velocity (m/s)	Poisson's Ratio ν
1	107.5	~~284~~	~~0.44~~
2	132.8	~~222~~	~~0.17~~
3	175.5	~~162~~	0.36
4	182.4	156	0.38

Table 2 – Ultrasonic Pulse Velocity Test Results

Moisture Content	10%		14%			16%			18%			20%		
γ_d (kN/m^3)	16.24		16.66			16.99			16.32			15.69		
Test ID	top	bottom	top	middle	bottom	top	middle	bottom	top	middle	bottom	top	middle	bottom
PV Density (Kg/m^3)	1797	1816	1904	1928	1931	1995	2018	2015	2025	2041	2044	1995	2025	2064
P-wave Velocity (m/s)	369	402	358	351	359	361	350	328	369	358	299	301	274	254
S-wave Velocity (m/s)	148	155	148	156	156	154	146	140	164	162	149	146	126	117
ν	0.40	0.41	0.40	0.38	0.38	0.39	0.40	0.39	0.38	0.37	0.34	0.35	0.36	0.37
G (MPa)	40	44	43	47	47	48	43	40	53	52	44	41	31	26
E (MPa)	113	124	120	130	131	133	119	111	145	141	116	111	84	72
K (MPa)	196	237	192	177	189	199	190	164	198	183	119	120	104	89

PV Density is the bulk density (wet density) of the samples used for pulse velocity testing and K is the Bulk Modulus
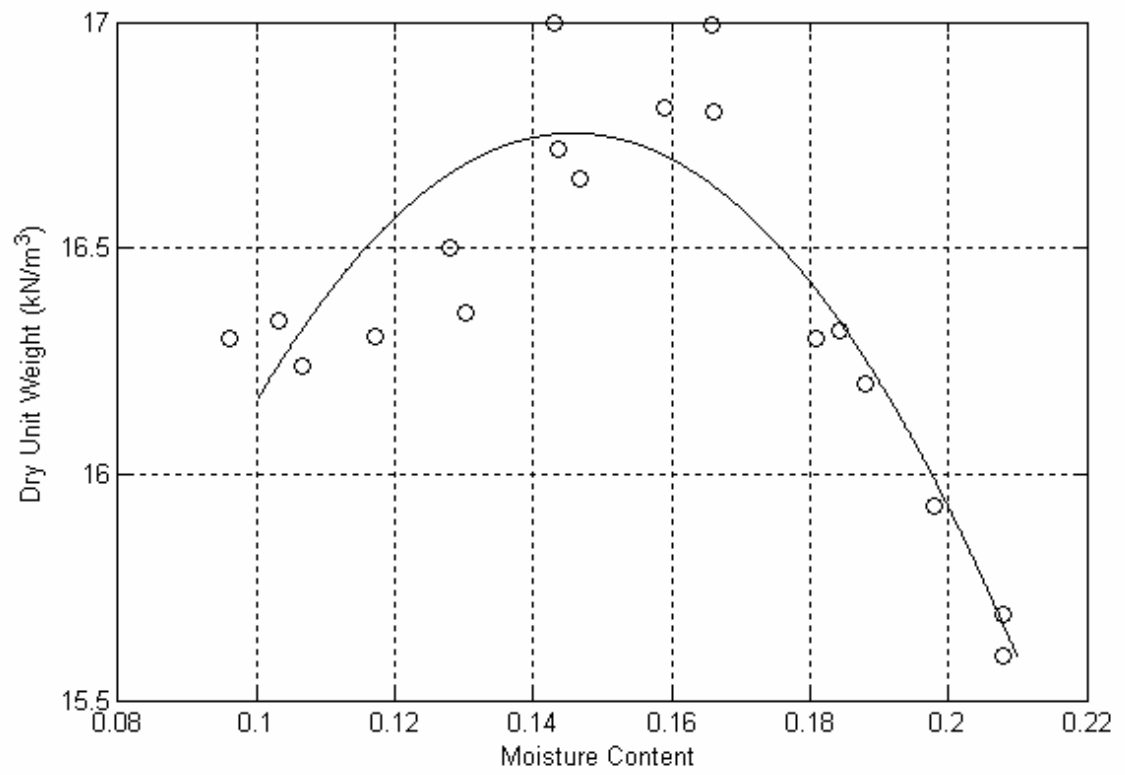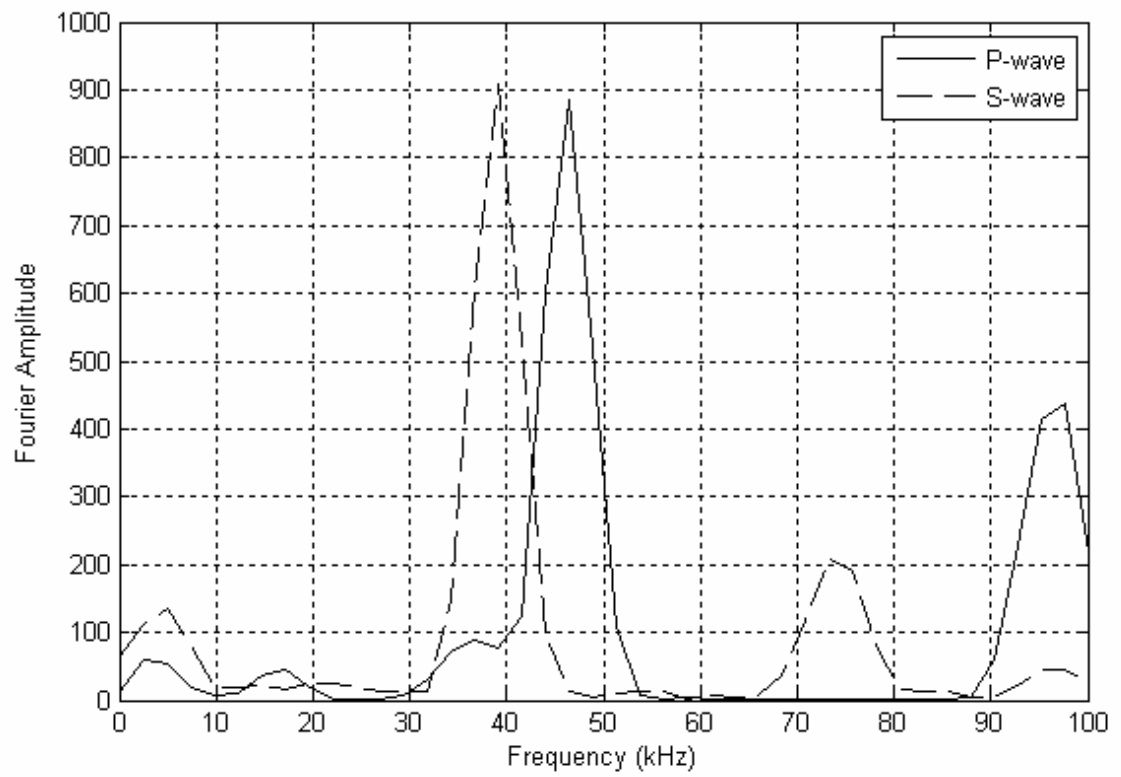
Fig. 1 – Standard proctor curve.

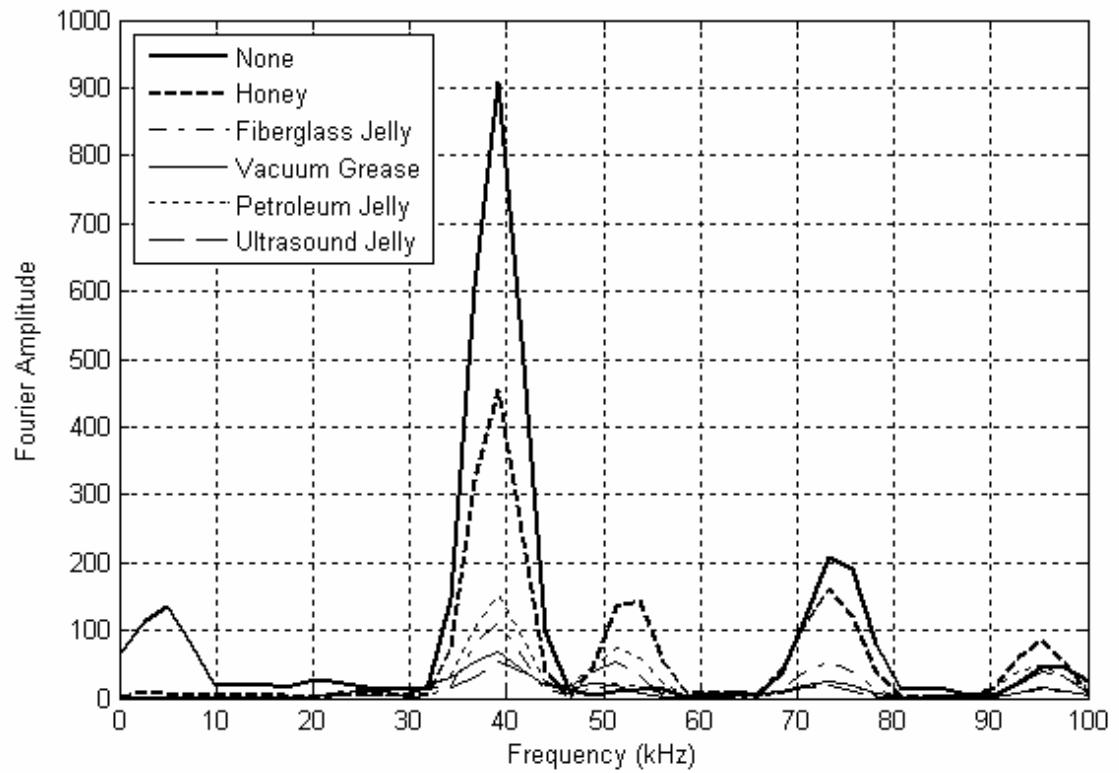Fig. 2 – FFT plot of the P-wave and S-wave.

Fig. 3 – FFT plot of the S-wave data for evaluation of acoustic couplant effectiveness.
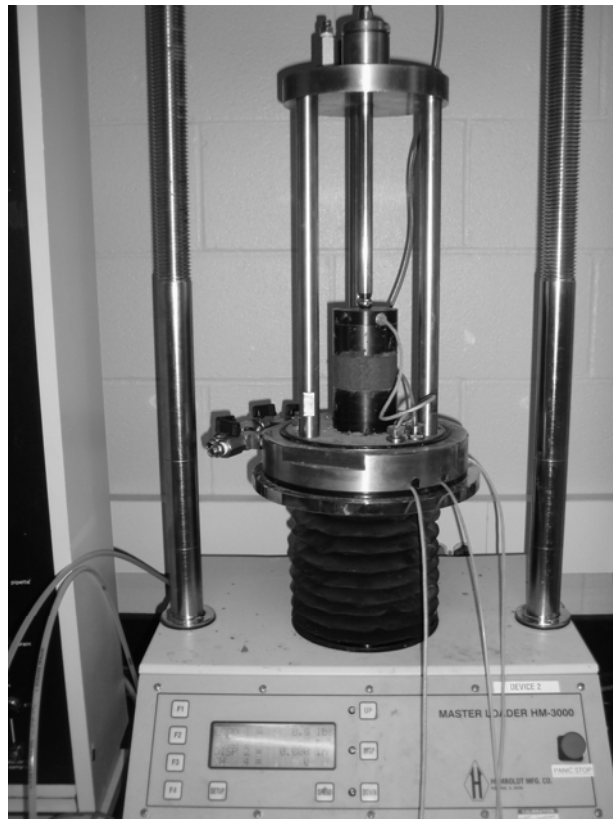
Fig. 4 – GCTS ULT-100 setup in triaxial cell with silt sample loaded.

Fig. 5 – Typical P-wave data unfiltered and filtered.

Fig. 6 – Plot of S-wave and P-wave data from a pulse velocity test on ASTM graded

sand.

Fig. 7 – Plot of S-wave and P-wave data from a pulse velocity test on silt showing P-

wave arrival and possible S-wave arrivals.

Fig. 8 – Ultrasonic pulse velocity results compared with bulk density and dry density.

Fig. 9 – Elastic properties vs. moisture content.

II. LABORATORY EVALUATION OF THE BRIAUD
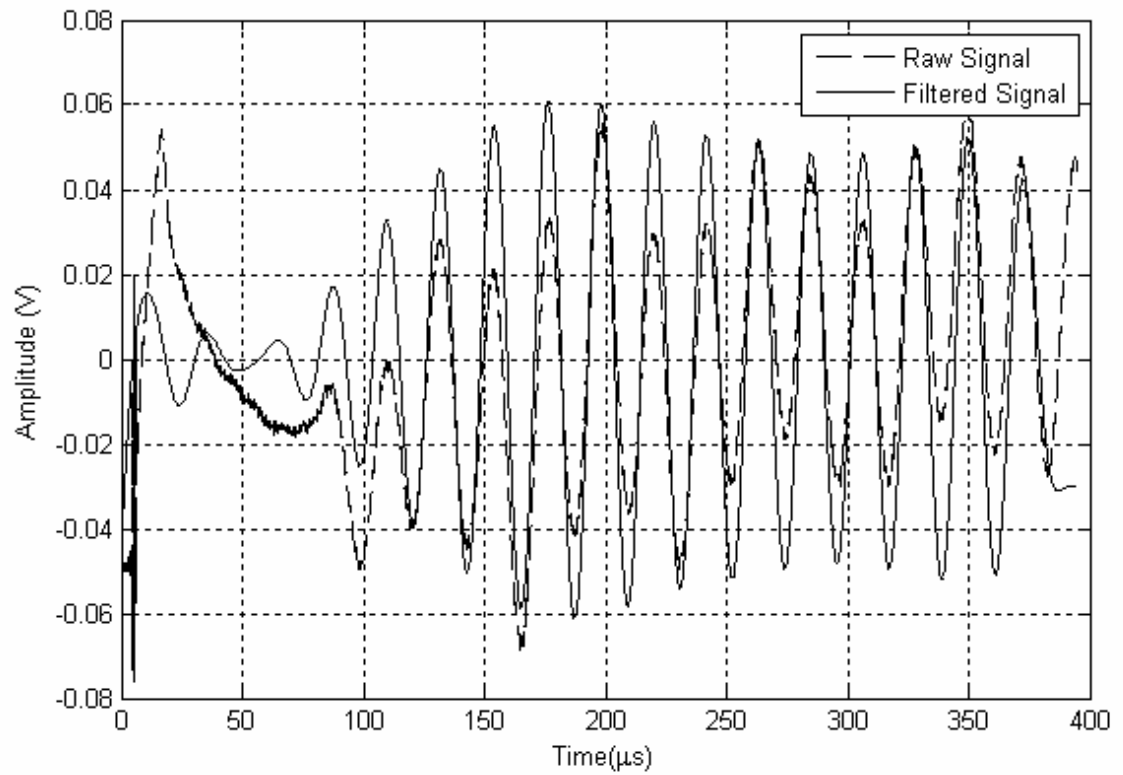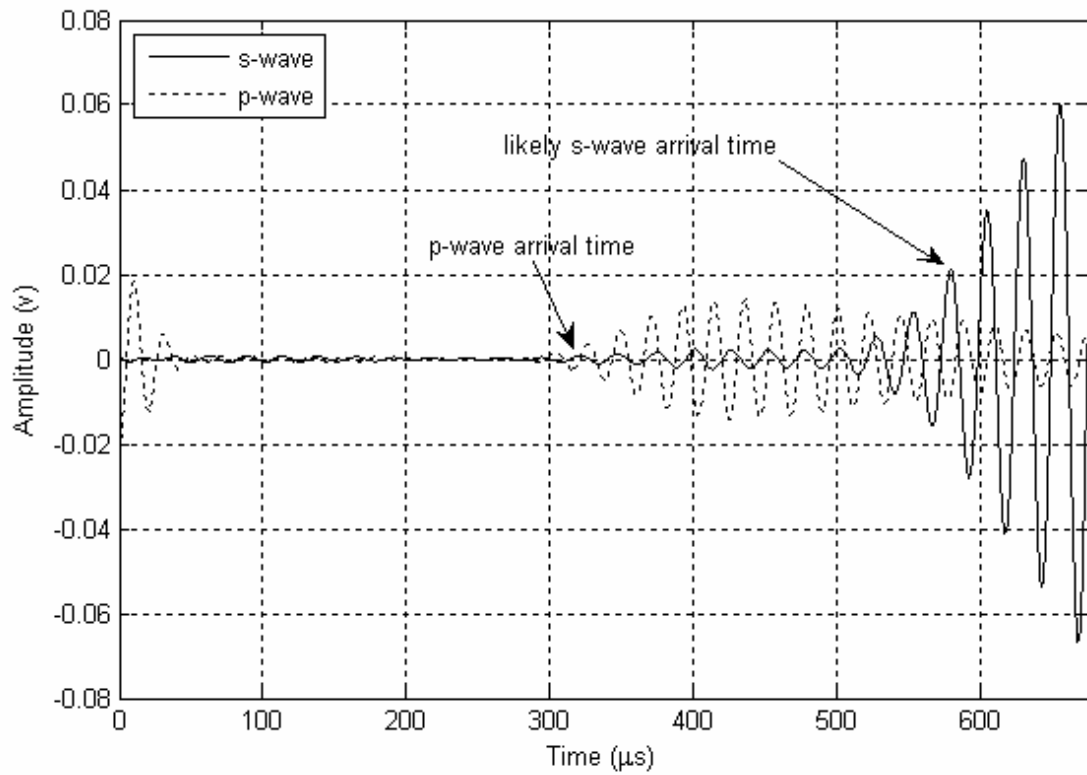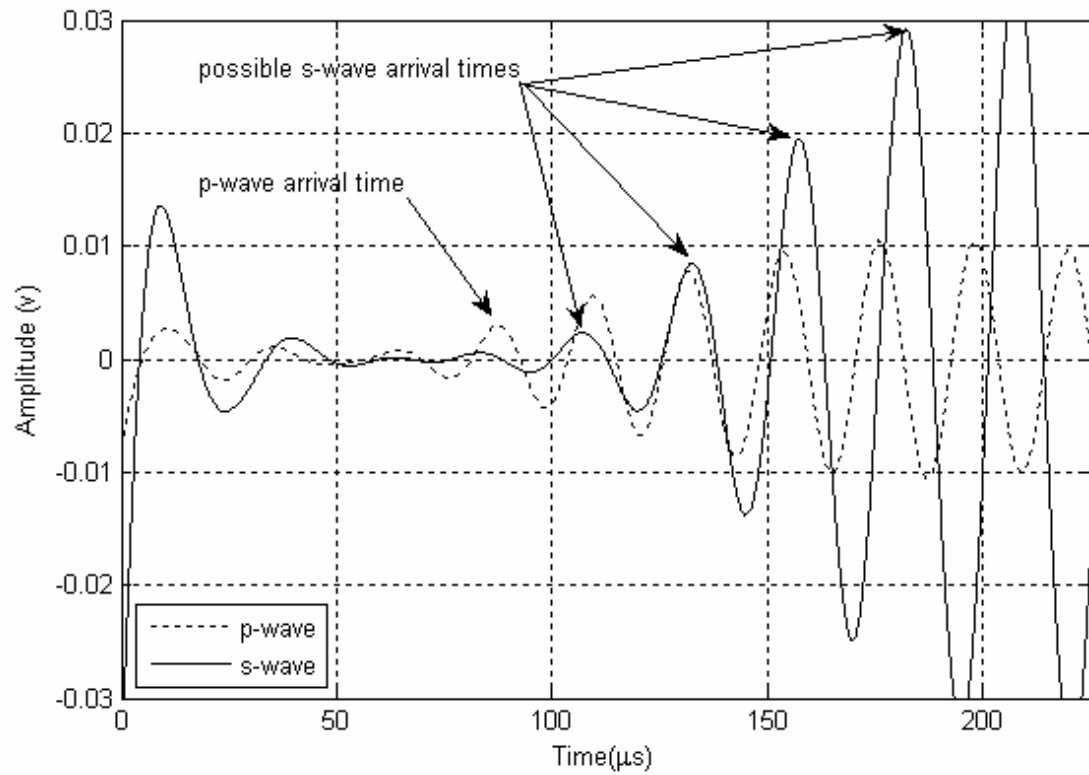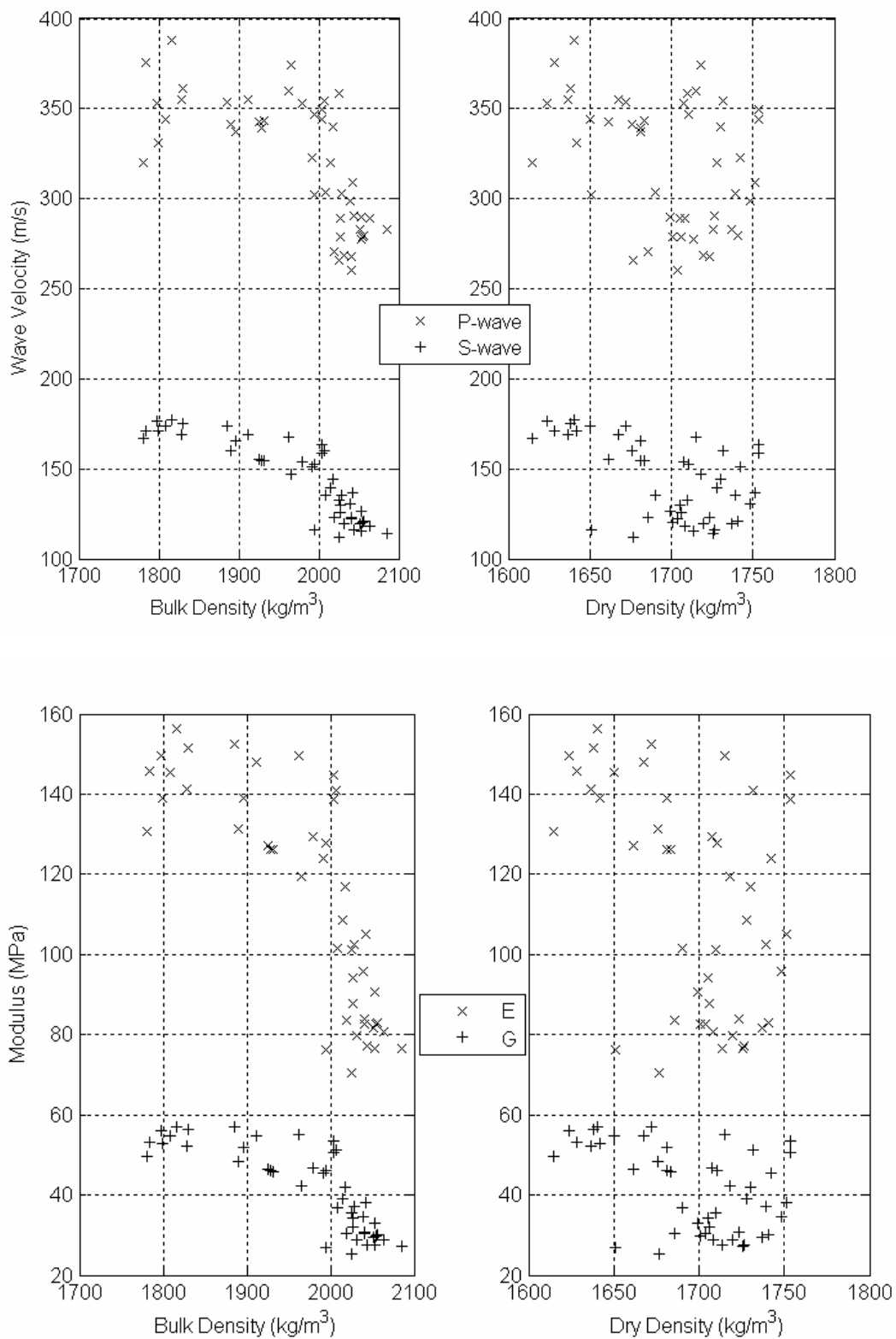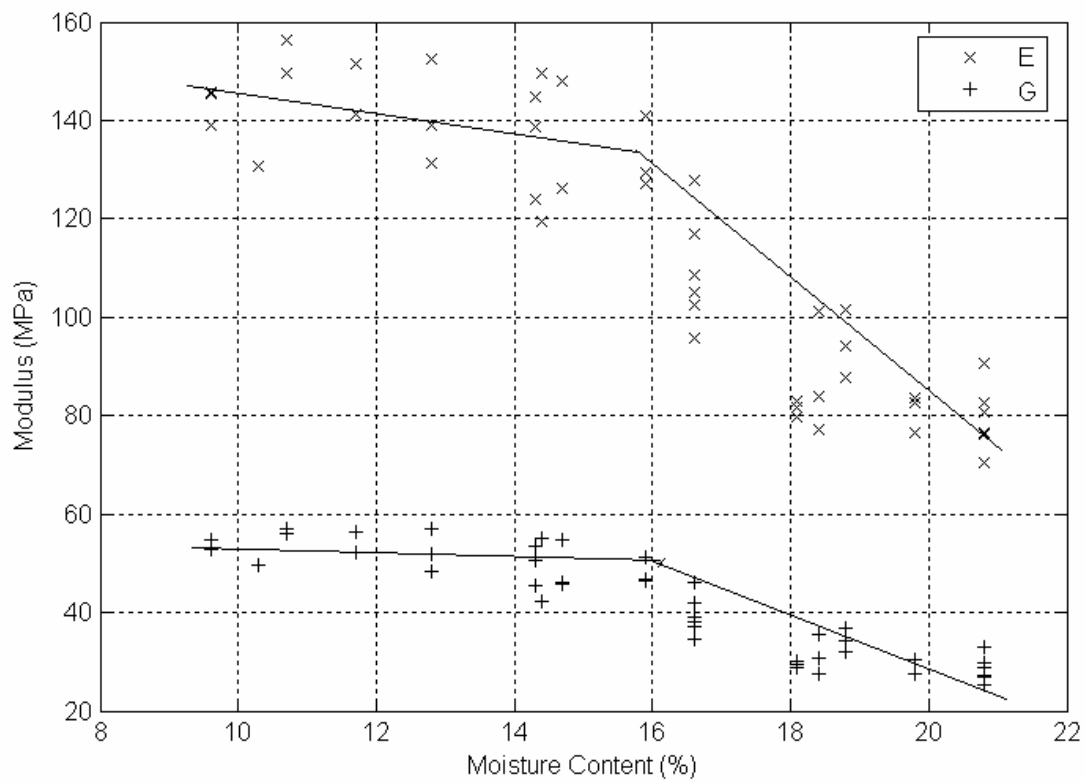
COMPACTION DEVICE

David Weidinger[1] and Louis Ge[2]

ABSTRACT

Soil compaction quality control accounts for a significant portion of the geotechnical practice. Compacted dry density is only loosely related to the actual strength of the compacted soil. Rather than using dry density as the controlling factor for compacted fills, it would be better to measure properties more closely related to soil strength. The Briaud Compaction Device (BCD) is a simple, small-strain, nondestructive testing apparatus that can be used to evaluate the modulus of compacted soils. The use of the BCD as a field testing device for compacted soil quality control may be more beneficial than the current practice of measuring institu dry density. In this study, the laboratory procedures of the BCD were evaluated for a compacted silt. The modulus determined by the BCD was compared to the dynamic elastic moduli (Young's and shear moduli) determined from ultrasonic pulse velocity testing on the same compacted silt samples. The BCD modulus correlated well with the ultrasonic pulse velocity results.

---

[1] Staff Geotechnical Engineer, Vector Engineering Inc., Grass Valley, CA 95945, USA. Formerly Graduate Student, Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO 65409. E-mail: dmwbnd@mst.edu

[2] Assistant Professor, Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 North Pine Street, Rolla, MO 65409. E-mail: geyun@mst.edu

1. INTRODUCTION

Several existing devices are capable of determining subgrade and base material soil moduli in the field including, the Falling Weight Deflectometer (FWD), the Lightweight Falling Weight Deflectometer (LFWD), the Geogauge, the Cleg Impact Hammer, and the Plate Load Test (PLT), to name a few. The Briaud Compaction Device (BCD) is another type of such device. The BCD is a simple, small-strain, nondestructive testing apparatus that can be used to evaluate the modulus of compacted soils. The BCD works by applying a small repeatable load to a thin plate in contact with the compacted soil of interest, and recording the resulting stains. A large strain indicates a weaker soil while a small strain indicates a stiffer soil. The load is applied to the plate manually by the operator. This load is recorded by a load cell. The resulting deflections of the thin plate are measured with an assortment of radial and axial strain gages mounted on the thin plate. The acquisition and processing unit within the device then displays the calculated BCD modulus. The software within the device uses correlations determined from field and laboratory tests in order to calculate a low strain modulus, referred to as the BCD modulus. The strain level associated with the BCD is on the order of 10^{-3} (Briaud et al., 2006).

Previous studies have shown that the BCD could be a viable alternative to current practices used for compacted soil quality control/quality assurance (QC/QA) (Li, 2004). Studies have shown that the BCD strongly correlates with other field compaction tests such as the Plate Load Test (Briaud et al., 2006). Current compaction control practices have been in place for decades and consist of determining a maximum dry unit weight in the laboratory then specifying a percentage of that maximum to be achieved in the field.

Dry density gives a measurement of how many soil particles are in a specific volume, but other factors such as suction, cementation and confinement have greater influence on the modulus (Briaud et al., 2006). It is well understood that at maximum dry density, a soil has the lowest potential for excessive settlement, highest shear strength, and lowest erosion problems Less understood, however, is the variation of soil moduli with dry density and moisture content. Studies by Seed et al. (1967) have shown that the Resilient Modulus varies depending on both dry density and moisture content, and varying testing conditions can yield largely varying soil response. Much of the soil compaction monitoring is conducted for pavement subgrades, a situation where moisture contents vary over seasons, and soil modulus is more important than most other soil properties. In this respect, perhaps it is more advantageous to specify field compaction based on a modulus value rather than a target dry density. There are several field testing devices available for field modulus evaluation (Lenke et al., 2003; Li, 2004; Alshibli et al., 2005; Chen et al., 2005; Ampadu and Arthur, 2006; Briaud and Rhee, 2006; Lin et al., 2006). Most are cumbersome, require specialized training, and only loosely correlate values obtained from the device with actual moduli values that can be determined in the laboratory. Unfortunately there does not exist a comprehensive and/or convenient test or method for determining modulus based compaction specifications in the laboratory that can be monitored easily in the field. The BCD was developed as a possible solution to these issues.

The strain response of a soil can be described by many different types of moduli. In addition, the testing conditions, confinement, strain level, and strain rate are all contributing factors to soil moduli (Li, 2004). The modulus defined by the BCD is a

stress strain relation corresponding to a strain level of 10^{-3}, stress level of 50kPa, and time of loading of a few seconds. Previous studies have shown that the BCD modulus corresponds well to other modulus defining tests (Rhee, 2008). This study attempts to correlate the BCD modulus to the dynamic moduli obtained from ultrasonic pulse velocity testing.

Ultrasonic pulse velocity testing is a pulse transmission test that sends waves that range in frequencies from 20 kHz to 1 GHz through a soil specimen to produce strains on the order of 10^{-5} (Leong et al., 2004). The test is nondestructive and can be used to determine the velocities of the longitudinal and shear waves that propagate through the soil specimen. The dynamic elastic constants can be determined using the wave velocities based on the theory of elasticity for homogenous, isotropic solids (Weidinger et al., 2008). The strain levels associated with the BCD and the ultrasonic pulse velocity device differ by as much as two orders of magnitude. Because of the smaller strain levels, moduli determined from the ultrasonic pulse velocity device can be expected to be larger than those of the BCD but should still correlate reasonably well.

2. EXPERIMENTAL SETUP

2.1. Material

The material used in this study a modified loessial low plastic silt that comes from the Mississippi River Valley near Collinsville, Illinois. The silt has a liquid limit of about 30, a plastic limit of about 24 and natural clay content of about 17.0%. The material is classified by the Unified Soil Classification System as an ML soil (Izadi, 2006). Previous

studies with the BCD have been focused primarily on clays and some sands, so an investigation on a low plastic silt should be beneficial to the development of the device.

Several standard and modified proctor compaction tests were performed on the soil to establish the standard and modified compaction curves. Three standard proctor compaction tests were conducted per ASTM D 698. Each test used six points to establish the 2nd-order polynomial best fit curve. The points ranged from 10% to 20% at increments of 2% in moisture content. Two modified proctor compaction tests were conducted to establish the modified proctor compaction curve per ASTM D 1557. Again, six points were investigated and they ranged from 8% to 18% at increments of 2% in moisture content. The BCD test uses a 6 inch (152.4 mm) proctor mold for testing. All compaction efforts were made with a mechanical automatic proctor hammer to tightly control compaction energy. The automatic hammer was recalibrated between each test. The two established proctor curves used for the remainder of this study are presented in Fig 1. The optimum moisture content and maximum dry density for the standard proctor compaction test is 14.5% and 16.8 kN/m^3 respectively; the optimum moisture content and maximum dry density for the modified proctor compaction test is 12.0% and 17.7 kN/m^3 respectively.

2.2. Specimen Preparation

The soil was first mechanically pulverized then passed through a #40 sieve (425 mm.). Samples were prepared to match dry densities and moisture contents previously determined from proctor compaction tests. The soil was moistened to a predetermined moisture content then allowed to cure for 24 hours. The soil was then compacted into a 152.4 mm (6 in.) split proctor mold. The inside of the proctor mold was lubricated with

silicone spray for BCD testing and to aid in specimen extrusion. Soil samples were then compacted according to the appropriate standard using an automatic hammer. Samples were compacted at both standard and modified energy. After soil compaction, the top of the samples were finished smooth then BCD tested. The soil samples were then gently extruded from the split mold, wrapped in plastic wrap, placed inside a sealed bag, and allowed to further cure in a moist cure room. Three samples at each moisture content (18 samples) were built for the standard energy compaction, and two samples at each moisture content (12 samples) were for built for the modified compaction energy. The samples and their properties are detailed in Table 1.

2.3. BCD Testing

The purpose of the BCD laboratory test is to establish a modulus versus moisture content relationship, similar to the dry density versus moisture content relationship established from proctor compaction tests. Once the soil was compacted in the 6 inch split mold, the surface was finished smooth with a straight edge and weighed per standard proctor testing procedures. After the soil and mold were weighed BCD test was conducted in accordance with the BCD User's Manual. This step is shown in Fig. 2. The BCD test is designed to complement the proctor compaction test. The BCD has two modes of operation, one for field testing and one for laboratory testing. The two separate modes of operation account for the boundary effects of the proctor mold that would not occur in the field (Li, 2004). It is important that the device is set to the laboratory setting in order to acquire meaningful results (BCD Manual, 2008). To get a good average of the BCD modulus, the manual recommends recording four measurements on the compacted

soil. The four measurements should be taken rotating the BCD 90 degrees between each test then averaged to get the BCD modulus (Li, 2004).

A repeatability and reproducibility study was also conducted on the BCD using the Gage Repeatability and Reproducibility (Gage R&R) analysis technique (Vardeman and Jobe, 1999). Gage R&R analysis is a simple way to numerically quantify the repeatability and reproducibility of a device. The results are reported as a standard deviation. For this study, three different operators conducted eight tests on three different materials. Materials used included a concrete floor, a concrete block, and an aluminum block. Each operator performed eight tests on the exact same location of each material, indicated by a black circle scribed on the surfaces. The orientation of the device was kept constant and all eight tests were conducted without moving the device.

During the BCD testing, several factors were identified that can significantly influence the test results. The BCD applies the load by the operator leaning on the unit. This stresses the soil the device is founded on and the displacement is recorded. If the operator does not apply the load vertically then the soil is loaded non-uniformly resulting in a lower modulus reading than expected. Currently, the BCD does not have a mechanism to determine if the device is plumb. The addition of a bubble level or similar type of mechanism might help eliminate this problem. Secondly, the diameter of the BCD loading plate is 150 mm, and the standardized 6 inch proctor mold diameter is 154.2 mm, allowing a little over 2 mm of spacing between the load plate and the proctor mold. The small 2 mm margin for the BCD to fit requires care to ensure the BCD is centered as closely as possible. Inattention to the BCD positioning can result in the load plate being too near or touching the mold. This can greatly alter the test result, typically by

increasing the recorded BCD modulus. The surface of the proctor compacted specimen

must be finished flat and smooth with all surface divots typical of proctor testing filled in

with soil of similar density. Undulations in the surface of the compacted soil puck will

cause increased load plate deformations, resulting in a lower BCD reading.

2.4. Ultrasonic Pulse Velocity Testing

Ultrasonic pulse velocity tests were conducted on the compacted soil samples in

an attempt to correlate BCD modulus with dynamic soil moduli. The ultrasonic pulse

velocity test can be used to determine the dynamic properties of materials. This is

possible by relating longitudinal and shear wave velocities to moduli through the theory

of elasticity for homogenous, isotropic solids. The strain levels associated with pulse

velocity testing are on the order of 10^{-4} to 10^{-5} (Leong et al., 2004),. The strains

associated with the BCD are around 10^{-3} (Briaud et al., 2006). Both tests use small strains

to determine soil modulus, but the BCD applies the load at a much slower rate (seconds

opposed to microseconds).

After the compacted soil was tested with the BCD, it was extruded, sealed and

placed in a moist cure room until ultrasonic pulse velocity testing could be conducted. All

pulse velocity measurements determined in this study came from a GCTS ULT-100

Ultrasonic Velocity Test System (GCTS Manual, 2004). For more information on the

ultrasonic test setup refer to Weidinger et al. (2008). The ULT-100 is a device developed

for accurate determination of the arrival times of longitudinal (P) waves and shear (S)

waves sent through a cylindrical sample. The device consists of sender and receiver

transducers housed in the top and bottom platens of a standard triaxial cell. The two, 70-

mm diameter test platens are wired to a data acquisition and processing unit. The

piezoelectric crystals housed in the platens are arranged for the transmission and reception of P and S-waves. The GSCT pulse velocity device operates in a through-transmission mode of testing, that is, a signal is produced at one end of the specimen and received at the other (GCTS Manual). The time required for the wave to propagate through the specimen can be determined by analyzing the received signal. The wave velocity is the specimen height divided by the arrival time of the wave (Stephenson, 1977).

The ultrasonic testing setup used could not accommodate 152.4 mm diameter samples, so a sample trimmer was used to carefully trim the samples to a diameter of 70 mm (2.8 in). The tops and bottoms of the samples were trimmed parallel and finished smooth. The top and bottom faces of the samples had to be smooth and free of voids for ultrasonic testing. Voids in the sample face create air pockets between the sample and the testing platen which will hinder wave transmission. The samples were loaded into a modified trixial cell for ultrasonic pulse velocity testing, as shown in Fig. 3. A normal load of 50.0±5.0 N (11.3±1.2 lbf) with no confinement pressure was applied. Initial tests revealed at full specimen height of 114 mm (4.5 in.), attenuation through the silt samples was too great and no conclusive arrival times could be retrieved. Therefore, the samples were sliced into thirds (approximately 40 mm) and finished smooth. Tests conducted on the shorter samples resulted in clean data with a high amplitude of frequencies matching the predetermined original wave frequencies (46 kHz for P-waves and 39 kHz for S-waves) (Weidinger et al., 2008) indicating a good test.

3. ANALYSIS OF RESULTS

3.1. BCD Testing

The dry density versus moisture content relationship determined from the proctor test is well understood and is presented in Fig. 5 and Fig. 6 for the standard and modified proctor tests respectively. The optimum moisture contents and maximum dry densities were found to be the same as mentioned before and are summarized in Table 2. For the modified proctor tests, the BCD modulus follows a similar trend as the compaction curve. The maximum BCD modulus for the modified test was found to be 23.7 MPa, and a corresponding moisture content of 11.5%. The modified proctor optimum moisture content is 12.0% for this soil, which is very close to the BCD modulus optimum moisture content. BCD results from the standard proctor tests yields a different curve. That is, the curve differs from the Standard Proctor compaction curve in both shape and location. The regression fit does not make a symmetric polynomial curve like the compaction curve does. Instead, the curve simply decreases with increasing moisture content and produces a slight peak around 12.0% moisture content. It appears that if more tests were conducted at lower moisture contents, a full curve might be established. Additional tests on lower moisture contents were not conducted in this study. The peak at 12.0% is drier than the optimum standard proctor moisture content of 14.5%, which is somewhat expected, soil suction and interpartical friction tend to increase modulus at lower moisture contents.

The fitted curves to the BCD Moduli versus dynamic elastic moduli show good correlations. Inspection of the Pearson's Coefficient (R^2) for each fitted curve gives a measure of how well the trend fits the data. A Pearson's Coefficient of 1 means a perfect correlation (Vardenman and Jobe, 1999). For the Standard and Modified Proctor BCD

tests, the Pearson's Coefficients were 0.745 and 0.695, respectively. The correlations between the data and the trend lines suggests that the moduli on compacted silt is influenced by moisture content and that, at a constant compaction energy, there exists an optimum moisture content that will yield a maximum modulus.

It is very important to be able to quantify the repeatability of a measuring device. The repeatability of the BCD was investigated using the BCD data collected from the five proctor curves (3 standard and 2 modified). In this case, repeatability was examined by conducting a "Gage R&R" analysis (Repeatability and Reproducibility), which determines the repeatability standard deviation. Typical gage R&R studies determine the effect of several operators (field/lab technicians) conducting multiple iterations of a test on several different specimen using one device. In that framework, variation in the results is a function of the operator, the device (the BCD), and the soil. For this study, operator variance was eliminated by conducting all tests with one operator. This makes the two test variables the device variance and the soil property variance. Under this framework the repeatability standard of deviation of the BCD was found to be ± 0.85 MPa. The average BCD modulus for the soil used was 20 MPa which means that repeated BCD measurements should be within ± 4% of each other. Reproducibility refers to the ability for different users to get the same reading when measuring a specific sample. Reproducibility could not be quantified with the proctor test data because the specimen properties changed from test to test.

To investigate the affects of varying the operator on the BCD performance, three materials of different properties were tested by three different operators. Each operator conducted 8 BCD tests on three different materials (concrete floor, concrete block, and

aluminum). Again a "Gage R&R" analysis was conducted on the results. For this analysis, the variables were consistent with standard gage R&R setup. That is, multiple operators conducting multiple measurement repetitions on multiple samples using one device. The repeatability standard deviation was found to be 1.5 MPa while the reproducibility was found to be 1.9 MPa. During this gage R&R analysis, reported BCD modulus values ranged from 27 MPa to 72 MPa. Therefore, from this study, the BCD consistently reports values at ± 2.5% to 7%.

3.2. Pulse Velocity

Ultrasonic pulse velocity testing is a quick non-destructive laboratory test that determines longitudinal and shear wave velocities transmitted through a medium. The dynamic elastic constants (Young's modulus, Shear modulus, Bulk Modulus and Poisson's Ratio) can be calculated from these velocities. Ultrasonic pulse velocity tests were conducted on the compacted soil samples as an additional means of evaluating the ability of the BCD to determine the Modulus. A BCD modulus was determined for each compacted soil specimen. After BCD testing, pulse velocity testing was conducted on the same sample to determine the dynamic Young's and Shear Moduli as well as the Poisson's Ratio.

Wave attenuation and limitations in the current setup used limited sample height for pulse velocity testing. The original sample height used for the BCD had to be sectioned into a top, middle, and bottom section with heights ranging from 25 mm to 40 mm. Ultrasonic pulse velocity testing can be used to calculate the modulus occurring throughout the tested specimen. Li (2004) reported that the influence depth of the BCD modulus decreases from 311 mm to 121 mm as the modulus increases from 3 MPa to 300

MPa under large loads. Numerical simulations using Plaxis show that the influence depth of the BCD under the actual testing loads (approximately 220 N) is much smaller. Fig. 7 shows that the influence depth resulting from a 220 N load are minimal, and that the BCD determines the modulus at the surface. It is assumed that pulse velocity tests on the top sections of the compacted soil samples correspond to the same material properties tested by the BCD. Therefore, only the pulse velocity data from the top soil samples were compared to the BCD modulus.

Ultrasonic pulse velocity tests produce signal time histories from which the arrival times of the longitudinal and shear waves can be determined. Noise in the system can make determining the arrival times difficult. Signal processing and filtering is often implemented to help refine the signal so that arrival times can more easily determined. Even with filtering, reflected waves, wave echo through the specimen, and other noise can still make arrival time determination subjective and non-discrete. Several techniques exist to help reduce the subjectivity of arrival time determination. The methods used in this study are detailed in depth in Weidinger et al. (2008). Arrival times were determined based upon assumed Poisson's Ratios and shear wave velocities. The assumption of a range of Poisson's Ratios and shear wave velocities gives an estimate of what the arrival times should be. Knowing this, helps determine what part of the signal to analyze. Table 2 displays the results from the pulse velocities tests for all samples.

The BCD Moduli versus corresponding Dynamic Young's Moduli found from pulse velocity tests are plotted in Fig. 7. The data has been separated according to compaction effort (i.e. standard proctor and modified proctor). Both sets of data produce well fitted trends with the standard proctor data having a steeper slope. High Pearson's

Coefficients (R^2) were determined from the linear fit of the data. Similarly, the BCD Moduli versus the corresponding Dynamic Shear Moduli are plotted for both standard and modified energy in Fig. 8. Again, high Pearson's Coefficients are determined from the fitted trends with a greater slope for the standard proctor trend. Though the BCD modulus is not the same as the dynamic Shear or Young's moduli determined for each specimen, the strong correlations to other moduli suggests that the BCD is indeed reporting a form of modulus that could be correlated with other moduli determining tests with significant accuracy.

4. DISCUSSION

The BCD is capable of producing a BCD Moduli versus moisture content trend similar to the well accepted dry density versus moisture content compaction curve. Results from this study, as well as results from other work (Lenke et al., 2003; Briaud et al., 2006), verify that the modulus follows a similar trend to that of the compaction curve with an optimum moisture content (OMC) occurring at or around the OMC for dry density. Fig. 5 shows this trend well for modified compaction efforts. The BCD results for the standard compaction energy does not have a pronounced peak, as shown in Fig. 4. This is likely to be the result of silt behavior and soil suction. The modified compaction effort may have enough energy to overcome some of these affects. In both the standard and modified tests the BCD modulus dropped quickly as the moisture content increased from the OMC, typically reducing by half with a 2% increase in moisture content.

The repeatability of the BCD has been investigated by Briaud et al. (2006) by conducting several repetitions of the test at one location then investigating the coefficient of variation (COV). They found the COV for the device to be below 4%. In this study,

two different Gage R&R analyses were conducted; one to investigate the variation of the

device under changing soil conditions, and another to investigate the variation of the

device from changing the operator. The first Gage R&R analysis resulted in a variation of

4% when only the soil properties were altered. The second Gage R&R analysis resulted

in a variation ranging from 2.5% to 7%. This indicates that operator error induces an

additional 3% of scatter in the results. This could be reduced if operating aids such as a

bubble level were incorporated in the device.

Comparison of the BCD moduli to the dynamic elastic moduli determined from

the ultrasonic pulse velocity test shows a high correlation. Other studies have reported

that the BCD test produces a modulus that correlates well with various moduli tests such

as the Plate Load and the Resilient Modulus tests (Li, 2004; Rhee, 2008). Therefore it is

not surprising that the BCD correlates well with the dynamic elastic moduli. The BCD

Moduli versus dynamic elastic moduli for the standard and modified proctor compaction

energies produced good linear trends with high correlations (R^2 values greater than 0.86).

The slope of the linear trends describing the relationship between the BCD Moduli and

dynamic elastic moduli was steeper for the standard compaction energy when compared

to the modified compaction energy. Varying the compaction energy alters the soil fabric,

meaning the two samples compacted to the same dry density with different energies will

produce soil with different particle arrangements, therefore different strength

characteristics. To account for the different compaction energies used, the BCD Moduli

was normalized by multiplying the moduli by the Relative Compaction. Relative

Compaction refers to the dry density obtained for each test divided by the maximum dry

density corresponding to the compaction effort (16.8 kN/m^3 for the standard proctor and

17.7 kN/m^3 for the modified proctor). The dynamic elastic moduli (G and E) did not require normalization because the density of the soil is already accounted for in the equations that derive the moduli from the wave velocities. The BCD moduli, however, does not account for soil density. Fig. 9 shows the dynamic Young's and Shear moduli versus the normalized BCD moduli. Good correlation occurs for the data with Pearson's Coefficients above 0.82.

5. CONCLUSION

The BCD is a simple non-destructive testing tool that can determine a modulus for soil compaction control. Other moduli tests can be used for determining a field modulus, but, due to their size and boundary effects, they cannot easily be conducted in a laboratory setting. This drawback limits their usefulness. Without a laboratory value to compare to, only correlations to other lab tests can be used to specify a target field modulus. Correlations are typically soil specific. With the BCD, the operator can conduct a laboratory test to produce a BCD Moduli compaction curve (similar to the proctor compaction curve), then compare BCD moduli values obtained from the field directly to BCD modulus values from the lab test. This is an attractive alternative to soil compaction control using the dry density method because 1.) the BCD directly measures a modulus to determine the compaction state of soils, 2.) the BCD can easily be used in the lab as well as the field so one tool will do it all.

Laboratory testing with the BCD is based on the proctor compaction test standards. Because the BCD is based on the proctor compaction test, no additional lab equipment is required. Conducting BCD tests on the proctor compacted soil is simple, and does not require a great deal of extra time on the technician's part, allowing two

important soil trends to be established: the dry density vs. moisture content compaction curve, and the BCD modulus vs. moisture content compaction curve. When used in parallel, field compaction specifications could be established based on both dry density and modulus, ultimately producing a compacted soil layer that would be both uniformly dense and strong.

In addition, this study indicates that the BCD modulus can be compared to other moduli determining tests such as the ultrasonic pulse velocity test. Trends such as the one determined from Fig. 10 could be used to determine the insitu dynamic moduli of a soil by simply conducting a BCD test in the field. This could prove useful in seismic and machine foundation design on existing compacted soil layers.

6. ACKNOWLEDGEMENTS

7. REFERENCES

Alshibli, K.A., Abu-Farsakh, M., and Seyman, E. (2005). "Laboratory evaluation of the geogauge and light falling weight deflectometer as construction control tools." *Journal of Materials in Civil Engineering*, Vol. 17, No. 5, pp. 560-569.

Ampadu, S.I.K., and Arthur, T.D. (2006). "The dynamic cone penetrometer in compaction verification on a model road pavement." *Geotechnical Testing Journal*, Vol. 29, No. 1, pp. 1-10.

Briaud, J., Li, Y., and Rhee, K. (2006). "BCD: a soil modulus device for compaction control." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 1, pp. 108-115.

Chen, D.-H., Lin, D.-F., Liau, P.-H., and Bilyeu, J. (2005). "A correlation between dynamic cone penetrometer values and pavement layer moduli." *Geotechnical Testing Journal*, Vol. 28, No. 1, pp. 42-49.

GCTS (2004). Data Acquisition and Ultrasonic Velocity Software User's Guide.

Izadi, A. (2006). Behavior of Undrained Monotonically Loaded Low Plasticity Silt Under Triaxial Compression. Department of Civil, Architectural, and Environmental Engineering, University of Missouri-Rolla. M.S.

Lenke, L.R., McKeen, R.G., and Grush, M. (2003). "Laboratory evaluation of the geogauge for compaction control." *Transportation Research Record*, Vol. 1849, pp. 20-30.

Leong, E.-C., Yeo, S.-H., and Rahardjo, H. (2004). "Measurement of wave velocities and attenuation using an ultrasonic test system." *Canadian Geotechnical Journal*, Vol. 41, pp. 844-860.

Li, Y. (2004). Use of a BCD for Compaction Control, Department of Civil Engineering, Texas A&M University, Ph.D.

Lin, D.-F., Liau, C.-C., and Lin, J.-D. (2006). "Factors affecting portable falling weight deflectometer measurements." *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 6, pp. 804-808.

Rhee, K. 2008. PhD Dissertation, Texas A&M Univ., College Station, TX.

Roctest (2008). Briaud Compaction Device User's Manual.

Seed, H.B., Miltry, F.G., Monismith, C.L., and Chan, C.K. (1967). "Prediction of flexible pavement deflections from laboratory repeated-load tests." National Cooperative Highway Research Program Report, No. 35, pp. 1-117.

Stephenson, R. W. (1977). "Ultrasonic testing for determining dynamic soil moduli." Dynamic Geotechnical Testing, ASTM Special Technical Publication 654, pp. 179-195.

Vardeman, S.B., and Jobe, J.M. (1999). Statistical Quality Assurance Methods for Engineers, John Wiley & Son, Inc.

Weidinger, D.M., Ge, L., and Stephenson, R.W. (2008). "Ultrasonic pulse velocity testing on compacted silt." submitted to *Geotechnical Testing Journal*.

Table 1. Compacted specimen properties.

	Test ID	Moisture Content	Dry Density (kN/m^3)	Saturation	Void Ratio
Standard Proctor	10A	10.3%	16.34	44	0.65
	12A	11.7%	16.31	49	0.65
	14A	14.4%	16.72	65	0.61
	16A	15.9%	16.81	72	0.60
	18A	18.8%	16.20	78	0.66
	20A	19.8%	15.93	79	0.69
	10B	10.7%	16.24	44	0.66
	12B	13.0%	16.36	55	0.65
	14B	14.7%	16.66	65	0.62
	16B	16.6%	16.99	78	0.59
	18B	18.4%	16.32	78	0.65
	20B	20.8%	15.69	80	0.72
	10C	9.6%	16.30	40	0.65
	12C	12.8%	16.50	56	0.63
	14C	14.3%	17.00	67	0.59
	16C	16.6%	16.80	76	0.60
	18C	18.1%	16.30	76	0.65
	20C	20.8%	15.60	79	0.73
Modified Proctor	8A	7.5%	16.97	35	0.59
	10A	9.7%	17.38	49	0.55
	12A	13.3%	17.58	69	0.53
	14A	13.3%	17.72	70	0.52
	16A	16.8%	16.84	77	0.60
	18A	18.2%	16.48	79	0.64
	8B	7.8%	17.34	39	0.55
	10B	9.9%	17.53	50	0.54
	12B	12.2%	17.72	64	0.52
	14B	13.9%	17.88	75	0.51
	16B	15.9%	17.03	75	0.58
	18B	17.7%	16.45	76	0.64

Table 2 – Ultrasonic pulse velocity and BCD test results.

| Test ID	Relative Compaction	BCD modulus	Dynamic E	Dynamic G
		(Mpa)	(MPa)	(Mpa)
-------	--------	-------	-------	-------
S10A	97.5%	17.17	130.58	49.75
S12A	97.4%	26.53	141.19	52.13
S14A	99.8%	25.68	149.72	54.98
S16A	100.4%	25.46	129.43	46.79
S18A	96.7%	12.70	101.47	36.89
S20A	95.1%	11.33	83.60	30.51
S10B	96.9%	25.94	149.56	56.08
S14B	99.4%	24.52	147.92	54.64
S16B	101.5%	19.56	127.70	46.26
S18B	97.4%	10.97	77.27	27.50
S20B	93.7%	10.98	76.19	26.96
S10C	97.3%	25.18	145.89	53.29
S12C	98.5%	24.97	131.36	48.31
S14C	101.5%	24.34	123.99	45.62
S16C	100.3%	14.36	95.91	34.70
S18C	97.3%	11.84	83.00	29.95
S20C	93.1%	11.25	86.91	31.38
M10	97.9%	24.11	187.84	67.79
M12A	99.1%	26.82	172.81	62.86
M14A	99.8%	26.27	172.23	62.76
M18A	92.9%	12.17	82.91	30.49
M8B	97.7%	31.09	197.37	71.43
M10B	98.7%	28.87	208.08	76.36
M12B	99.8%	25.38	190.20	68.34
M14B	100.7%	16.08	121.81	43.66
M16B	95.9%	12.34	81.62	28.93
M18B	92.7%	10.37	83.87	31.43
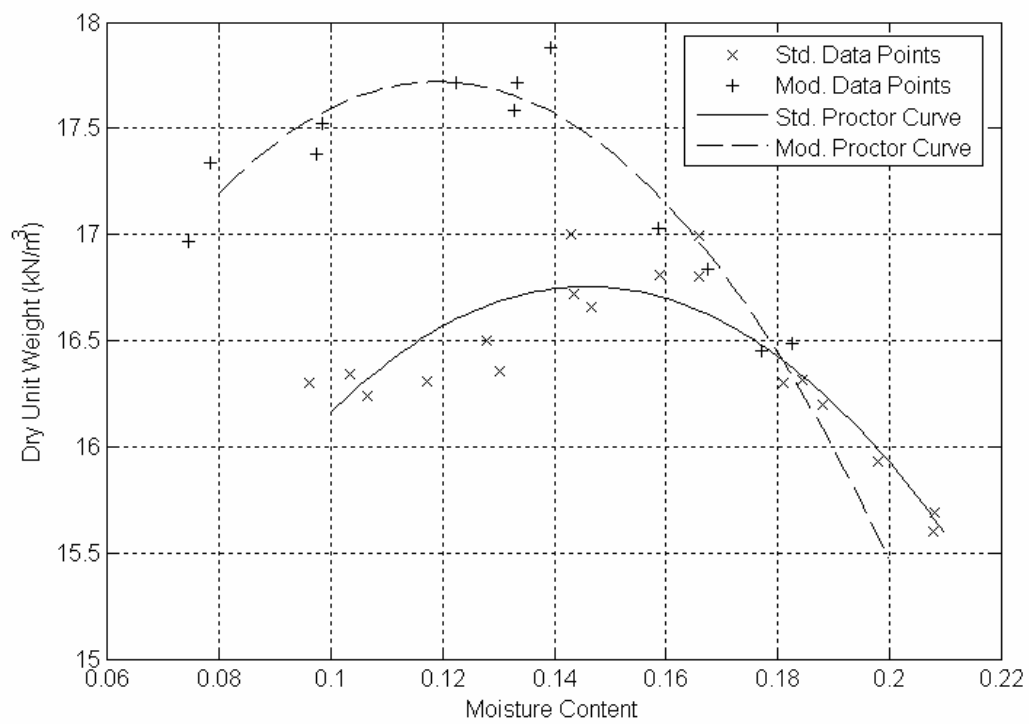
Fig. 1 – Best fit compaction curves, standard and modified energies.

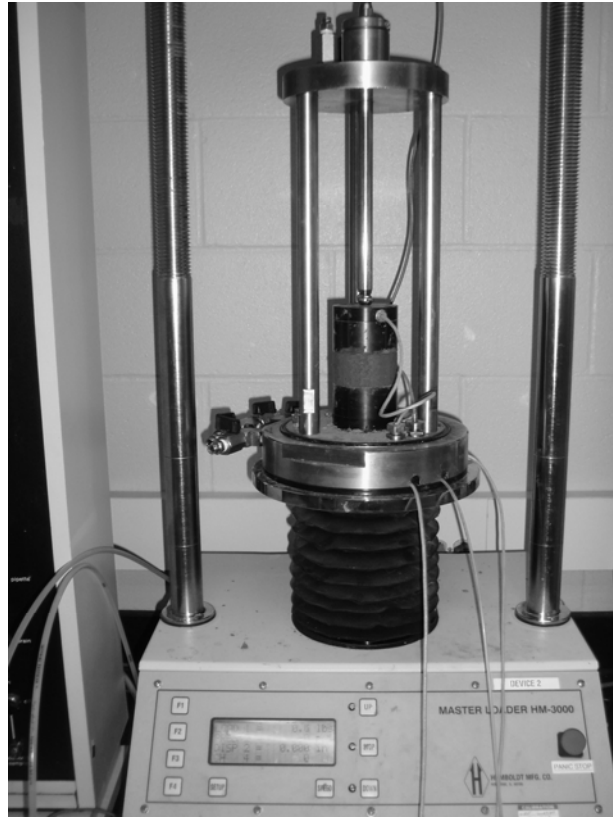Fig. 2 – BCD testing on a compacted soil sample in a 6" split mold.

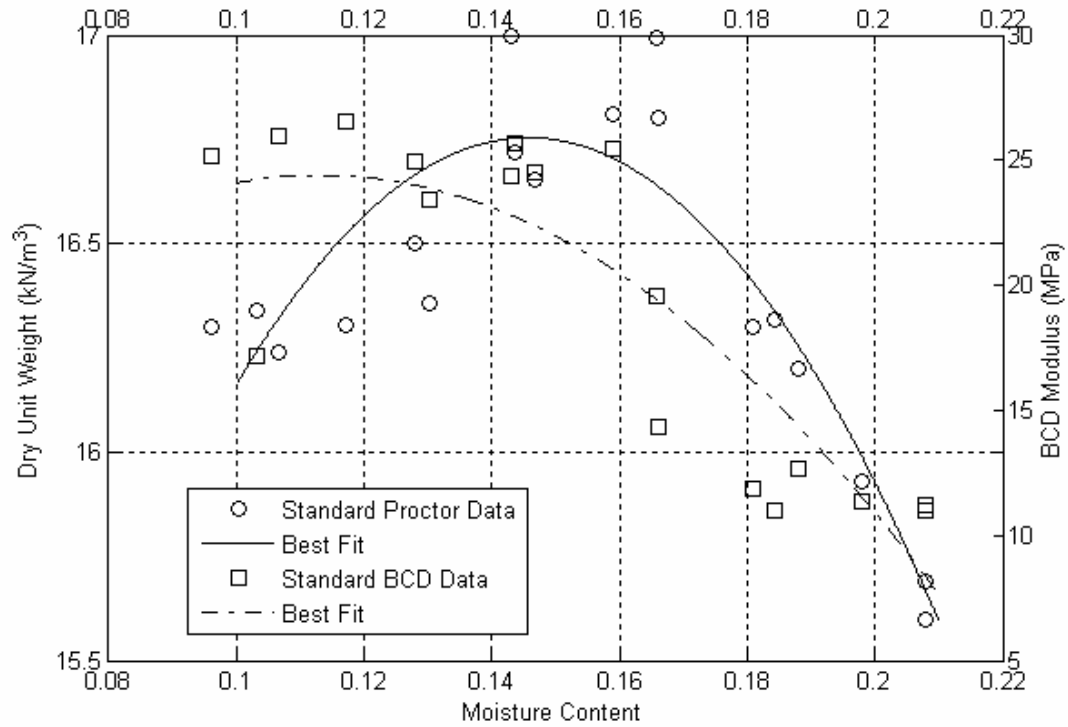Fig. 3 – Modified triaxial cell with ultrasonic pulse velocity test platens and soil loaded.

Fig. 4 – BCD raw data and fitted curve and standard proctor raw data and fitted curve for

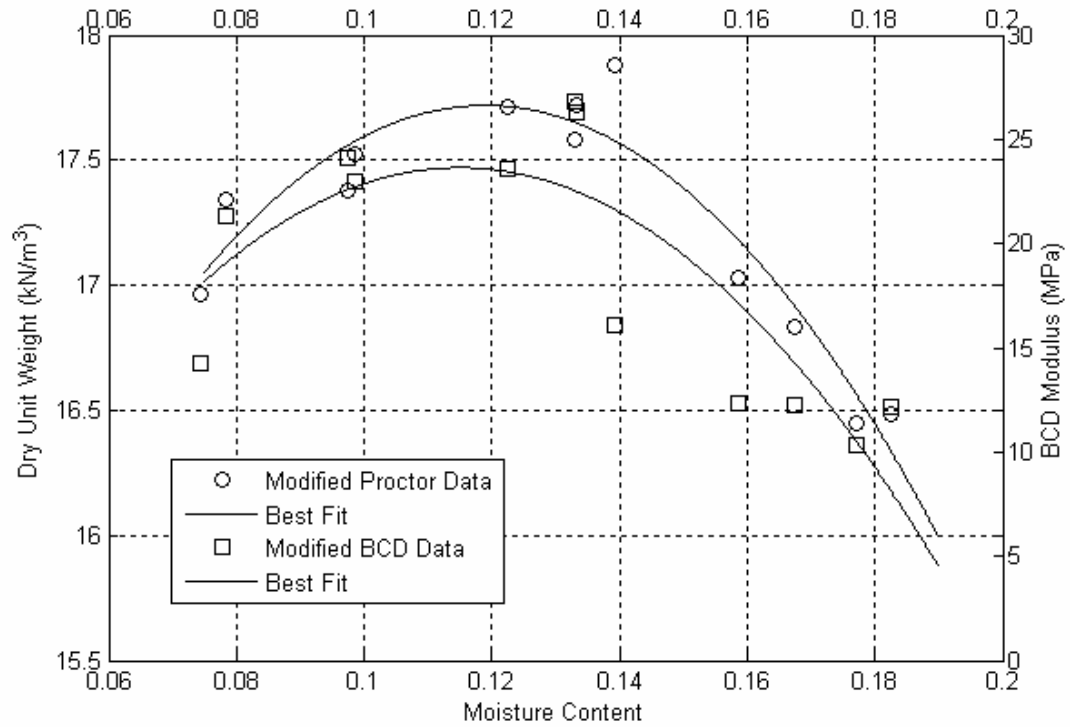3 6-point standard proctor compaction tests.

Fig. 5 – BCD raw data and fitted curve and modified proctor raw data and fitted curve for
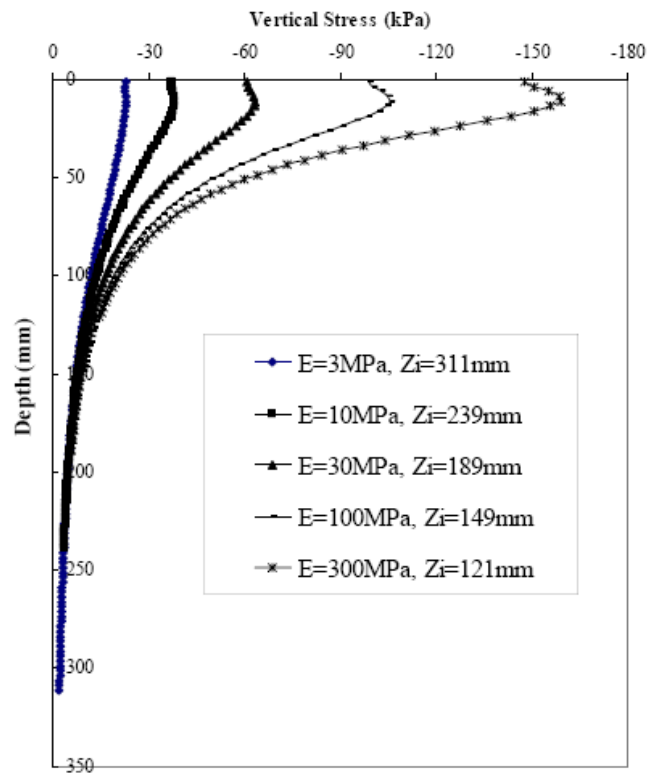
2 6-point modified proctor compaction tests.

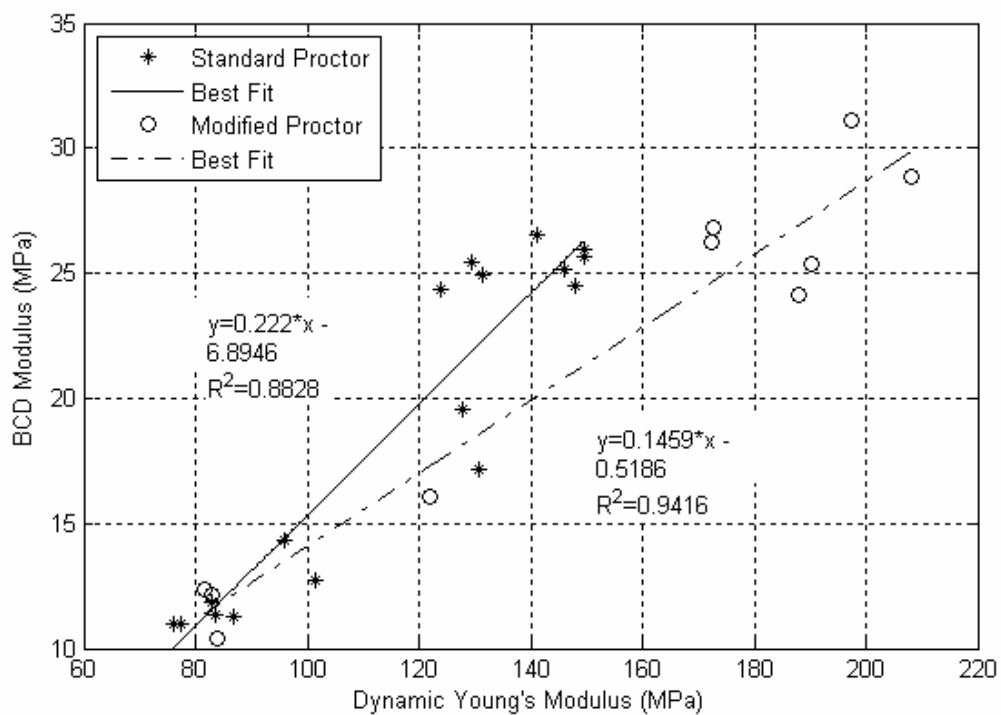Fig. 6 – BCD influence depth (Li, 2006).

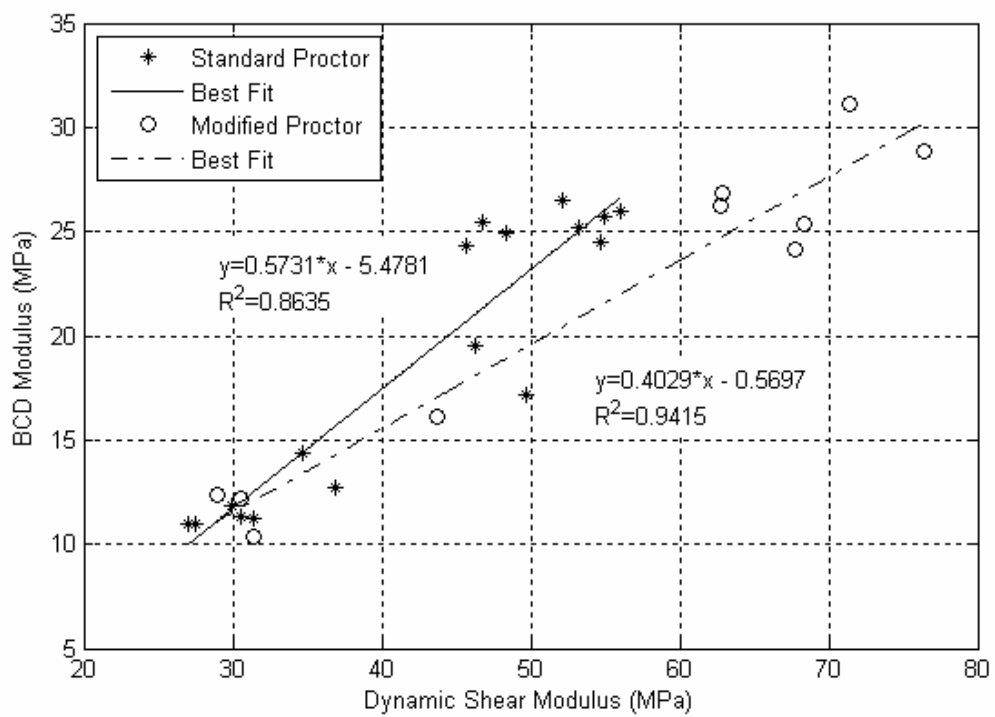Fig. 7 – BCD modulus vs. dynamic Young's modulus.

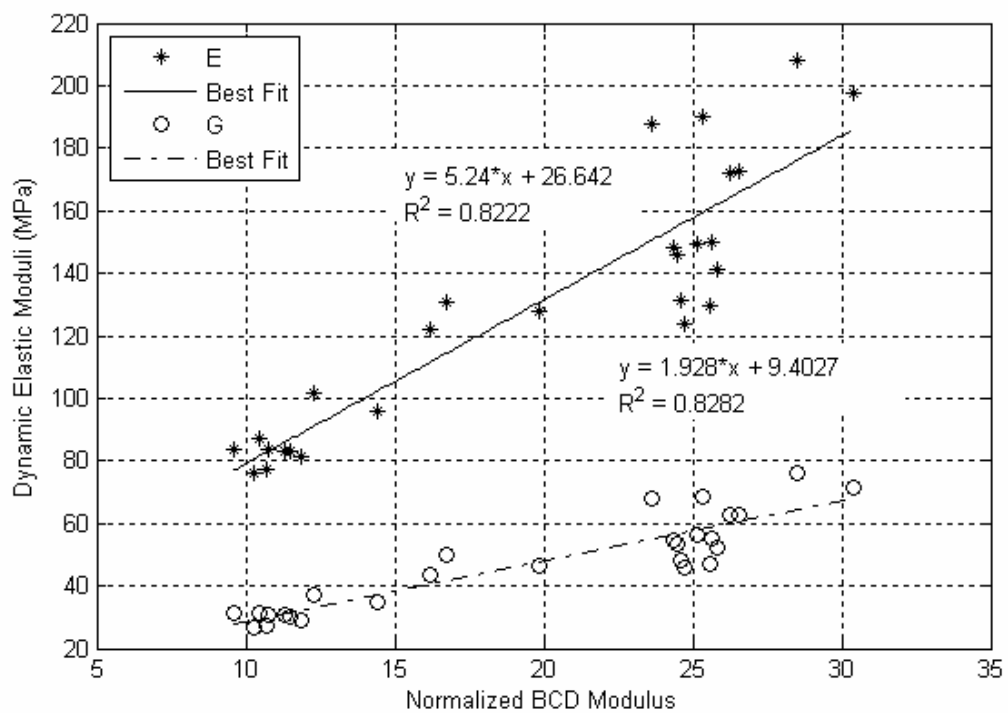Fig. 8 – BCD modulus vs. dynamic shear modulus.

Fig. 9 – Dynamic elastic moduli (E and G) vs. normalized BCD modulus.

VITA

David M. Weidinger was born April 2, 1985 in Jefferson City, Missouri. He received his primary education in Vienna, Missouri at the Visitation Inter-parish Catholic School. His secondary education was obtained from Maries R-1 High School in Vienna, Missouri. He graduated from the University of Missouri Rolla with a BS in Civil Engineering in 2007.

May of 2007, he enrolled in graduate school at Missouri University of Science and Technology (formerly University of Missouri – Rolla) to pursue an MS in Civil Engineering. Received MS in December 2008.

David's professional career started August 2008 with Vector Engineering Inc. in Grass Valley, CA where he is currently working as a staff geotechnical engineer.