Ultrasonic Testing for Compacted Clayey Soils

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Abstract

In this study, tests were conducted to investigate the use of ultrasonic methods to determine compaction characteristics of clayey soils. In particular, through-transmission test method was used to determine P-wave velocities in compacted clayey soils. Effects of soil type and compaction conditions on velocity were investigated. Tests were conducted on three soils that had low, medium, and high plasticity. Soils were prepared at water contents ranging from dry to wet of optimum using standard and modified compaction efforts. It was observed that velocity increased with increasing compactive effort and decreasing plasticity and clay content. Moreover, the variation of ultrasonic velocity with water content was similar to the variation of dry density with water content. Shapes of the water content versus velocity plots correlated well with the shapes of compaction plots. Access to two opposite surfaces of samples was required to perform through-transmission measurements. Additional tests were conducted to determine the feasibility of using surface-transmission with access required only to top surface of soils to measure velocity. Velocities that were similar to through-transmission velocities were obtained with surface measurements using correction factors. Through-transmission can be used in the laboratory; whereas surface-transmission can potentially be used in the field to determine ultrasonic velocity of compacted clayey soils. This method shows promise for determination of compaction properties of clayey soils in the field.

Introduction

Clay soils are compacted for construction of various structures and facilities. Compacted clay soils are commonly used as liners for waste containment facilities; as

embankments, subgrades, bases, and backfills for foundations and transportation facilities; and as hydraulic barriers for various facilities. Verifying the properties and condition of compacted clay soils is a significant component of design and construction with these materials. Compaction characteristics of soils are required for design, material selection, and quality control purposes.

Compaction characteristics of soils are determined by analyzing the relationship between water content and dry density (or unit weight) of soils. Proctor compaction tests are commonly used in the laboratory to determine the variation of dry density with water content. The relationship between dry density and water content of soils is demonstrated using a compaction curve. Compaction properties of field soils are compared with the compaction properties of the soils determined in the laboratory to verify the effectiveness of construction procedures. Destructive and nondestructive methods are used to determine density and water content of field soils.

Destructive test methods that are used most commonly include sand cone and rubber balloon methods. These methods involve excavating a hole in the compacted soil. The volume of the hole and the weight of the excavated soil are determined to calculate the density of the soil. Care must be exercised in determination of the weight and volume of the soil. Part of the excavated soil is used to determine the water content of the soil. The total density and water content are used to calculate the dry density of the soil. These methods can both be time consuming. The predominant nondestructive method is nuclear density meter. Both the density and water content of a compacted soil can be determined in a short period of time using this method. The density and water content of a soil are inferred from transmission properties of gamma rays in the soil. Water content is determined with transmission on the ground surface. The gamma source in the density meter is placed in a small hole excavated in the soil to obtain a representative density for a lift of soil. Presence of radioactive material in the density meter requires special handling procedures and licensed personnel. Agreement has not been fully reached on the reliability of nuclear methods (Brown 1996). Various other destructive, nondestructive, and empirical methods are available for determining compaction characteristics of soils. Extensive background information is available on determination of compaction characteristics of soils in the laboratory and in the field and also on verification of field compaction procedures (Winterkorn and Fang 1975, Brown 1996).

Ultrasonic testing can provide a fast and simple approach for determining characteristics of compacted clayey soils. This nondestructive method can be used as an alternative to existing methods to analyze laboratory or field compacted soils. This investigation was conducted to assess the feasibility of using ultrasonic testing (in this case ultrasonic velocity measurements) to determine compaction characteristics of clayey soils. Variation of ultrasonic velocity with water content and density of compacted soils was analyzed. Effects of soil type and compaction conditions on the velocity were analyzed. Transducer arrangements that would facilitate use of the method in the field were investigated.

Ultrasonic Testing for Compacted Soils

Ultrasonic testing is used for nondestructive evaluation of materials and structures. Ultrasonic waves are stress waves with frequencies higher than 20 kHz that propagate in mass media. Propagation of ultrasonic waves in a material is affected by the properties and condition of the material. Transmission of waves in a material is quantified generally using two parameters: velocity and attenuation. Ultrasonic velocity can be correlated to elastic constants and mechanical properties of a material, whereas ultrasonic attenuation can be correlated to microstructural properties of a material (McIntire 1991).

An extensive investigation of the use of ultrasonic testing for compacted soils was reported in an early study by Sheeran et al. (1967). Velocities of P-waves were determined on three types of soils. It was observed that peak velocities and maximum dry densities occurred within ± 0.5% water content for laboratory compacted soils. The ultrasonic velocities increased with increasing dry density until the optimum water content. However, at water contents higher than the optimum water content, the velocities decreased with increasing dry density. Field tests were conducted on a low plasticity sandy silt. Velocities for laboratory compacted samples (Proctor compaction) of the soil varied between 300 m/sec and 1400 m/sec. Field velocities for the soil were within the range of laboratory velocities.

Significant progress has been made in ultrasonic testing equipment, data acquisition, and data analysis since the study reported by Sheeran et al. (1967). However, ultrasonic testing has been used on compacted soils to a limited extent in recent studies. Wang et al. (1991) conducted a simple study to determine the variation of ultrasonic velocity with water content and pressure for a silt loam compacted under static pressure. The compaction pressure and water content ranged from 143 kPa to 430 kPa and 11% to 20%, respectively. The ultrasonic wave velocities in the soil were between 360 m/sec and 560 m/sec. The velocities increased with increasing compaction pressure. In general, the velocities increased with decreasing water content with some exceptions. The increase in the wave velocity at low water contents was attributed to the high bulk modulus of the soil at low water contents. Sologyan (1990) provided a brief summary of applications of ultrasonic testing to determine density of soils in the field. The information provided was related to agricultural applications. It was suggested that ultrasonic testing was used effectively to determine density, water content, and microstructural properties of soils. However, specific details were not provided.

Materials

Tests were conducted on three soils with varying plasticities, with the intent to use local soils. Soils 1 and 2 were obtained from two landfills located in Southeast Michigan. However, a high plasticity soil could not be located in this area. Therefore, Soil 2 was mixed with 25% bentonite (by weight) to make Soil 3. Index properties of the soils are presented in Table 1.

Table 1 – Soil Properties

Property		Soil 1	Soil 2	Soil 3
Classification (USCS)		SC	CL	CH
Particle Size (%)	Sand	56	3	2
	Silt	27	38	34
	Clay	17	59	64
Atterberg Limits	Liquid Limit	16	40	83
	Plasticity Index	7	17	60
Specific Gravity		2.68	2.68	2.69

Equipment

The electronic equipment used for velocity measurements consists of three units: (1) P-wave transducers, (2) pulser-receiver, and (3) data acquisition system (Fig. 1). Two transducers are used for measurements, one transducer for transmitting ultrasonic waves, the other for receiving ultrasonic waves that travel through the test sample. The transducers are 50-kHz-center frequency narrowband transducers with diameters of 44.5 mm. The transducers are actuated by a pulser-receiver which is connected to a computer for digitization of data (Fig. 1). The 10-MHz-bandwidth broadband pulser-receiver has an adjustable repetition rate in the range of 20 Hz to 2 kHz, with a 1V output for synchronous triggering of the signal acquisition board during data acquisition. The data acquisition system includes a computer equipped with an A/D (analog to digital converter) board with 100 MHz sampling rate and a digital oscilloscope software package which is used for viewing waveforms and for adjusting data acquisition parameters.

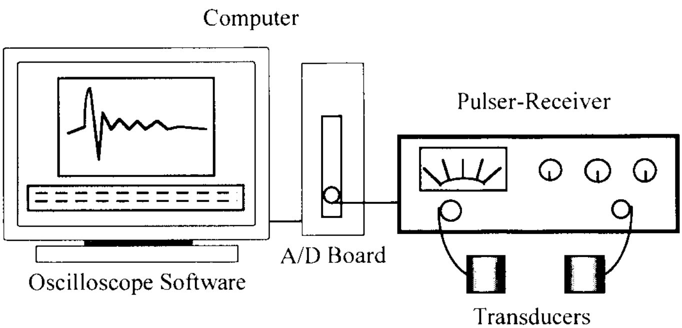

Figure 1. Electronic Equipment

Ultrasonic Test Procedure

The ultrasonic tests conducted for this study consisted of determination of velocity of P-waves in the test soils using two transducer arrangements. The test configurations used in the study are presented in Fig. 2. The tests were conducted using through-transmission and surface-transmission methods. The through-transmission test technique is also referred to as direct transmission. In this method, ultrasonic waves are sent from one surface of a material with a transmitting transducer and the transmitted waves are received by a receiving transducer placed on the opposite surface of the material. This method is used mainly for testing highly attenuating materials such as soils. In surface measurements, the transducers are placed on the same surface of a material and waves are transmitted from the transmitting transducer to the receiving transducer along the surface of the material.

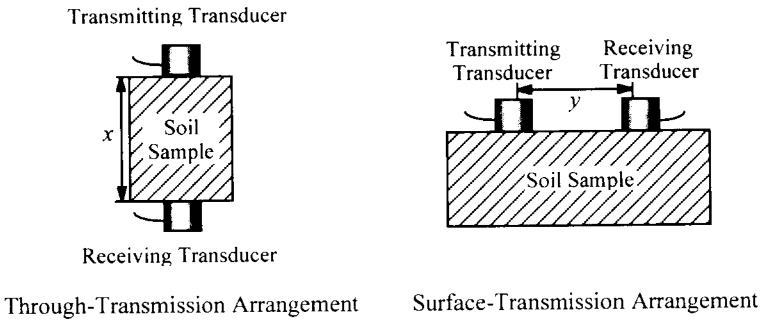

Figure 2. Test Configurations

The velocity of the P-waves is obtained as the ratio of the travel path to the travel time of the waves. In the through-transmission test technique, the travel path is the thickness of the samples (indicated by x in Fig. 2). In the surface measurements, the travel path is the distance between the transducers along the surface of the soil (indicated by y in Fig. 2). The travel path of the waves for both test configurations is determined using mechanical measurements (i.e. using a pair of calipers with an accuracy of 0.02 mm).

The travel time for both of the test methods is obtained from ultrasonic measurements as the first arrival time of the waves at the receiving transducer. The first arrival time was calculated as the difference between the time of application of the pulse by the transmitting transducer and the arrival time of the waveform in the receiving transducer. The A/D board was synchronized with the pulser-receiver such that data collection started at the time of pulse application. Therefore, there was no uncertainty in the determination of the pulse application time which was equal to 0

μsec. Wave averaging and calibration procedures were used to minimize random and systematic errors associated with determination of the first arrival time of the waves at the receiving transducer. A single waveform recorded in the computer consisted of an average of 32 waveforms. For each measurement, four such waveforms were recorded. The average of these four waveforms was further processed using a computer code to determine the first arrival time. A schematic description of the procedure is presented in Fig 3. Initially, a baseline was determined on the early portion of the waveform using a statistical procedure. Also, the waveform was rectified to facilitate the analysis of the waves. A threshold was then determined as twice the amplitude of maximum variation (representative of noise in the waveform) in the baseline. Finally, the first arrival time was determined as the intersection point of the waveform with the threshold. Similar procedures are described in literature for the determination of first arrival time (Jones and Facaoaru 1969, Komlos et al. 1996).

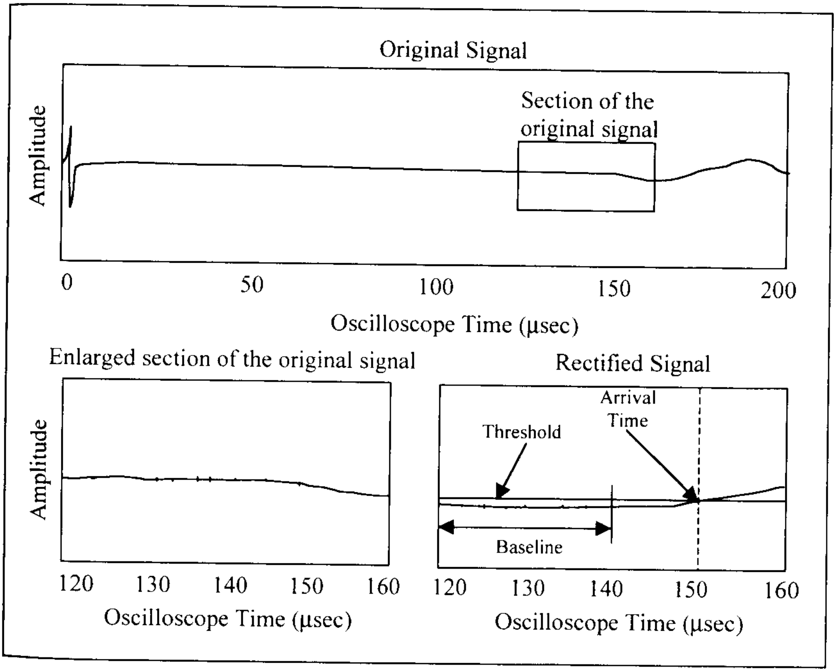

Figure 3. Signal Processing

Testing Program

Laboratory tests consisted of determination of P-wave velocity on compacted soils using the through-transmission and surface-transmission methods. The soils were compacted using standard and modified Proctor efforts. Effects of soil

properties and compaction conditions on velocity were analyzed. Comparisons were made between traditional compaction plots (dry density vs. water content) and compaction plots obtained with ultrasonic measurements (velocity vs. water content). Comparisons were also made between direct and surface measurements.

In the tests using the through-transmission test technique, samples were used for determination of density and water content as well as P-wave velocity. Velocity was determined on each sample that was used for determination of compaction characteristics of the soils. In most cases, three samples were prepared at each target water content. Compaction plots were generated using dry density vs. water content and velocity vs. water content (Figs. 4 - 6). In addition, plots of total density versus water content and void ratio versus water content are presented in Figs. 4 – 6. Maximum dry density, maximum velocity, maximum total density, and minimum void ratio with corresponding water contents are presented in Table 2.

Table 2 –Properties of Compacted Soils

Property	Soil 1		Soil 2		Soil 3	
	STD	MOD	STD	MOD	STD	MOD
Max. $\gamma_{(dry)}$ (kN/m^3)	20.5	21.6	15.9	18.2	15.3	16.7
w_{opt} (%)	9	7.2	22	15	25	19
Max. Velocity (m/sec)	1350	1550	980	1470	920	1040
$w_{vel\ max}$	8.3	7	22	16.5	25	18.5
Max. $\gamma_{(total)}$ (kN/m^3)	22.4	23.2	19.6	21	19.1	19.9
$w_{\gamma t\ max}$ (%)	10	7.6	23.2	16.2	25	21
Min. e	0.28	0.22	0.65	0.45	0.73	0.58
$w_{e\ min}$	9	7.2	22	15	24.5	18

It was observed that the variation of ultrasonic velocities with water content was similar to the variation of dry density with water content (Figs. 4 - 6). Velocity increased with increasing water contents up to the optimum water content. Beyond optimum, velocity decreased with increasing water contents. The maximum velocity was obtained approximately at the optimum water content. The highest variation with respect to maximum dry density, 1.5%, was for Soil 2 compacted with modified effort (Table 2). The variation of velocity with water content was also similar to the variation of total density with water content. In addition, the variation of velocity with water content was similar to inverse of the variation of void ratio with water content. The maximum velocity was obtained approximately at maximum total density and minimum void ratio (Table 2). The highest variation with respect to total density, 2.5%, was for Soil 3 compacted with modified effort. The highest variation with respect to void ratio, 1.5%, was for Soil 2 compacted with modified effort. For Soil 3, variation of velocity with water content was closer to variation of total density with water content than variation of dry density with water content. The location of maximum dry density was not clear for Soil 3 (LL = 83). Similar compaction plots were reported in the literature for soils with LL>70 (Brown 1996).

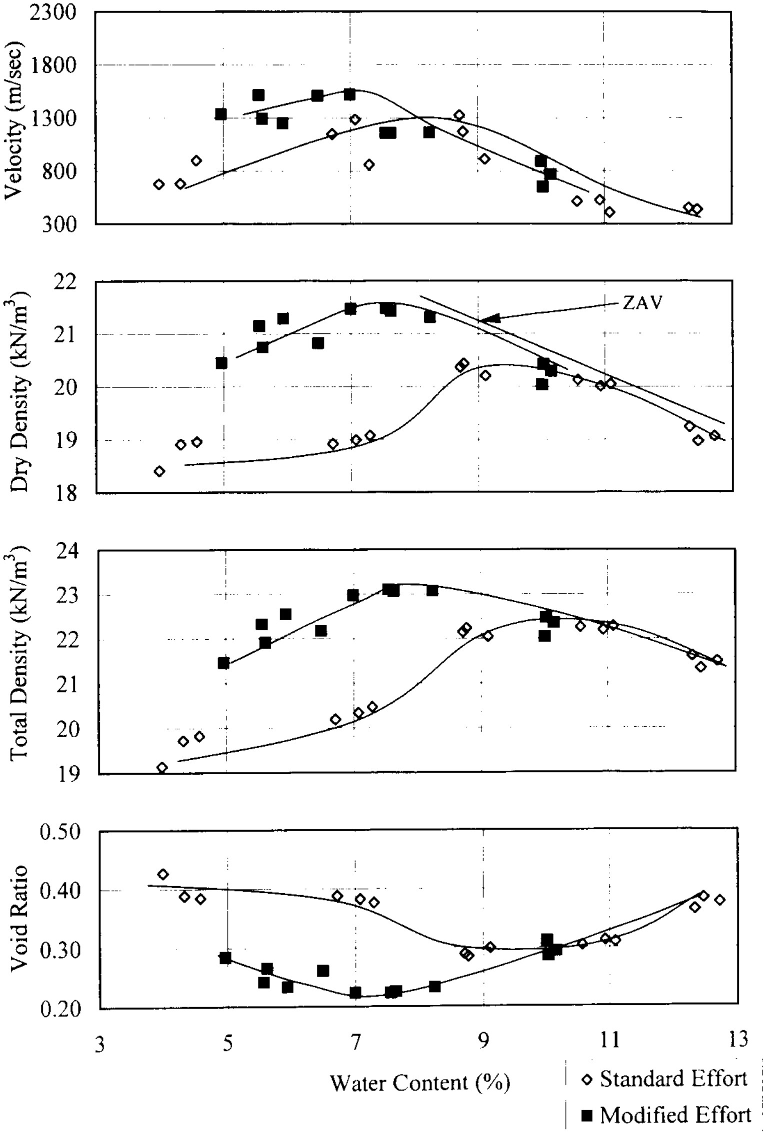

Figure 4. Compaction Characteristics of Soil 1

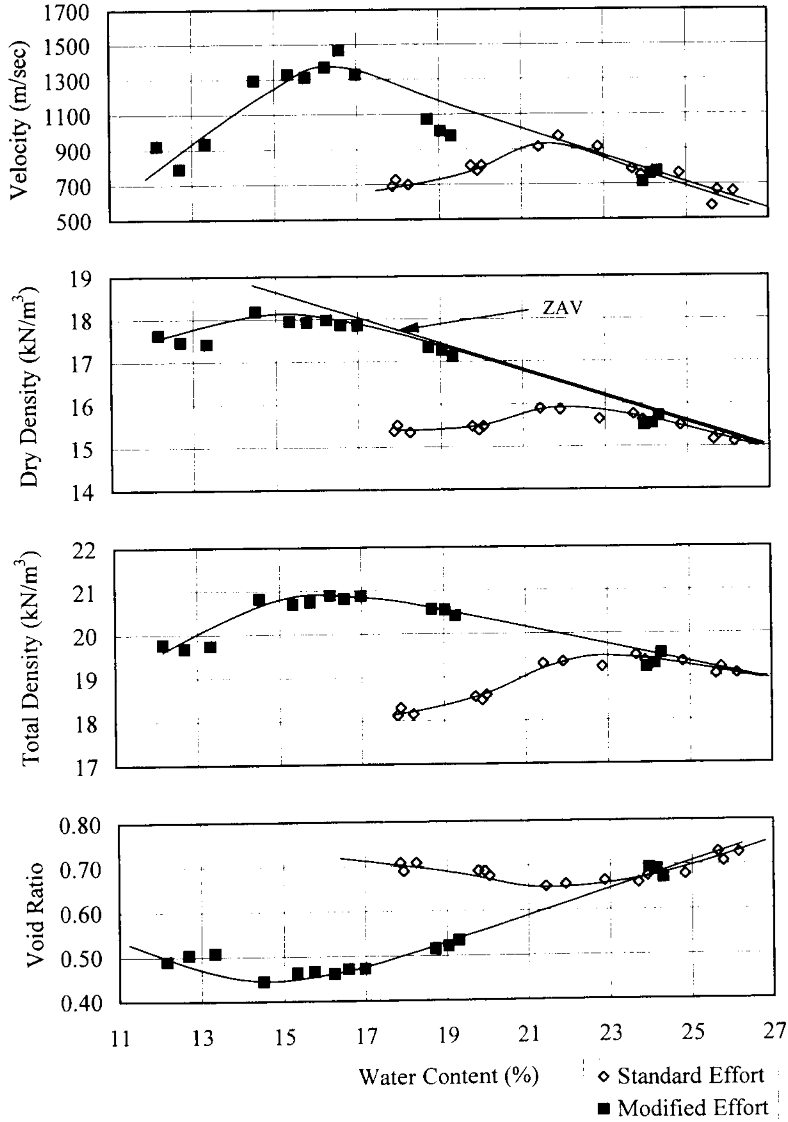

Figure 5. Compaction Characteristics of Soil 2

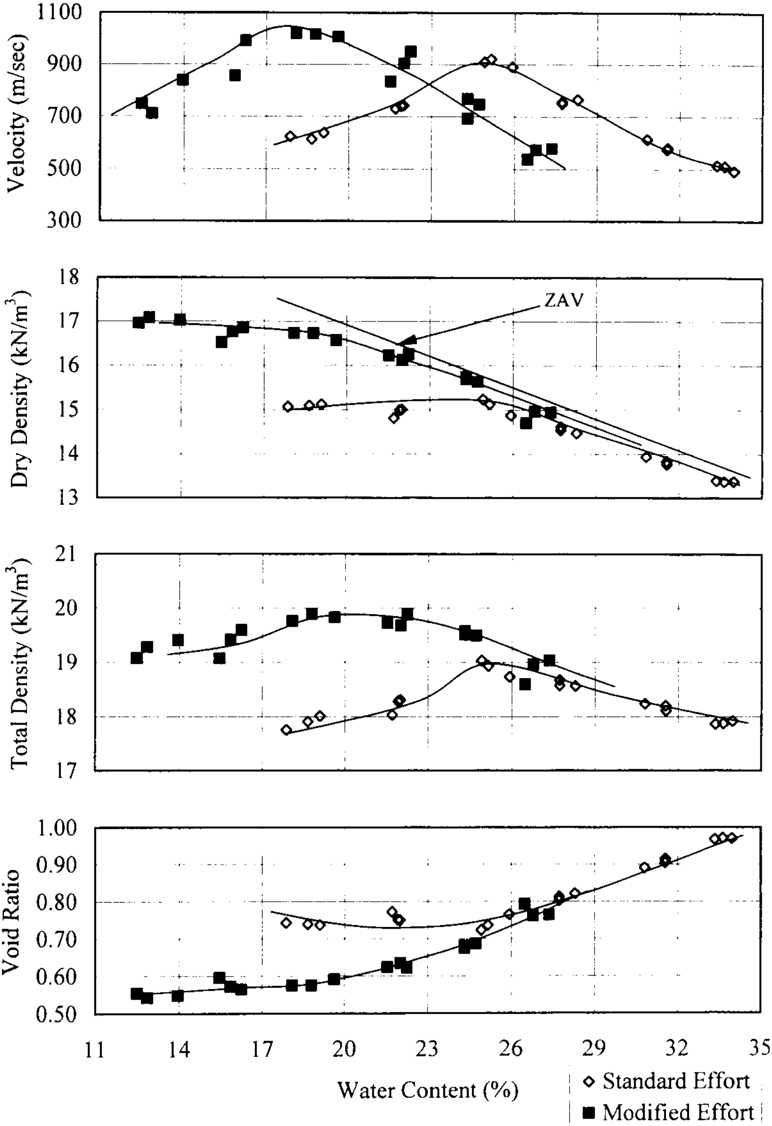

Figure 6. Compaction Characteristics of Soil 3

In a three-phase system such as a compacted soil, wave transmission occurs through all of the phases. In general, velocities in solids are higher than velocities in liquids, which are higher than velocities in gases (McIntire 1991). Therefore, it is expected that high velocities occur at high solid and low water and air contents. Highest solid and lowest void contents indicated by maximum dry density and minimum void ratio occur at optimum water content in compacted soils. Hence, maximum velocity occurs at the optimum water content. The velocities are lower than the maximum value both at the dry and wet side of the optimum as the solids contents decrease and water or air contents increase in the soils.

At the same water content the velocities for samples compacted with modified effort were higher than the velocities for samples compacted with standard effort (Figs. 4 - 6). Soils compacted with modified effort have higher solids content and lower voids content than soils compacted with standard effort. High solids content results in high velocities. Velocity in the test soils decreased with increasing clay content and plasticity. The highest maximum velocity was obtained for Soil 1 and lowest maximum velocity was obtained for Soil 3 (Table 2). As the plasticity and the clay content of the soils increase, the porosity also increases resulting in a decrease in the densities and increase in water contents. High densities and low water contents result in high velocities, whereas low densities and high water contents result in low velocities. In addition, it is expected that there were some particle contacts between the sand grains in Soil 1. Particle contacts could also have facilitated transmission of the waves which resulted in early arrival times and high velocities.

Variation of velocity with dry density was also analyzed (Fig. 7). In general, velocity increased as the dry density of the soils increased. The rate of this increase was more for Soil 1 than Soils 2 and 3. For Soil 1, significant changes in the travel path of the waves could have occurred as more contacts between particles (sand grains) occurred with increases in density. Increases in solid-to-solid contacts could increase velocity more than decreases in voids content (without increases in particle contacts). It must be noted that microstructural analyses were not conducted in this study to verify potential changes in the structure of the soils during compaction.

Use of through-transmission method in the field requires obtaining samples for the ultrasonic tests. However, access only to top surface of soils is required in surface-transmission without any need for sampling. Additional laboratory tests were conducted to compare velocities determined using through-transmission and surface-transmission measurements. The objective of these tests was to determine the feasibility of using surface measurements to determine P-wave velocity of the soils for potential field application of this method.

Surface transmission tests were conducted on samples prepared in 45.7-cm-diameter and 15.7-cm-deep molds. The compaction energy used was similar to the standard Proctor compaction energy. For each soil, three samples were prepared: one at approximately 5% dry of optimum, one at approximately optimum, and one at approximately 5% wet of optimum water content. The transducers were placed on

the surface of the samples. Measurements were conducted at varying transducer separations. Velocity was determined as the ratio of the path length of the waves (distance between transducers) to the first arrival time of the waves. Through-transmission tests were also conducted.

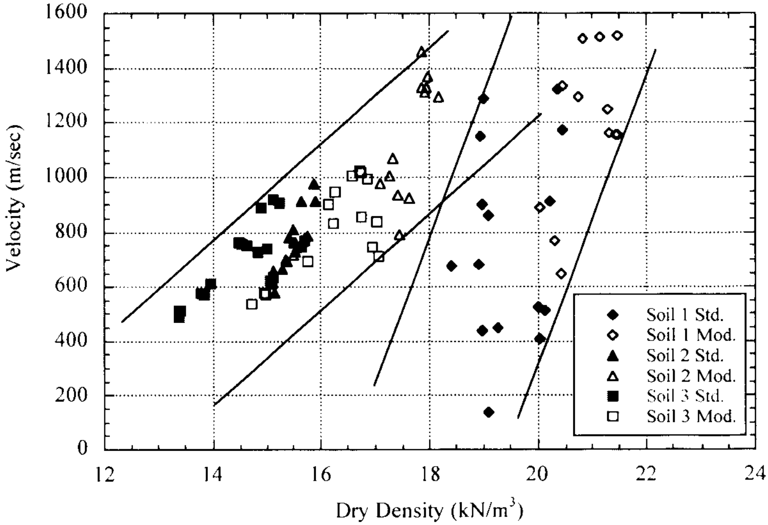

Figure 7. Variation of Velocity with Dry Density

There are uncertainties in the determination of the path length of the waves in surface-transmission. The path length can be affected by the non-uniform distribution of excitation over the cross sectional area of the piezoelectric crystal in a transducer (Krautkramer and Krautkramer 1983). The path length depends on the position of the portion of the crystal that undergoes maximum deformation. The velocity can vary depending on the assumed path length, three possible variations are presented below:

$$v = \frac{L_{c-c}}{t_{arr}}, \quad v = \frac{L_{ir-ir}}{t_{arr}}, \quad v = \frac{L_{or-or}}{t_{arr}} \qquad (1)$$

where:
v is the velocity,
L_{c-c} is the distance between the center of the transducers,
L_{ir-ir} is the distance between the inner rim of the transducers,
L_{or-or} is the distance between the outer rim of the transducers.

The center-to-center transducer separations were varied between 5 cm and 25 cm at 5-cm increments. Velocities were determined using the three path lengths for each particular transducer separation. In addition, velocities were determined using through-transmission measurements. It was observed that the direct velocities (Fig. 8) were similar to the direct velocities obtained in the previous set of tests (Figs. 4 - 6). For Soil 1, the density of the soil compacted at the optimum water content was lower than the density obtained in the previous tests. As a result the velocity for the sample was lower than the velocity expected to be obtained at the optimum water content (Fig. 4 and Fig. 8).

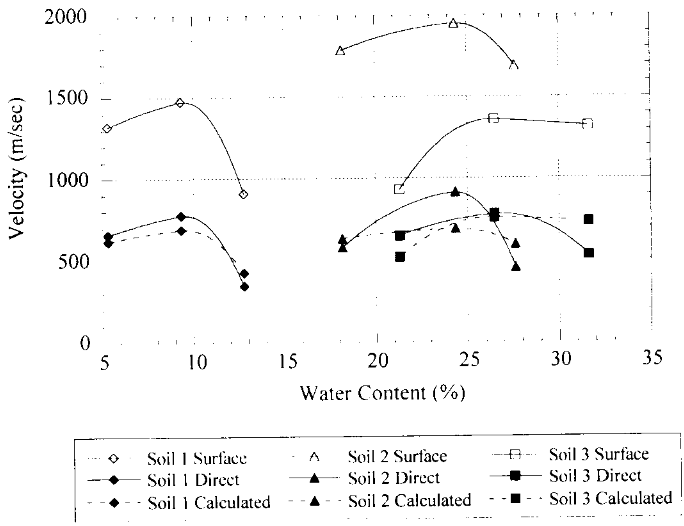

Figure 8. Direct and Surface Measurements

In most cases, velocities obtained from the surface measurements were not similar to direct velocities. There were differences in the magnitude of the velocities as well as differences in the variation of the velocities with water content (i.e. surface and direct measurements indicated dissimilar trends). For all of the soils, the variation of direct velocities with water content followed similar trends with the variation of 5-cm center-to-center surface velocities with water content (illustrated on Fig. 8). However, the magnitudes of these surface velocities were not similar to direct velocities. Variations in surface and direct velocity measurements were

observed in ultrasonic testing of concrete (Komlos et al. 1996). A correction factor was suggested to be used in European standards to convert surface velocities to direct velocities. A similar approach was used in this study. A correction factor was calculated for each soil using the average of the ratios of the direct velocity to indirect velocity. The correction factors were 0.47, 0.35, and 0.56 for Soils 1, 2, and 3, respectively. The variation between measured and calculated (using the correction factor) direct velocities were between 2.6% to 38% with a mean variation of 20% (with 11% average deviation from the mean). The calculated direct velocities are also presented on Fig. 8. It is believed that an average variation of 20% between direct and surface measurements can be acceptable for compacted clayey soils.

Conclusions

Tests were conducted to analyze the use of ultrasonic methods to investigate compaction characteristics of clayey soils. Ultrasonic tests were conducted to determine P-wave velocity in the soils. It was observed that variation of velocity with water content was similar to the variation of density with water content. Maximum velocities and dry densities were within ± 1.5% water content for the test soils. Velocities increased with increasing compactive efforts and decreasing plasticities. These results were explained with the distribution of various phases in a compacted soil mass. High velocities occur at high solids contents and low water and air contents and conversely, low velocities occur at low solids contents and high water and air contents. The magnitude and variation of velocities obtained in this study correlated well with the distribution of the phases in the soil masses. In addition, it was observed that velocities increased with increasing dry density. The rate of velocity increases with density was higher for Soil 1 than Soils 2 and 3. Significant changes in the travel path of the waves could have occurred for Soil 1 as more particles (sand grains) contacted with increasing densities. Particle contacts could have facilitated transmission of the waves which resulted in early arrival times and high velocities. Potential changes in the structure of the soils during compaction were not verified by microstructural analysis in the study.

Through-transmission (with access required to opposite surfaces of soils) and surface-transmission (with access required only to top surface of soils) arrangements were used to determine velocity. Through-transmission arrangement was used to obtain baseline velocity measurements. Velocities that were on average within 20% of through-transmission velocities could be obtained with surface-transmission using soil-dependent correction factors.

In summary, it is believed that ultrasonic testing can be used effectively to determine compaction characteristics of soils both in the laboratory and in the field. Through-transmission tests can be conducted in the laboratory, whereas surface-transmission can be used in the field to determine velocity of compacted clayey soils. This method shows promise for determination of compaction properties of clayey soils in the field. The method can be used as an alternative to existing field methods. However, field verification is required to complete the development of the method.

Acknowledgement

Funding for this study was provided by the National Science Foundation under Grant CMS-9713922. Ms. Tarhonda Rhodes and Mr. Gnanatilake Gamage assisted with laboratory tests and data analysis. Their efforts are greatly appreciated.

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