UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

INTERPRETATION OF SHEAR WAVE VELOCITY IN UNSATURATED SOILS

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

in partial fulfillment of the requirements for the

DEGREE OF

DOCTOR OF PHILOSOPHY

BY

TAREQ ZIAD THABET ABUAWAD

Norman, Oklahoma

2023

INTERPRETATION OF SHEAR WAVE VELOCITY IN UNSATURATED SOILS

A DISSERTATION APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

BY THE COMMITTEE CONSISTING OF

Dr. Gerald A. Miller, Chair

Dr. Amy Cerato

Dr. Tohren Kibbey

Dr. Kanthasamy Muraleetharan

Dr. Andrew Elwood Madden

Acknowledgment

I am deeply grateful for the invaluable guidance and unwavering support of Dr. Gerald Miller, my mentor and advisor. His steadfast belief in me served as a constant source of motivation throughout my academic journey at the University of Oklahoma.

To my parents Ziad and Hanan, for their unconditional love and support. My brothers Yazan and Husam for believing in me. My uncle’s family Nasir, Anna, Khalid, Ismael, and Ibrahim Marakah for being my home away from home. Thank you all!

Thank you to my committee: Dr. Cerato, Dr. Andrew Madden, Dr. Muraleetharan, and Dr. Kibbey.

Thank you to Dr. James Nevels for all the help throughout this journey.

Thank you to Midwest Engineering and Testing Corporation (METCO): Nasir Marakah, Omar Karmid, Shafe SaadAldin, and Tina Morgan.

Thank you to the Oklahoma Department of Transportation (ODOT).

Thank you to all my friends and Colleagues for always being there when I needed them and listening to me talk about my research and being interested in what I am doing at work.

Table of Contents

List of Tables

List of Figures

Abstract:

Shear wave velocity measurements in soil can provide estimates of small strain stiffness and are used for seismic site classification. In comparison to saturated soils, there has been relatively little research on the behavior of shear wave velocity in unsaturated soils. Current research was conducted to understand the behavior of shear wave velocity in unsaturated soil. The objectives of this research were to: 1) Investigate the effect of various soil properties on the behavior of shear wave velocity in unsaturated soils. This included studying the effect of soil type, moisture content, suction, confining stress, wetting-drying hysteresis, density, and soil structure. 2) Compare and analyze shear wave velocity measurements taken in the field and the laboratory. 3) Investigate the effect of seasonal changes in moisture content on shear wave velocity measurements from the Seismic Cone Penetrometer (SCPT), and the potential impact on seismic soil properties and site classification. And finally, 4) develop a model that uses the physical and mechanical properties of the soil to estimate the shear wave velocity for different soil types under various saturation conditions.

To achieve the objectives of this study the following tasks were completed: 1) Performed shear wave velocity laboratory testing on soil samples undergoing the vapor equilibrium suction control for wetting and drying paths using the bender elements method with and without confining stress. 2) Performed SCPTu shear wave velocity measurements at twelve sites and recorded seismic velocity measurements at 1 m depth intervals. 3) Performed shear wave velocity testing in the laboratory on soil samples from the field under stress conditions similar to the field. 4) Investigated proposed relationships in the literature and based on them, develop a new model for predicting shear wave velocity that includes the desired properties and stress conditions of the soils.

The major contributions of this research include: 1) Shear wave velocity was tested under various conditions where soil type, water content, suction, density, confining stress, and soil structure were varied and the combined effect of changing these parameters was assessed. 2) An investigation of shear wave velocity with the seismic cone penetrometer in the field at nine test sites during wet and dry seasons demonstrates the importance of considering changes in shear wave velocity due to changes in moisture content and suction in the active zone of the soil profile. This has important implications for the determination of soil dynamic properties and seismic site class based on field measurements of shear wave velocity in unsaturated soils. 3) A systematic comparison of shear wave velocity determined using SCPT in the field and bender element testing in the laboratory on Shelby tube samples obtained on the same day was accomplished for three different test sites. The study revealed that field measurements were nearly the same as lab measurements made under similar confining stress. These results indicate that measurements of shear wave velocity, whether in the field or lab, are robust and reliable. 4) Existing power models for predicting shear wave velocity with effective stress were examined and a new linear model was developed and found to provide better predictive capability than the power model.

Chapter 1: Introduction

1.0 Overview

The study of soil mechanics is essential for the assessment of ground behavior under various loading conditions. In this regard, understanding the shear wave velocity in unsaturated soils is important as it plays a significant role in determining the seismic site class and calculating the shear modulus of the soil. Determination of seismic site class and shear modulus, among other soil characteristics, are important for proper earthquake design. Additionally, shear wave velocity measurement in the field and laboratory is rapid and repeatable making it a reliable and efficient way of assessing soil mechanical properties in general.

During a seismic event, the soil experiences dynamic shear forces, which propagate through the soil profile as shear waves. The shear wave velocity is a measure of the speed at which the shear wave propagates within a soil profile under dynamic loading. The severity of the shear forces depends not only on the initial energy of the seismic event but also on the type of soil, porosity, density/compactness, and water content, among other properties. Therefore, it is essential to understand how different soil properties affect the shear wave velocity under unsaturated conditions.

Limited research has been conducted on how different soil properties, including water content, density, suction, confining stress, soil type, soil structure, and compaction, collectively affect the behavior of shear waves under unsaturated conditions. To address the knowledge gaps, the research described in this dissertation aimed to examine and understand the changes in shear wave velocity measured in the laboratory and field in unsaturated soils representing different soil conditions. Laboratory testing was conducted on three test soils composed of various amounts of sand and clay. Shear wave velocity measurements were obtained at known moisture contents and suction levels, and then the moisture content of the soil specimens was altered by adding or removing water, and the corresponding shear wave velocities were measured. This process was repeated for several different moisture contents. The moisture content and suction levels of the soil specimens was varied by placing them into a controlled relative humidity environment to achieve the desired suction, and the corresponding changes in shear wave velocity were measured. This process was also repeated to achieve multiple levels of suction. For one set of specimens, the confining stress was also varied to examine its impact on shear wave velocity.

The data collected was used to develop a mathematical model that relates changes in shear wave velocity to changes in moisture content and stress state. This model was developed based on the effective stress concept proposed by Lu and Likos (2006) for unsaturated soil and calibrated using the empirical data from this research. The predicted shear wave velocity values were compared to the measured values to assess the accuracy of the model.

The results of this study demonstrated that changes in soil properties, such as moisture content, suction level, density, and confining stress, among others, significantly affect the shear wave velocity in unsaturated soils. This research focused on the influence of initial structure, hysteresis (during wetting and drying cycles), and other factors mentioned previously, on the shear wave velocity of unsaturated soils. The developed mathematical model reasonably predicts the changes in shear wave velocity under different soil conditions, which can be used to estimate changes in shear wave velocity for different soil types as a function of changes in moisture content and suction levels. This model uses the soil's physical and mechanical properties to estimate the shear wave velocity during wet and dry seasons and the variation occurring during wetting and drying.

1.1. Motivation for Research

Problems related to unsaturated soils are frequently encountered in geotechnical engineering works. Under unsaturated conditions, the soil is in a state between fully saturated and completely dry, which is common in soils around the world due to the seasonal wetting and drying. The unsaturated soil is made of three phases including solid, water, and air. Fredlund and Rahardjo (1993) suggested the air-water interface, or contractile skin, is considered a fourth phase. Generally, there is no consensus on how best to represent the state of stress in unsaturated soils. However, the two-stress state variable approach is commonly adopted and includes the net normal stress (σ-u_a) and the matric suction (ψ). Matric suction, also known as the capillary pressure, is defined as the difference between pore air and water pressure (u_a-u_w). The presence of matric suction changes in unsaturated soils, particularly finer soils, strongly influences soil behavior (e.g. Fredlund and Rahardjo 1993 & 2012). Studying different soil properties and behaviors in unsaturated conditions has become of great interest for engineers around the world.

Recently, researchers started paying more attention to the behavior of the dynamic soil properties in unsaturated soils. Determining the dynamic soil properties including shear wave velocity and small-strain shear modulus is an important task in the evaluation of earthquake engineering problems. For geotechnical engineers, the measured shear wave velocity is typically used in determining the seismic site class and the small strain shear modulus *G* of the soil. The ability to properly classify the seismic site class and determine *G* using the shear wave velocity measured in the field is important for proper seismic analysis and design.

Shear wave velocity is generally measured in the field using a variety of methods including: cross-hole, down-hole, and seismic cone penetration tests. Seismic cone penetration testing (SCPTu) is becoming more popular because it is simple, rapid and provides other useful parameters including the tip resistance (q_c), sleeve friction (f_s) and pore water pressure (u_o) during penetration. The seismic cone is instrumented with geophones to detect and record small motions caused by shear waves in the soil profile. Figure 1 (Tschuschke et al. 2020) shows a schematic of a cone truck, pushing the cone into the ground and an example of the shear wave velocity testing, along with other cone test parameters that can be obtained.

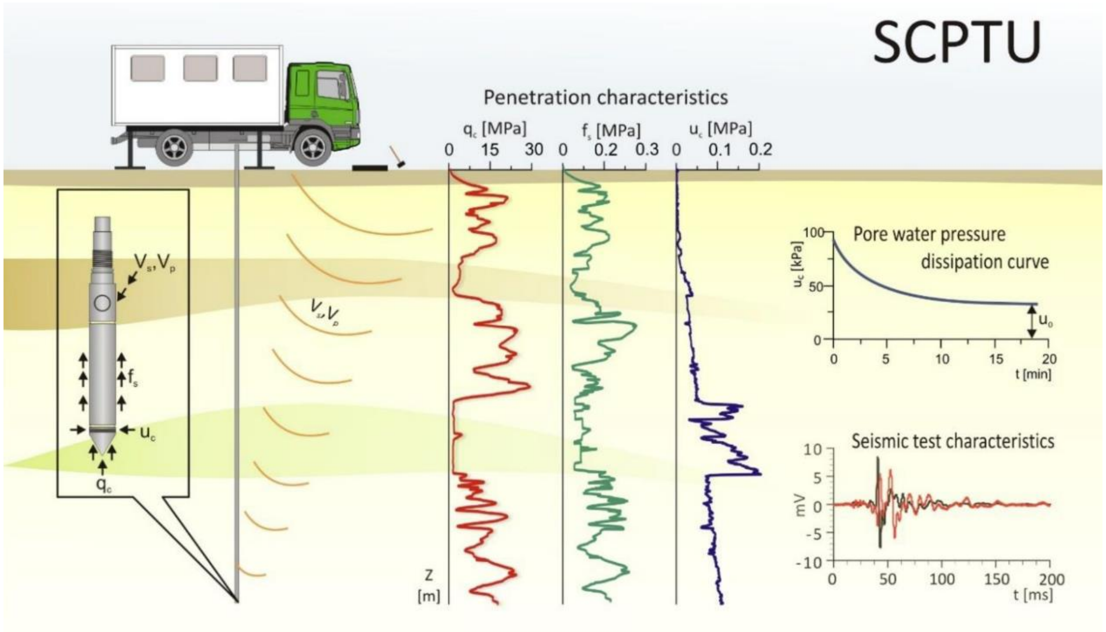

Figure 1. SCPTu schematic (from Tschuschke et al. 2020).

It is important to consider that the shear wave velocity measurements, as well as the other cone testing parameters, obtained in the field in unsaturated soils are applicable to the in-situ moisture conditions of the soil at the time of testing. For example, on a given date, these tests provide the shear wave velocity under the moisture conditions present in the soil profile that day, which may change due to variable seasonal weather conditions. This is an issue since the shear wave velocity changes with changes in water content (e.g. Cho and Santamarina 2001, Yang et al. 2008, Lu and Sabatier 2009, Asslan and Wuttke 2012). The changes in shear wave velocity with water content in the field could lead to inappropriate seismic site classification or estimates of soil properties during the design process, leaving a structure under-designed for earthquakes.

Many factors can affect the shear wave propagation in unsaturated soils. As the inter-particle forces and interaction between phases change, the shear wave velocity behavior changes (e.g. Santamarina et al. 2001). Changes in soil density, soil suction, confining pressure, and soil structure all affect the shear wave velocity. Currently, there are few methods for interpreting shear wave velocity in unsaturated soils (e.g. Sawangsuriya et al. 2008, Whalley et al. 2012, Asslan and Wuttke 2012). The difficulty in interpreting the shear wave velocity in unsaturated soil comes from the lack of understanding of how changes in some soil properties affect the wave velocities. For example, there is very little literature on the effect of changing the soil density and soil structure, i.e. flocculated versus dispersed, on shear wave velocity. This is an important aspect since the shear wave velocity is related to the small strain shear modulus G and the soil density ρ.

The current methods of interpreting shear wave velocities rely on direct measurement in the soil in-situ or in the laboratory. The problem is that the in-situ conditions on the day of testing may or may not represent the worst-case scenario. For laboratory testing the issue lies in the effect of disturbance on soil samples and the difficulty of setting up tests that replicate the in-situ conditions of the soil. Additionally, the difference in testing scale between the laboratory and the field may produce differences between laboratory and field measurements of shear wave velocity. That is, shear wave velocities measured for intact samples in the laboratory may be different from those measured in the field due to the presence of macro features and heterogeneities in the soil profile not captured in intact samples.

The research presented in this dissertation studied the behavior of shear wave velocity in unsaturated soils using field and laboratory testing methods. These methods were used to investigate the changes in shear wave velocity under controlled laboratory, and uncontrolled field environments. For the laboratory part, testing included observing the effects of water content, suction, density, confining pressure, wetting and drying, percent of fines, and soil structure on shear wave velocity. This was done by preparing soil samples at various water contents, densities, and percent of fines, then controlling the soil suction to apply wetting and drying cycles on the samples. For some tests, once the samples reached different target moisture contents, confining pressure was applied, and shear wave velocity measurements were made using the bender element method. For the field part, tests were conducted to investigate the effect of seasonal changes on shear wave velocity by conducting the SCPTu at different times of the year. Additionally, a comparison to determine the differences between shear wave velocities measured in the field and the laboratory was accomplished.

To determine the effect of seasonal changes on shear wave velocity in the field, SCPTu testing was conducted at multiple sites and shear wave velocity measurements were taken at discrete depths. For each site, SCPTu was conducted once during the dry season and once during the wet season. For shear wave velocity comparisons between the field and the laboratory, SCPTu testing was conducted at multiple sites and shear wave velocity measurements were taken at discrete depths. Then, undisturbed soil samples were taken to the laboratory and shear wave velocity was measured under similar conditions to the in-situ conditions, i.e. similar water content and confining pressures.

This research is important in that it contributes to fundamental understanding of factors affecting the shear wave velocity in unsaturated soil and advances related theories. Results from laboratory testing provided information on the effect of changing soil properties on shear wave velocity; which included the effect of water content, suction, density, soil structure, soil type, and confining stress. Furthermore, results from the field testing helped build on the observations made in the laboratory and provided a means of comparison between data measured in the field and the lab. Using the results from the laboratory and field testing, an improved analytical framework for interpreting shear wave velocity in unsaturated soils was proposed.

1.2. Objectives of Study

The goal of the research work described in this dissertation is to improve the interpretation and analysis of shear wave velocity in unsaturated soils. To do so, the primary objectives include the following.

a. Investigate the effect of various soil properties on the behavior of shear wave velocity in unsaturated soils. This included studying the effect of moisture content, suction, confining stress, wetting-drying hysteresis, density, and soil structure. To support this objective the following tasks have been completed.

   1. Prepared soil specimens using a mixture of fine sand and kaolinite clay. The percentage of sand and clay in the specimen varied to achieve sand and clay contents between 10% and 90%. A detailed presentation of the testing matrix is shown in the next chapter.
   2. Suction was varied in test specimens made of manufactured fine sand and kaolinite prior to determination of shear wave velocity. The vapor equilibrium method was used to change the moisture content and suction in the tested specimens.
   3. Performed shear wave velocity laboratory testing on soil samples undergoing the vapor equilibrium suction control for wetting and drying paths using bender elements method with and without confining stress. The testing included repeat tests on selected samples for confirmation of the testing repeatability.

4. Plotted and analyzed the results collected from the lab to examine the relationships between shear wave velocity and various soil conditions.

b. The second objective of this study was to compare and analyze shear wave velocity measurements taken in the field and the laboratory. To support this objective the following tasks have been completed.

   1. Performed SCPTu shear wave velocity measurements at three sites and recorded seismic velocity measurements at 2 to 3 ft. depth intervals.
   2. Performed in-situ disturbed and undisturbed sampling to retrieve soil samples from the field that were used for laboratory testing.
   3. Performed shear wave velocity testing on retrieved field soil samples under conditions similar to the field (i.e. confining stress and moisture condition) using the bender element system.
   4. Plotted and analyzed the results collected from the field and the lab to compare and explain the differences, if any, between field and lab measurements.
   5. Developed a framework for interpreting shear wave velocity from SCPTu in light of comparisons to laboratory measurements.

c. The third objective of the study was to investigate the effect of seasonal changes in the field on shear wave velocity measurements from SCPTu and the impact on seismic site classification. This investigation was used to improve the general knowledge of shear wave velocity measured in the field. To support this objective the following tasks were completed.

   1. Performed SCPTu shear wave measurements at four sites during wet and dry seasons and recorded shear wave velocity measurements at 2 to 3 ft. depth intervals.

2. Plotted, compared, and analyzed data collected in the field on different testing dates.
3. Implemented the laboratory testing-based framework developed in Objective 1 to estimate changes in shear wave velocity for various soil types, based on alterations in moisture content and suction levels.

d. The final objective of this study was to develop a model that uses the physical and mechanical properties of the soil to estimate the shear wave velocity under various saturation conditions. To support this objective the following tasks were completed.
   1. Analyze the results collected in the lab and the field and find common trends.
   2. Investigate proposed relationships in the literature and based on them, develop a new model for predicting shear wave velocity that includes the desired properties and stress conditions of the soils.
   3. Validate the results by using data from this study and that found in the literature.

1.3.Organization of the dissertation

The dissertation is structured in a logical and cohesive manner. Chapter 2 presents the literature review, where the relevant subject matter is discussed, and the gaps in current knowledge are identified. In Chapter 3, the experimental procedures for both laboratory and in-situ testing are described in detail. Moving forward, Chapter 4 dives into the analysis of results from laboratory testing, which addressed Objective 1, while Chapter 5 and 6 focuses on the results from the field and the combination of field and lab testing, which addressed Objectives 2 and 3. The proposed shear wave velocity model is presented in Chapter 7. Finally, Chapter 8 provides the conclusions and recommendations based on the findings of this research.

2.0 Literature Review

2.1 Organization of Literature Review

This literature review begins with a general overview of the application of the seismic shear wave velocity in geotechnical engineering. In the second section the theory of wave propagation is discussed with particular emphasis on shear waves. In the following sections, factors influencing shear wave propagation based on the general equation of shear wave velocity are discussed; these include the degree of saturation, soil suction, and hysteresis. Next, the influence of confining stress and compaction on shear wave velocity are discussed. Then shear wave velocity measured in the field using the seismic cone penetration test method (SCPTu) is discussed. Finally, the observed knowledge gaps are highlighted, and the importance of this research is discussed in the final section.

2.2 Application of Shear Wave Velocity in Geotechnical Engineering

In earthquake prone areas, seismic activity is a potential source of hazardous loading. Seismic loads disrupting the soil profile could occur before, during, and after construction. Prior to construction, it is required that buildings and other structures be designed for non-collapse due to earthquake shaking and geologic hazards associated with seismic events. These geologic hazards include liquefaction, lateral spreading, downdrag on piles, landslides, and settlement (e.g. ODOT 2017). In order to design against seismic hazards, geotechnical engineers measure the dynamic soil properties in the field to quantify the quality of the soil involved in construction and how well it reacts to seismic events. The dynamic soil properties include shear wave velocity, small strain shear modulus, and damping ratio.

The most commonly measured dynamic soil property in the field is the shear wave velocity (V_s), which is used for different applications in earthquake design. By measuring V_s we can calculate the small-strain shear modulus G of the soil, which is used for the analysis of the earthquake ground response. Equation 1 shows the relationship between shear wave velocity, shear modulus (G) and density (ρ). This equation is used to define the wave velocity in a homogenous material based on the physical properties, and is also commonly used to define shear wave velocity in soils.

$$V_s = \sqrt{\frac{G}{\rho}} \qquad (1)$$

Another important utilization of the measured shear wave velocity is to classify soils into seismic classes. The seismic site class is an identification process that is based on the average conditions present within 100 feet of the ground surface. The classifications are designated as A through F with 'A' being hard rock and 'F' being collapsible soils. The table provided by the ASCE 7-05 is shown below (Table 1). This table provides engineers with the criteria to classify soils into different seismic classes. An important aspect of earthquake design is based on the assessment of seismic site class shown in Table 1. This assessment is usually based on the soil properties determined on the day(s) of the subsurface investigation. However, in an unsaturated soil profile, the soil properties in the active zone will change with changes in moisture content. If the shear wave velocity of the soil changes due to changes in soil properties during or post construction, the site class of the soil profile may also change. Further, any site specific seismic analyses that depend on these properties will only be valid for the state of soil as it existed at the time of subsurface investigation. Thus, changes in the shear wave velocity and other properties could lead to inadequate performance or failures during seismic events. Therefore, it is essential that geotechnical engineers consider impacts of possible changes in shear wave velocity and other soil properties due to variable moisture conditions in unsaturated soils over the life of the structure being designed.

Table 1. ASCE 7-05 seismic site classification table (from ASCE 2007).

Site Class	Site Profile Name	Soil Shear Wave Velocity, v_s(ft/sec)	Standard Penetration Resistance, $\bar{N}$ or Nch	Undrained Shear Strength, $\bar{S}_u$ (psf)
A	Hard rock	$\bar{v}_s > 5{,}000$	NA	NA
B	Rock	$2{,}500 < \bar{v}_s \le 5{,}000$	NA	NA
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_s \le 2{,}500$	> 50	> 2,000 psf
D	Stiff soil	$600 < \bar{v}_s \le 1{,}200$	15 to 20	1,000 to 2,000 psf
E	Soft clay soil	$\bar{v}_s \le 600$	<15	<1,000psf
		Any profile with more than 10 ft of soil having the following characteristics: • Plasticity index PI > 20 • Moisture content $w \ge 40\%$, and • Undrained shear strength $S_u < 500$ psf		
F	Soil requires site response analysis	Liquefiable soils, peat, high plasticity clay		

Further, understanding how different soil properties influence the behavior of shear wave velocity in unsaturated soils will provide important insight for determination of shear wave velocity for seismic design. In the following sections, theoretical and experimental studies on shear wave velocity are discussed.

2.3 Theory of Wave Propagation

Much research has been dedicated to understanding the nature and behavior of seismic wave propagation in soils. To demonstrate the shear wave propagation in soils, a one-dimensional torsional elastic stress wave in a bar was used as an example. The general equation governing torsional wave propagation in a bar is presented as,

$$d^2\theta/dt^2 = (G/\rho)\, d^2\theta/dx^2 \qquad (2)$$

where θ is the angle of rotation, t is time, x is the direction of propagation, and $(G/\rho) = V_s^2$ as mentioned in Equation 1.

Equation 2 is derived using Newton's second law. The forces acting on the soil bar are shown in Figure 2.

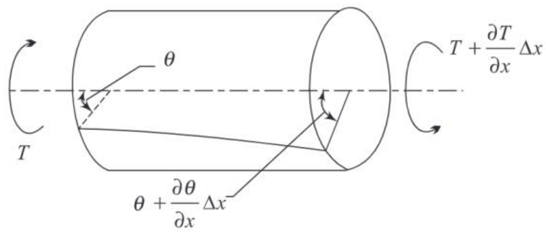

Figure 2. Schematic drawing of the forces acting on the soil bar during the propagation of a torsional wave (from Das and Ramana 2011).

Using newton's second law, gives

$$-T+[T+(d\mathrm{T}/dx)dx] = (\rho J dx)\, d^2\theta/dt^2 \tag{3}$$

Where T is the torque, ρ is the density, J is the polar moment of inertia of the cross-section. This equation is simplified into:

$$dT/dx = \rho\, d^2\theta/dt^2 \tag{4}$$

knowing that,

$$T = JG\varepsilon_x \text{ and} \tag{5}$$

where ε_x is the shear strain

$$\varepsilon_x = d\theta/dx\,, \tag{6}$$

we can differentiate the equation to get,

$$dT/dx = G\, d^2\theta/dx^2 \tag{7}$$

where G is the shear modulus of the soil. Plugging Equation 7 into Equation 4 we get

$$G\, d^2\theta/dx^2 = \rho\, d^2\theta/dt^2 \tag{8}$$

and by simplifying,

$$d^2\theta/dt^2 = (G/\rho)\, d^2\theta/dx^2$$

or,

$$d^2\theta/dt^2 = (V_s)^2\, d^2\theta/dx^2 \tag{9}$$

where V_s is the shear wave velocity.

This equation describes the general propagation of a shear wave in soil; the propagation of the wave is derived from the change in torque of the bar at a given time. This equation is limited since it is derived for the elastic bar and does not take into consideration the presence of water and air in the pores of the soil. This analysis is extended to develop the governing equation for the wave propagation in an elastic half space under a normal line load source on the surface which is given by Equation 10 (e.g. Biot 1956).

$$\begin{aligned} \frac{\partial \sigma_{11}}{\partial x} + \frac{\partial \sigma_{12}}{\partial y} &= \rho \frac{\partial^2 u}{\partial t^2}, \\ \frac{\partial \sigma_{12}}{\partial x} + \frac{\partial \sigma_{22}}{\partial y} &= \rho \frac{\partial^2 v}{\partial t^2}, \end{aligned} \tag{10}$$

Where: ρ denotes the density of the material, $u = u(x,y,t)$ and $v = v(x,y,t)$ denote the displacement into the *x*- and *y*- direction, $\sigma_{11} = \sigma_{11}(x,y,t)$ and $\sigma_{22} = \sigma_{22}(x,y,t)$ denotes the normal stresses into *x*- and *y*- direction and $\sigma_{12} = \sigma_{12}(x,y,t)$ denotes the shear stresses into the *x*- and *y*- direction.

Biot 1956 advanced the analysis of shear wave velocity to account for porosity and the presence of pore fluids in the soil. The theory for porous media proposed by Biot (1956 a and b) can be used to understand the behavior of shear wave velocity in soils. The theory assumes the following:

1. a homogenous distribution of pores in the medium,
2. conditions are isothermal,
3. stress distribution in the pore fluid is hydrostatic,

4. the material is isotropic.

Biot's theory was used to predict the behavior of wave propagation in a porous fully saturated medium; this was done by analyzing the propagation through the solid matrix and the fluid in the pores. Biot came to a conclusion that in a fluid filled porous media there exist two types of waves, compression and shear waves also known as P and S waves. P waves propagate by compressing the soil skeleton, while S waves propagate by shearing the particles. He also found that P waves, which are the faster waves, can travel through the solid particles and the fluid within the pores whereas S waves can only propagate through the solid particles.

Biot derived the equation for rotational waves (S-waves) along the *x*-direction resulting in Equation 11,

$$V_s = [\frac{N}{\rho_{11}\left(1-\frac{{\rho_{12}}^2}{\rho_{11}\rho_{22}}\right)}]^{\frac{1}{2}} \qquad (11)$$

where V_s is shear wave velocity, N is shear modulus, and ρ_{11}, ρ_{12}, and ρ_{22} are mass coefficients that define the density of the soil. The mass coefficients account for the relative motions between the solid particles and pore fluid. When there is no relative motion between the fluid and the solid during wave propagation, $\rho_{11}+2\rho_{12}+\rho_{22}=\rho$, and Equation 11 becomes similar to Equation 1 for an elastic continuum. Note, ρ is the mass density of the fluid-solid aggregation, or total soil density.

Many researchers have relied on Biot's theory for application purposes using the finite element method and other constitutive models to estimate shear wave velocities. A variety of models have been proposed to build on Biot's theory since then (e.g., Prevost 1980, Zienkiewicz et al. 1977, Coussy 1995). Some studies were done to analyze the theoretical behavior of wave propagation in unsaturated soils. In unsaturated soils, the presence of water, air, and the contractile skin has been found to affect wave propagation (e.g. Muraleetharan and Wei 1999, Ashayeri et al. 2009). Theoretical results showed that the presence of air and water has an effect on the wave propagation.

In their 2002 study, Wei and Muraleetharan developed a continuum theory to analyze wave propagation behavior within multiphase porous media, specifically addressing unsaturated mediums. Their research highlighted the generation of three compression waves and one shear wave due to interface interactions during dynamic activities within these media. This groundbreaking development extends Biot's initial theory of wave propagation in porous media and offers valuable insights into wave behavior within unsaturated soils.

Furthermore, Wei and Muraleetharan demonstrated the sensitivity of wave propagation characteristics to changes in water content within unsaturated soils. This observation underscores the significant influence of moisture variations on the behavior and properties of wave propagation in these materials.

Results from the theoretical analysis opened the way for engineers to have a better understanding of the seismic behavior of soils in the unsaturated conditions. With theory in mind, many studies have been done to evaluate the effect of different soil properties on seismic waves in unsaturated soils. These studies are discussed in the next sections.

2.4 Factors Affecting Shear Wave Velocity

Looking at the general equation of shear wave velocity (Equation 1), the major properties influencing the shear wave velocity are the stiffness, as reflected by the shear modulus, and the density of the soil. Firstly, soil stiffness depends on interparticle forces as reflected by effective stress. Generally, the effective stress plays an important role in the stiffness of the soil. As the effective stress increases the contact stress between soil particles increases and the stiffness increases.

In unsaturated soils, the effective stress represents the intergranular forces between the soil particles within the soil body. Equation 12 shows the relationship proposed by Bishop (1959) between effective stress, pore water pressure, and pore air pressure in unsaturated soils; as the pore saturation and water pressure increase the soil suction (u_a-u_w) and effective stress decrease. Reduction of effective stresses results in decreased intergranular forces in the soil, which leads to a decrease in soil stiffness. Based on Equation 1, as the soil stiffness decreases the shear wave velocity decreases. Therefore, the higher the degree saturation of the soil the lower the shear wave velocity.

$$\sigma' = \sigma - u_\mathrm{a} + \chi(u_\mathrm{a} - u_\mathrm{w}) \tag{12}$$

Where χ= a soil parameter related to degree of saturation and ranging from 0 for dry soil to 1 for saturated soil.

In addition to total stress, σ, and pore air pressure, u_a, another factor that affects the effective stresses as shown in Equation 12 is the soil matric suction, u_a-u_w. Suction is directly proportional to the effective stress, which means that as suction increases the effective stress increases. Hence, changes in suction are related to changes in shear wave velocity. This is an important observation to consider since factors affecting the soil suction influence the shear wave velocity. In general, suction depends on the water content, void ratio (or dry density) and the type of soil. The third factor affecting the effective stress in unsaturated soils is the confining stress or net normal stress, σ-u_a; as the confining stress increases the effective stress increases.

The second property influencing the behavior of shear wave velocity based on Equation 1 is density. Changes in density due to construction, for example due to compaction, have an influence on shear wave velocity. Density has an inversely proportional relationship to shear wave velocity. As the density of the soil increases, the shear wave velocity decreases. Theoretically, this relationship can be explained using the particle interaction in a soil body; as the density increases the interaction and closeness of soil particles increases, which increases the resistance to shear deformation. The higher the shear deformation resistance is, the harder it is for shear waves to travel through the body of the soil, which causes the shear wave velocity to decrease. As soil density increases, the shear stiffness of the soil also increases. While higher density might cause a decrease in shear wave velocity, the heightened shear stiffness has a more significant impact, resulting in an overall increase in shear wave velocity with density. Therefore, in denser materials like rock, the shear wave velocity is higher compared to soils. In the next sections, the factors affecting the shear wave velocity, mentioned above, are discussed.

2.5 Degree of Saturation and Shear Wave Velocity in Unsaturated Soils

To understand the effect of degree of saturation on shear wave velocity, researchers measured the shear wave velocity in the laboratory under varying moisture contents (e.g. Cho and Santamarina 2001, Claira and Rinaldi 2006, Youn et al. 2008, Lu and Sabatier 2009, Asslan and Wuttke 2012, Dong and Lu 2016).

Dong and Lu (2016) investigated the effect of degree of saturation on shear wave velocity by studying seven soils including sand, three silts, clay, claystone and kaolinite. Soil samples were placed in an environmental chamber where the relative humidity was controlled. By controlling the relative humidity, the desired degree of saturation of the soil was achieved. As saturation level of the soil changed the shear wave velocity was measured using bender elements mounted to the soil sample. Results indicated that the shear wave velocity is directly correlated to water content; as degree of saturation increased shear wave velocity decreased. Another important observation was that fine grained soils (clays and silts) tended to have higher shear wave velocities compared to coarse grained soils (sand). These results are found to be in agreement with other studies done in the field and the laboratory (e.g. Yang et al. 2008, Sawangsuriya et al. 2008, Sawangsuriya et al. 2009, and Whalley et al. 2012).

As for the soil type, Dong and Lu (2016) found that fine grained soil tends to have relatively higher shear wave velocities than coarse grained soils as saturation level decreased. For higher saturation level, fine grained soils and coarse-grained soils had similar shear wave velocities. Differences in shear wave velocities between clay and sand can be explained by looking at the formation of the soil skeleton within different soil types. For example, in sands the presence of larger particles within the soil skeleton creates larger voids between the soil particles in comparison to clay. Larger voids constrain shear waves which are unable to propagate though water and air. The larger the voids between soil particles the harder it is for waves to propagate through the soil skeleton, which leads to decreases in the velocity of shear waves because of the limited contact area between particles during propagation.

Another reason for the differences in wave velocities in different soil types is the presence of soil plasticity and cohesiveness due to the diffuse double layer (DDL) in clays. Results from Dong and Lu (2016) show that clays exhibit higher shear wave velocity than sands at lower saturation levels. In clays the DDL has a major effect on the behavior of the soil particles and the forces acting between particles. As the soil is going through a drying process, the short-range attractive forces become stronger between particles, increasing the intergranular stress. The resulting increase in shear stiffness allows the shear waves to propagate faster.

2.6 Suction and Shear Wave Velocity

As shown in Equation 11 the effective stress of the soil is partially dependent on the matric suction (u_a-u_w). In unsaturated conditions, soil is a four-phase media that includes solid, fluid, gas, and contractile skin as discussed by Fredlund and Rahardjo (1993). As the degree of saturation of the soil changes, the energy state changes due to the changing interaction between the soil, water and air present in the soil. As soil desaturates, the energy state creates a negative pressure "called suction" within the soil skeleton. The presence of suction affects different soil behaviors including interparticle forces, permeability, stiffness and strength (e.g. Edil 1973, Fredlund and Rahardjo 1993, Likos 2006).

Recently, the influence of soil suction on shear wave velocity has been of greater interest for engineers. Some experimental investigations have focused on the relationship between suction and shear wave velocity including those discussed in Likos (2000), Take and Bolton (2003), and Lu and Likos (2006), Yang et al. (2008), Sawangsuriya et al. (2008), Sawangsuriya et al. (2009), and Whalley et al. (2012). Different methods were used to control the soil suction and most methods used were indirect methods (moisture chamber, sample preparation at different moisture content, air drying) due to the difficulties associated with suction control.

Whalley et al. (2012), investigated the combined effect of suction and confining pressure on shear wave velocity. A loamy sand and a sandy clay loam were tested in a modified Bishop and Wesley triaxial cell to obtain a range of saturation and consolidation states. For each soil, the shear wave measurements were taken at various confining pressures ranging from 100 kPa to 1000 kPa. For shear wave measurements under varying suction potentials, a constant confining pressure was applied. Whalley et al. (2012) observed that there is a non-linear relationship between the confining pressures acting on the soil and the shear wave velocity. As the confining pressure increases the shear wave velocity increases. Moreover, results from testing showed that as suction increases the shear wave velocity increases.

The relationship between soil suction and degree of saturation is well established (e.g. Fredlund and Rahardjo 1993). As the degree of saturation of the soil increases the suction forces in the soil decrease. Many studies have been done to investigate the effect of both saturation and suction on the mechanical behavior of unsaturated soil (e.g. Vernay et al 2016, Rahardjo et al. 2019). For shear wave velocity in unsaturated soils, relatively fewer studies have examined the effect of saturation and suction on wave propagation. Sawangsuriya et al. (2009) used a modified triaxial device that allows control of two stress state variables, the net confining pressure and matric suction. In their work, clayey sand (SC), silt (ML), lean clay (CL) and fat clay (CH) were tested under different suction and a constant confining pressure of 35 kPa. Saturated specimens were prepared and placed in the triaxial cell to start applying the matric suction. Matric suction was increased incrementally and the shear wave velocity measurements were taken after equilibrium was established for each increment. Results showed that as the soil suction increases, the shear wave velocity increases. Changes in soil types affected the magnitude but not the behavior of shear wave velocity with suction. Higher shear wave velocities were recorded for fine grained soils compared to coarse grained soils. Using the shear wave velocity, the authors calculated the shear modulus $G_{\max}$ using Equation 1. An empirical relationship was proposed between moisture content, suction, and small strain shear modulus.

Most studies focused on measuring the shear wave velocity during drying, this is because suction control is difficult and takes a long time to reach the desired suction. Few studies have been done on soils during wetting and drying, these studies are discussed in the next section.

2.7 Hysteresis and Shear Wave Velocity in Unsaturated Soils

Degree of saturation and suction are considered two of the key variables in unsaturated soil behavior (e.g. Anandarajah and Amarasinghe 2012). The relationship between soil suction and degree of saturation is expressed using the Soil Water Characteristic Curve (SWCC). Water content is plotted against suction in a logarithmic scale to produce the SWCC. During the observation of the SWCC it was found that there is a difference in the curve between the wetting and drying cycles (e.g. Haines 1930, Philip 1964, Topp 1969). These differences are associated with the phenomenon known as hysteresis.

Hysteresis is a major consideration in geotechnical engineering; this is because soils can experience cycles of wetting and drying due to seasonal changes in the field. Hence it is important to understand the effect of hysteresis on unsaturated soil behavior. It has been established that shear wave velocity is influenced by suction, but most tests done on the relationship between suction and shear wave velocity have concentrated on the drying cycle in the soil. This is due to the difficulties and time associated with controlling the soil suction.

Few studies have been done to investigate the effect of hysteresis on dynamic soil properties, including shear wave velocity (Khosravi and McCartney 2012, Dong and Lu 2016, Khosravi et al. 2018). Dong and Lu (2016) investigated twelve soils under wetting and drying conditions. Results showed that the shear wave velocity behaved differently during wetting and drying. Dong and Lu (2016) concluded that shear wave velocity was higher during drying when compared to wetting.

Khorsavi and McCartney (2012), investigated the effect of hysteresis on small shear modulus in low plasticity soils. Specimens were subjected to drying and wetting cycles using a suction-saturation controlled apparatus. Results showed that for a given water content, the small strain modulus is higher during the drying process compared to the wetting process. These results are important since the small strain modulus is directly proportional to the shear wave velocity.

Most studies done on the effect of hysteresis on dynamic soil properties focused on the influence of wetting and drying on the small strain shear modulus and the changes in stiffness. Very few studies have focused specifically on how shear wave velocity changes during hysteresis.

2.8 Confining Stress and Shear Wave Velocity

As discussed above, the interparticle forces within the soil skeleton have a direct relationship with shear wave velocity of the soil. The confining stress acting on the soil in the field is an important factor in influencing the behavior of the shear wave velocity. Confining stress is the stress applied on the soil at a specific depth due to the weight of the overlying soil. As the depth increases, the confining stress acting on the soil increases. This increase in the confining stress increases the interparticle forces which, stiffens the soil causing increases in shear wave velocity.

Sawangsuryia et al. (2008), Sawangsuryia et al. (2009), Whalley et al. (2012), Asslan and Wuttke (2012), and Liu et al (2019) investigated the shear wave velocity under confining stresses. Tests results showed that similar relationships between the confining stress and the shear wave velocity exist for different soils; as the confining stress increased the shear wave velocity increased. Whaley et al. (2012) tested two soils under various confining stresses using a triaxial cell with embedded bender elements in the platens. They found that the relationship between confining stress and shear wave velocity is non-linear. Shear wave velocity increases with increased confining stress, but eventually the shear wave velocity tends to stop increasing even when the confining stress keeps increasing. This could be explained due to the changes in the soil skeleton. As the confining stress increases the soil particles are pressed together and the void ratio decreases; at a certain point the particles stop moving and the soil skeleton remains the same with increasing confining stress which, causes the nearly negligible changes in shear wave velocity.

2.9 Shear Wave Velocity in Compacted Unsaturated Soils

As mentioned previously, changes in soil density due to compaction affect shear wave velocity. During compaction, soil particles align together based on the initial moisture content prior to the compaction process. The soil structure is related to the moisture content relative to the optimum moisture content obtained during the Proctor compaction test used to create the moisture-density curve. When the soil is on the dry side of the compaction curve (dry of optimum) the soil structure tends to be more flocculated. When soil is compacted on the wet side of the compaction curve (wet of optimum) the soil structure tends to be more dispersed. The changes in soil structure from the dry to the wet side is known to have a profound effect on the shear strength, stiffness and other properties of the soil (e.g. Mitchell 1993, Yimsiri and Soga 2000, Sachan and Penumadu 2007).

Sawangsuriya et al. (2009) conducted bender element testing on soil samples compacted at various initial moisture contents to measure the small strain shear modulus of the soil. Samples were prepared at -4% dry of optimum moisture content, +4% wet of optimum moisture content, and at optimum moisture content. Samples were fully saturated and then the drying process was conducted while measuring the shear wave velocity at discrete suction values. The observation made was that samples compacted dry of optimum showed a higher shear modulus compared to the ones compacted wet of optimum. Additionally, soil structure was found to have an influence on the results in this study; soils compacted wet of optimum had higher changes in shear modulus compared to soils compacted dry of optimum.

Another important factor influencing the soil behavior during compaction is the compaction energy used, this is represented in the number of rammer blows used during compaction of each layer. Using higher compaction energies increases the maximum dry density of the soil and lowers the optimum moisture content. Some researchers have investigated the effect of soil compaction on the behavior of shear wave velocity (Khoury and Zaman 2004, Sawangsuriya et al. 2005, Rindali and Claira 2006, Yang et al. 2008, Sawangsuriya et al. 2009, Indraratna et al. 2012).

The effect of compaction energy on shear wave velocity of silty-sand soils was tested by Indaratna et al. (2012). During their study the soil was compacted to a reduced, standard, and modified compaction energy by altering the number of blows per layer during sample preparation. The reduced method was done using 15 blows, the standard was done with 25 blows, and the modified testing was done with 35 blows per layer in a standard 102 mm diameter mold. Samples were prepared at various moisture contents including dry of optimum, wet of optimum, and at optimum. Results showed that for samples prepared dry of optimum the compaction energy influenced the shear wave velocity. The higher the compaction energy the higher the shear wave velocity. The results also showed that wet of optimum the changes in the compaction energies had almost no influence on the shear wave velocity.

Studies done on shear wave velocity in compacted unsaturated soils are important, but there are some factors not addressed during the studies which include: 1) most of the studies focused on the effect of densities on shear wave velocity in soils with low plasticity like silty clays and low PI clays, and 2) studies did not thoroughly investigate the effect of soil structure, i.e., flocculated or dispersed, on shear wave velocity. In the studies mentioned above, the soils were tested wet and dry of optimum however specimens were not subjected to a full wetting and drying cycles, Sawangsuriya (2009) subjected the specimens to a drying cycle only, while Indaratna only tested samples at one moisture content (e.g. optimum, or wet of optimum, or dry of optimum).

2.10 Measuring Shear Wave Velocity using SCPTu

Various methods are used to measure the shear wave velocity in the field. The seismic cone penetration test (SCPTu) is a common field tests used to measure the shear wave velocity in the soil profile. This method is attractive for its simplicity and speed, and it also provides other parameters, which include the tip resistance (q_c), sleeve friction (f_s), friction ratio (FR), and pore water pressure (u_o). These parameters are used to estimate various soil properties including undrained shear strength, compressibility and preconsolidation stress of clays, relative density and friction angle of sands, unit weight, and soil type, among others.

One of the biggest limitations to measuring the shear wave velocity using this method is that the measurements taken during testing represent data for the current situation in the soil. This is an issue since changes in soil properties, including shear wave velocity, happen continuously due to seasonal changes in moisture content in the active zone of unsaturated soils.

Lehanne et al. (2004) investigated changes in cone parameters in a sand site during seasonal changes (wet and dry seasons). The shear wave velocity was measured in the lab using reconstituted samples from the field to determine changes in small shear strain modulus, *G*, with changes in moisture content. Results showed that as the soil saturation level changed, *G* tended to change. This is an important indication that the shear wave velocity in the field is affected by seasonal changes. These results align with the findings from other studies done in the lab; however, there were no tests reported to investigate changes in shear wave velocity in the field using SCPTu during seasonal changes.

Another limitation to SCPTu is the lack of soil sampling during testing. This is a problem since results from the field are not verified in the lab. To target this issue, few studies have been done to compare shear wave velocity measurements from the field and the lab including Landon et al. (2004), Markowska-Lech and Szymanski (2007) and Valsson et al. (2021).

Valsson et al. (2021) measured shear wave velocity for one site in the field, using the SCPTu, and in the laboratory using the bender element method under controlled confining stresses. For laboratory testing, high quality mini-block samples were taken from the field. Results showed a good agreement between the shear wave velocity measured in the field and the laboratory. Landon et al. (2004) measured shear wave velocities in the field and using SCPTu and a portable bender element system, samples were extruded in the field for the bender element testing. Test results showed that SCPTu measurements gave higher velocities when compared to the bender element testing; this may be due to the lack of confining stress during bender element testing.

Studies done on comparing shear wave velocities measured in the field and the laboratory show contradicting results. Few papers have been published regarding this topic and a limited amount of soil types have been investigated. In the current study, three sites were tested to compare results between field and laboratory shear wave velocity measurements.

2.11 Summary of Knowledge Gaps and Contributions of this research

The literature reveals that tests done on unsaturated soils using shear wave velocity measurements mainly focused on interpreting the data in terms of small shear strain modulus *G*. While important, it does not discuss in detail the changes in shear wave velocity under various conditions, which is important since shear wave velocity is used in determining the seismic site class of the soil during earthquake design. No data were found in the literature that correlates the changes in soil saturation level, suction, density, or soil structure to seismic site class as shear wave velocity changes.

Moreover, published research focuses on factors individually and does not take into account the combined effect of changing various soil properties together. For example, Whalley et al. (2012) and Asslan and Wuttke et al. (2012), studied saturation level, suction, and confining stress without taking into consideration density, soil structure, or hysteresis. On the other hand, some research was done to investigate the effect of hysteresis by itself without considering density, or soil structure (Khorsavi and McCartney 2012, Dong and Lu 2016).

For compacted soils, some research has focused on investigating the effect of compaction energy on shear wave velocity (Khoury and Zaman 2004, Sawangsuriya et al. 2005, Rindali and Claira 2006, Yang et al. 2008, Sawangsuriya et al. 2009, Indraratna et al. 2012), but no tests were done to study compacted soils regarding how soil structure affects shear wave velocity during wetting and drying.

Furthermore, as mentioned in the previous section, limited testing has been done in the field using the SCPTu to investigate the effect of seasonal changes on shear wave velocity data in the field. Also, studies comparing shear wave velocity results from the field and the laboratory are limited to very few sites (Landon et al. 2004, Markowska-Lech and Szymanski 2007, Valsson et al. 2021).

In this study, the gaps mentioned above were targeted by testing soils under various conditions. Table 2 below summarizes the research done on shear wave velocity in unsaturated soils and the gaps in the studies. The factors examined in the current study included the effect saturation level, suction, density, soil structure, confining stresses, and the wetting and drying paths on shear wave velocity. Additionally, field tests were conducted to investigate the seasonal effects on shear wave velocity measured in the field using SCPTu. Results from multiple sites were analyzed and compared. Further, field and laboratory shear wave velocities were compared for three sites around the state of Oklahoma to investigate differences in shear wave velocities based on the testing method, i.e., field or laboratory.

Table 2. Literature summary of findings and knowledge gaps.

Paper	Findings	Knowledge gaps
Claria and Rindali, 2006, Shear wave velocity of a compacted silt	Measured shear wave velocity for compacted soils under various densities, water content, and confining stress. Found that shear wave velocity is influenced by density, water content, confining stress, and soil structure.	Tested samples at one level of saturation only, did not account for wetting and drying cycles during testing.
Dong and Lu, 2016, Dependencies of shear wave velocity and shear modulus of soil on saturation	Tested 12 soils under wetting and drying cycles. Found that shear wave velocity behaves differently during wetting when compared to drying. Higher velocities were found during drying.	Did not take into account the effect of density, compaction, confining stress, and soil structure.
Asslan and Wuttke, 2012, Wave velocity change and small-strain stiffness in unsaturated soils: experimental investigation	Tested sand soil under confining stress and suction. Found that as suction and confining stress increases shear wave velocity increases.	Only tested soils under a drying cycle. Used sand soil only. No account for density or soil structure.
Sawangsuriya, 2009, Modulus-suction-moisture relationship for compacted soils in post compaction state	Calculated shear modulus by measuring shear wave velocities under varying suction and confining stress.	Focused on shear modulus and not shear wave velocity. Determined shear modulus under drying cycle only.

Paper	Findings	Knowledge gaps
	Found that as suction and confining stress increases shear modulus increases.	Did not investigate the effect of soil structure on shear wave velocity.
Whalley et al., 2012, The velocity of shear waves in unsaturated soil	Measured shear wave velocities under varying suction and confining stress. Found that as suction and confining stress increases shear wave velocity increases.	Measured shear wave velocities under drying cycle only, and did not consider density or soil structure in testing.
Indraratna et al., 2012, Effect of compaction energy on shear wave velocity of dynamically compacted silty sand soil	Measured shear wave velocity for compacted soils under various compaction energies. Found that as the compaction energy increased the shear wave velocity increased.	Did not account for wetting and drying cycles. Did not apply confining stress to the samples.
Sawangsuriya et al., 2008, Modulus–suction–moisture relationship for compacted soils	Calculated shear modulus by measuring shear wave velocities under varying compaction energies. Found that as the compaction energy increased the shear wave velocity increased.	Did not account for wetting and drying cycles. Did not apply confining stress to the samples.
Yang et al., 2008, Shear wave velocity and suction of unsaturated soil using bender element and filter paper method	Investigated the effect of suction and water content on shear wave velocity, and found that as suction increases shear wave velocity increases.	Tested compacted samples under no confining stress or wetting/drying cycles.
Khosravi and McCartney, 2012, Impact of hydraulic hysteresis on the small-strain shear modulus of low plasticity soils	Discussed small strain shear modulus along wetting and drying under controlled confining stresses. Found that the shear modulus behaves differently during wetting and drying cycles.	Did not discuss shear wave velocity. Did not consider density, and soil structure in testing.
Landon et al., 2004, Comparison of shear wave velocity measured in situ and on block samples of a marine clay	Measured shear wave velocity in the field using SCPTu and the bender elements. Results showed that field velocities are higher than bender element velocities.	Only tested one site in the field. Did not apply confining stress to the samples tested with bender elements.
Khosravi et al., 2018, Impact of hydraulic hysteresis on the small strain shear modulus of unsaturated sand	Measured shear wave velocities under wetting and drying cycles under a controlled confining stress and calculated the shear modulus.	Focused on shear modulus and not shear wave velocity Testing was conducted on sand samples only.

Paper	Findings	Knowledge gaps
	Results showed that the shear modulus behaved differently during wetting and drying cycles.	Did not take density, or soil structure into consideration.
Lehanne et al., 2004, Seasonal dependence of in situ test parameters in sand above the water table	Measured CPT parameters and shear wave velocity during wet and dry seasons. Found that CPT parameters and shear wave velocity are influenced by saturation levels in the field.	Only one site was tested in this study. Only measured shear wave velocity in the lab, no field testing was done to measure the velocities.
Valsson et al., 2021, Estimating shear wave velocity with the SCPTu and Bender element	Measured shear wave velocity in the field using SCPTu and in the lab using bender elements under controlled confining stresses. Results showed a good match between the field and lab data.	Only conducted the testing for one site and one type of soil.

Chapter 3: Experimental Procedures

3.1 Overview

This study involved two experimental approaches to investigate soil shear wave velocity in unsaturated soil. The first approach involved conducting laboratory testing to examine how various soil properties impact shear wave velocity in unsaturated soil. The second approach involved a combination of field and lab testing to investigate the effect of seasonal changes in water content on shear wave velocity. Additionally, the experimental plan allowed for a comparison of shear wave velocity measurements taken in the lab using the bender elements method and in the field using the seismic cone penetration test method. In this chapter, the experimental procedures conducted in the laboratory and/or the field are discussed.

3.2 Laboratory Study of Shear Wave Velocity

3.2.1 Test Soils and Soil Properties

Three manufactured soils were used during testing. Soil mixtures were designed to target different plasticity indices and percentages of fines. Soils were created by mixing a commercially available kaolin (70.8% kaolinite, 22.4% quartz, 4.5% feldspar, 2.3% miscellaneous trace minerals) and a fine sand (specific gravity of solids, G_s=2.65; median grain size, D_{50}=0.14 mm; Coefficient of uniformity, C_u=1.6; Coefficient of curvature, C_c=1). Three mixtures were made with dry weight ratios of 1:9, 1:1, and 9:1 kaolin:sand. Some of the engineering soil properties for the three soil mixtures are summarized in Table 3.

Table 3. Soil properties for Test Soil 1, 2 and 3.

	Soil-1	Soil-2	Soil-3
Kaolin:Sand ratio	1:9	1:1	9:1
USCS classification	SP-SC	CL	CL
Liquid limit (%)	9	21	31
Plasticity index (%)	4	11	21
Percent passing #200 sieve	10	50	90
Optimum moisture content (%)	8	11	21
Maximum dry density (g/cm^3)	1.63	1.87	1.47
Specific gravity	2.63	2.54	2.45

3.2.2 Specimen Preparation

To prepare each specimen for testing, a series of precise steps were followed to ensure uniformity and accuracy of the results. Firstly, dry fine sand and kaolinite clay were mixed together in the desired percentages for each specimen to create a homogeneous mixture. Next, the required weights of water and soil were calculated based on the target dry density and moisture content, and the soil was carefully wetted with the water to ensure a uniform distribution. The wetted soil was then compacted in a 63.5mm diameter x 71mm height mold in three equal layers to ensure uniform compaction throughout the specimen. Soil specimens were compacted in three equal layers using a solid steel rod with a diameter of 25mm and weighing 1.5 kg hammer in the mentioned mold. The soil and water weights were used to prepare the specimen to the desired density and moisture content. After compaction, the specimen was extruded from the mold and trimmed to the dimensions of 63.5mm diameter x 63.5mm height. Additionally, sacrificial specimens were prepared using the same procedure to allow for testing soil suction. The WP4-T device, a chilled mirror hygrometer, was used to measure total suction. The initial weight and water content of the specimen were determined, and then it was placed in a sealed glass chamber to begin the wetting and drying or drying and wetting process using the vapor equilibrium method of suction control.

Additional sacrificial specimens were prepared to test the uniformity of moisture contents in lab specimens during the wetting and drying process using vapor equilibrium. The sacrificial specimens were removed mid-way through testing and three moisture content measurements were taken from the top, middle, and bottom of the specimen. Two specimens were prepared for Soil-2; one wet of optimum and one dry of optimum. The specimen prepared wet of optimum was subjected to drying and the dry of optimum specimen was subjected to wetting. Results showed that the moisture contents due to drying and wetting processes were uniform in the tested specimens as shown in Table 4.

Table 4. Moisture content results for soil specimens.

Drying				Wetting			
Specimen section	Top	Middle	Bottom	Specimen section	Top	Middle	Bottom
Moisture content (%)	12.96	13.08	13.04	Moisture content (%)	13.41	13.45	13.43
Suction (kPa)	720	690	700	Suction (kPa)	410	400	400

3.2.3 Vapor Equilibrium Suction Control Method

The vapor equilibrium suction control method is used to control the relative humidity (e.g. Tessier 1984, Villar 2000, Tang and Cui 2005, Blatz et al. 2008) in the glass chamber in which the specimens are placed. During the vapor equilibrium process the water vapor in the air surrounding the specimen and in the soil pores achieves thermodynamic equilibrium with the condensed water phase at a given temperature in a closed system (Speight 2019). Using the concept of vapor pressure and relative humidity, the soil saturation level and suction can be controlled by changing the relative humidity of the atmosphere in the sealed chamber. Water will flow into or out of the specimen depending on the osmotic potential in the chamber atmosphere created by the chemical solution in the bottom of the chamber used during testing. Using different solution molality, the osmotic potential generated in the glass chamber is controlled. In this research, different solution molalities were used to allow for specimens to be wetted then dried, or vice versa, to investigate the influence of wetting-drying or drying-wetting hysteresis on shear wave velocity.

For example, when a wet soil specimen was placed in a low relative humidity system, the water content decreased and suction increased as water moved out of the soil specimen. In a low relative humidity system, the amount of water vapor in the air is low. This means that the water will flow out of the specimen and into the chamber atmosphere for equilibrium to be achieved between the soil pore air and chamber air relative humidity.

Specimens prepared according to Section 3.2.2 were placed on the perforated plate and left in the glass chamber for suction control. Below the perforated plate, the glass chamber was filled with a water and salt mixture solution to the desired molality. Figure 3 shows the glass chamber used in testing. Once the saltwater mixture was ready, the perforated plate was placed over the solution, allowing the soil specimen to suspend in the vapor environment.

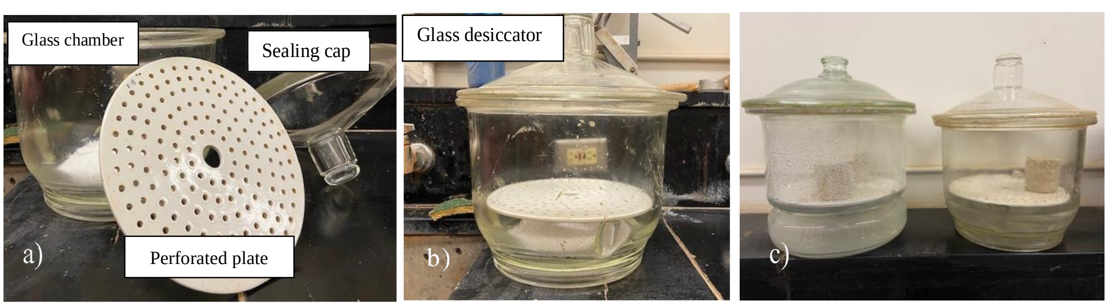

Figure 3. Glass chamber used for vapor equilibrium. a) Glass chamber, sealing cap and the perforated ceramic plate. b) Empty glass chamber. c) Glass chambers with soil specimens.

Soil specimens were prepared and placed in the glass chamber under specific osmotic pressures, which allowed the water content to change. Measurements of the specimen weight were taken regularly to monitor the changes in water content. As the water content changed, the specimen was removed at desired times, and the shear wave velocity was measured using the bender element method. Simultaneously, a small amount of soil was removed from the sacrificial specimen and suction was measured using the WP4-T device. Once the first sequence of wetting or drying ended, the specimen was moved to another glass desiccator with a different osmotic pressure to alter the water content and allow it to dry or wet for the second sequence. The process was repeated for subsequent steps until the drying or wetting sequence was completed. The concentration of the solution used in testing was based on results found in Bulut et al. (2001). Bulut et al. (2001) investigated the concentration of different solutions by measuring the suctions generated using the vapor equilibrium method and verifying the results using the filter paper method. Using Bulut's data, NaCl salt solution was chosen for the desired testing. This solution was chosen because of the suction that was achieved using the NaCl solution. The chosen concentrations in this research are shown in Table 5.

Table 5. Solution concentration, target total suction, and saturation path.

Salt used	Solution concentration (m)	Target total suction (kPa)	Saturation path
NaCl	0.05	234	Wetting
NaCl	1.6	7631	Drying

3.2.4 Shear Wave Velocity Measurements

The bender element testing method is one of the most common methods used in measuring the shear wave velocity in the laboratory. The bender elements are piezoelectric ceramic plates that are placed on the top and bottom surface of the soil specimen to generate shear waves within the specimen. When voltage is introduced, the ceramic plates expand, and contract. The deformation in the bender elements causes strains in the soil that produce shear waves as shown in Figure 4 below. Shear waves were induced at one end of the specimen and received at the other end.

The bender element system consisted of an oscilloscope, function generator, and piezoelectric ceramic plates. Waves were generated using the function generator; different kinds of waves can be generated including sine, rectangle, and pulse waves through the soil. For the purpose of this study, sine waves were used during testing. The oscilloscope was used to record the waves generated in the system where two sources of waves were recorded; one that comes directly from the function generator and the other wave was recorded after it passes through the tested soil specimen. The time difference between the direct wave and the wave propagating through the soil specimen is used to calculate the shear wave velocity as shown in Equation 13.

$$V_s = \frac{Distance\ between\ the\ ceramic\ plates}{time\ of\ first\ arrival} \tag{13}$$

Lee and Santamarina (2006), examined the performance and signal interpretation of the bender elements in soils. They performed experimental and analytical analysis to study the effect of coupling, directivity, frequency, near field effects, and wave detection and analysis on the bender element results. Determination of the arrival time of the wave using various methods were discussed by Lee and Santamarina (2006), and first arrival and cross correlation methods were compared in the study as shown in Figure 4.

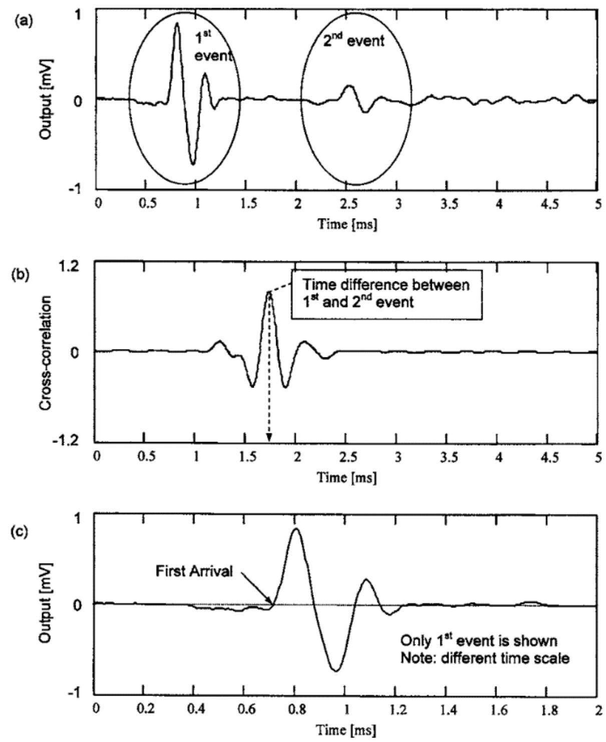

Figure 4. a & b) Cross correlation method, c) First arrival method (from Lee and Santamarina 2006).

Figure 4a) represents the wave reading collected during bender element testing. Using the difference in time at which the wave is at its peak output between the two events one can calculate the shear wave velocity. This method is referred to as the cross-correlation method. Figure 4c) represents the first arrival method approach where the time at which the wave arrives is used to calculate the shear wave velocity.

Leong and Rahardjo (2009), measured shear wave velocity of soils using bender elements. They found that results gathered from using the first arrival method in determining the shear wave velocity were in a reasonable range when compared to cross correlation method. This is an important observation since first arrival method is a faster analysis method to calculate the shear wave velocity. Recommendations made in Leong and Rahardjo's study were taken into consideration during the study conducted in this research. These include type of waves used, frequency, distance between the source and the receiver, voltage, and wave interpretation methods (first arrival method).

In this research the bender element system included the following devices used during testing: 1) a RIGOL DG1022Z function generator which produced a sine wave output signal to the transmitting bender element, 2) Rigol MSO1074Z digital oscilloscope was used to display and collect the signals from both the function generator and the receiving bender element, and 3) a pair of bender elements housed in custom Geotechnical Consulting and Testing Systems (GCTS) end platens (source and receiver). Figure 5 shows a picture of the oscilloscope, function generator, and platens containing the bender elements used in testing.

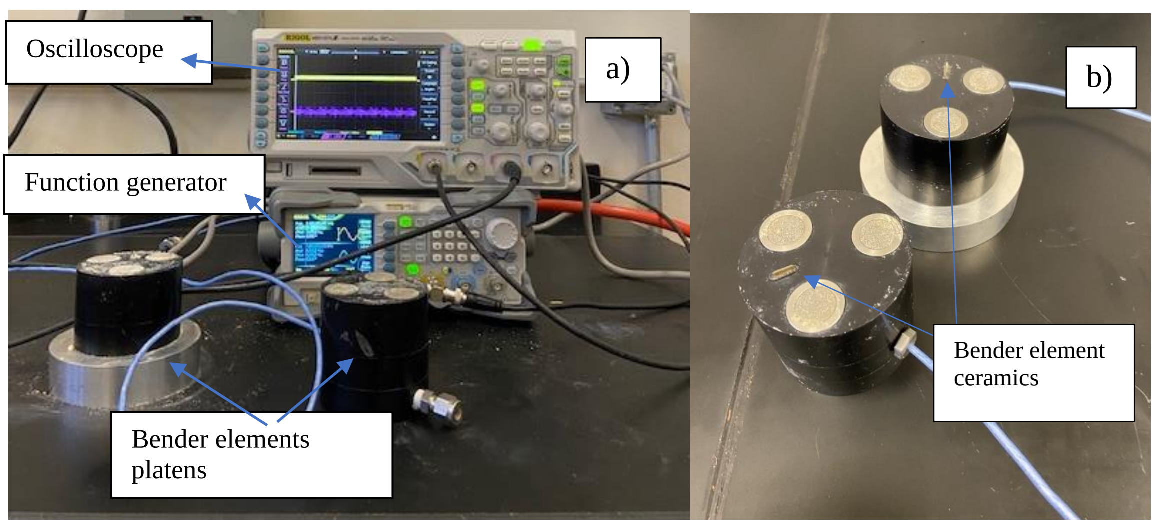

Figure 5. a) Bender Element system, and b) bender element ceramics embedded in end caps used for testing the shear wave velocity of soil specimens.

When using confining pressure during testing, the GCTS platens were mounted inside a Global Digital Systems Ltd (GDS) triaxial cell. This system consisted of a) bender element system mentioned above, b) triaxial cell used to host the soil specimens, and c) air pressure control system to apply cell pressure. The specimen was enclosed in a rubber membrane inside the triaxial cell to isolate it from the air used to control the confining pressure within the cell. Figure 6 shows the modified shear wave velocity testing system used to apply confining pressure.

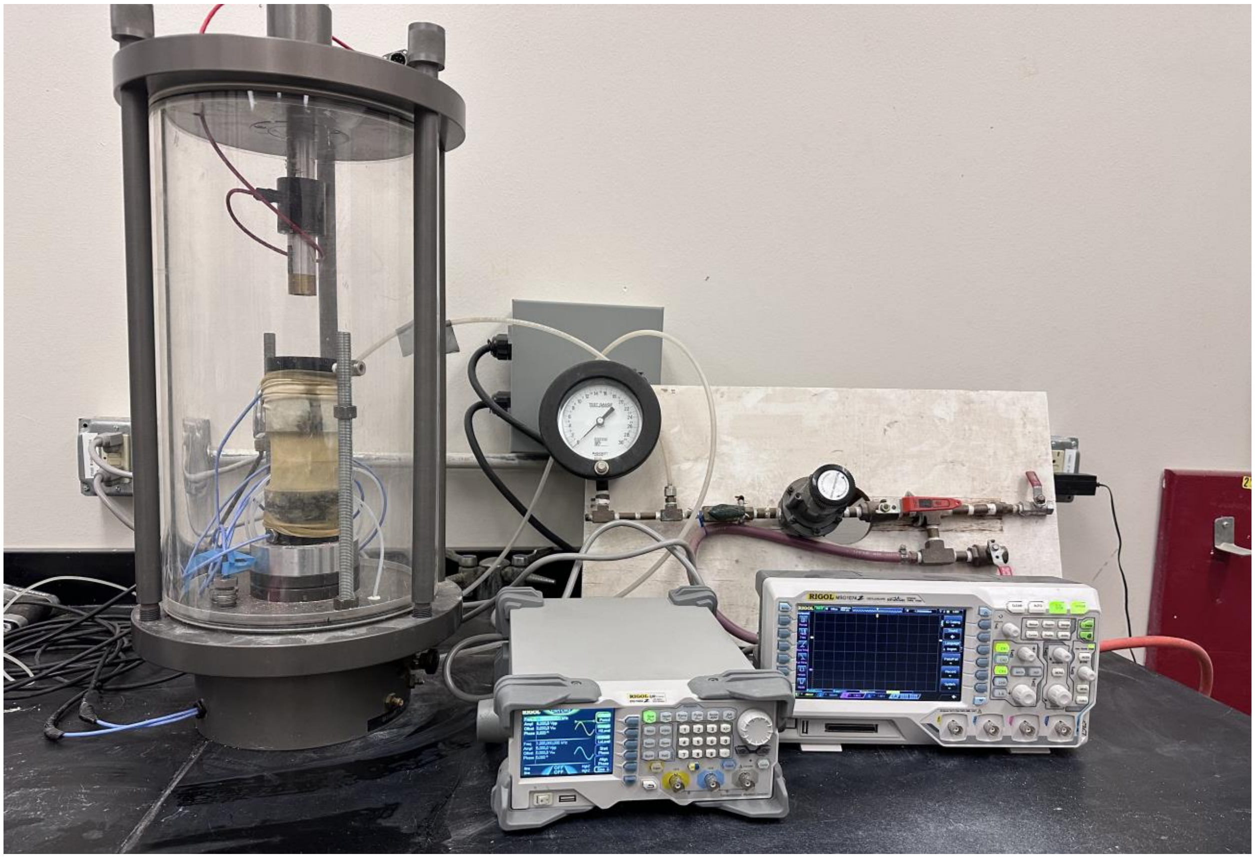

Figure 6. Shear wave velocity system consisting of oscilloscope, function generator, air pressure system to apply confining stress and a triaxial cell.

3.2.5 Testing Matrix

Table 6 shows the different soil mixtures, densities, initial water contents, and confining pressures used during testing. Each specimen was wetted or dried based on the initial water content of the sample. Once the first drying/wetting stage was finished the second stage of wetting/drying started, and so on for subsequent wetting or drying.

Water content and densities were chosen based on the results from the standard compaction testing performed on soils 1, 2, and 3. The moisture contents were chosen to represent the wet and dry sides of the compaction curves ranging from -3% of the optimum to +3% of the optimum.

Densities were chosen to represent the maximum dry densities and 95% of the maximum dry density interpreted from the compaction curve. These values represent range of scenarios that are found in practice.

Table 6. Laboratory testing matrix for soils including soil composition, initial density, initial moisture content, drying and wetting sequences, and confining stress.

Soil mixture	**Density**	**Initial Moisture Content**	**Stage 1**	**Stage 2**	**Confining stress (kPa)**
50% Kaolinite-50% Fine sand	Maximum dry density	+4 Optimum moisture content	Drying	Wetting	0
50% Kaolinite-50% Fine sand	Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0
50% Kaolinite-50% Fine sand	95% Maximum dry density	+4 Optimum moisture content	Drying	Wetting	0
50% Kaolinite-50% Fine sand	95% Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0
10% Kaolinite-90% Fine sand	Maximum dry density	+4 Optimum moisture content	Drying	Wetting	0
10% Kaolinite-90% Fine sand	Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0
10% Kaolinite-90% Fine sand	95% Maximum dry density	+4 Optimum moisture content	Drying	Wetting	0
10% Kaolinite-90% Fine sand	95% Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0
90% Kaolinite-	Maximum dry density	+4 Optimum	Drying	Wetting	0

Soil mixture	Density	Initial Moisture Content	Stage 1	Stage 2	Confining stress (kPa)
10% Fine sand		moisture content			
90% Kaoinite-10% Fine sand	Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0
90% Kaolinite-10% Fine sand	95% Maximum dry density	+4 Optimum moisture content	Drying	Wetting	0
90% Kaolinite-10% Fine sand	95% Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0
50% Kaolinite-50% Fine sand	Maximum dry density	+4 Optimum moisture content	Drying	Wetting	0,25,50,100
50% Kaolinite-50% Fine sand	Maximum dry density	-4 Optimum moisture content	Wetting	Drying	0,25,50,100

3.3 Investigation Comparing Field and Laboratory Determinations of Shear Wave Velocity

3.3.1 Introduction

The field study consisted of two phases. The first aimed to compare the shear wave velocity measurements obtained in both field and laboratory settings, while the second component involved the measurement of shear wave velocity in the field under varying moisture contents due to seasonal changes. Seismic velocities were determined in the field using the seismic cone penetration test.

3.3.2 Soil Properties and Soil Profiles

Twelve sites were tested across the state of Oklahoma, USA. Sites were chosen to represent a wide range of soil types. From the twelve sites, eight were chosen for analysis and data collection based on the quality of the results collected. The selection of soils for testing was carefully carried out with the aim of encompassing a diverse range of soil profiles. By intentionally choosing a variety of soil types, comprehensive data was gathered to conduct in-depth analysis on the behavior of shear wave velocity in different soil types. The site number, soil type, and site location in Oklahoma are shown in Table 7.

Table 7. Location number, soil types, and location of the tested sites.

Location Number	**Soil Types**	**Location**
1	Wind blown silts and silty sands (SPT Calibration Site)	Curtis
2	Clay soils	Lake Hefner
3	Mixed clay soils	Muskogee
4	Clay soils	Wagoner
5	Clay soils	Hobart
6	Paleoterrace, clayey and loamy colluvium or alluvium over clayey residuum weathered from shale	Wewoka
7	Fine sand	Norman
8	Mixed clay soils	Fairview
9	Mixed clays, sands and silty clays	Fears Lab-University of Oklahoma
10	Mixed clays, and silty clays	Oklahoma City
11	Mixed clays, and silty clays	Tuttle
12	Mixed clays, and silty clays	Norman

3.3.3 Seismic Cone Penetration Testing for Comparison to Laboratory Tests

The seismic cone penetration test (SCPTu) was performed at three sites to measure the shear wave velocity at various depths. The SCPTu was performed in general accordance with ASTM standard D5778-12 "Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils" and ASTM standard D7400/D7400M-19 "Standard Test Methods for Downhole Seismic Testing". The HT 10 cm^2 Vertek VTK probe was used during testing; this probe was designed to withstand a maximum tip cone force of 10 tons. The probe is equipped with a dual axis geophone feature which produced two shear wave velocities during each seismic wave measurement in the soil profile. The geophones are placed close to the tip of the cone. An example of the probe used during testing is shown in Figure 7.

Figure 7. Vertek HT 10 cm^2 probe used during SCPTu testing.

For each site, two soundings were obtained and the cone was pushed to refusal during each sounding. A shear wave was generated by hitting a metal plate (anchored using the drilling rig) at the ground surface with a 2.2-kg hammer. Shear wave velocity measurements were taken when the cone penetration was halted at every 1-meter depth increment during testing. Geophones embedded in the cone penetrometer were used to detect the shear wave arrival after it passed through the soil. The data was automatically recorded via the data acquisition system during testing. For each site the data were analyzed and the shear wave velocity was calculated for each layer of soil between each cone position where the measurements were made.

The First Arrival Method was used during testing to analyze the shear wave velocity data collected in the field. This method relies on analyzing the first arrival of the shear wave recorded by geophones during seismic testing. The principle behind this method involves measuring the time it takes for the shear wave to travel a known distance between the surface and the geophone placed at specific intervals along the soil profile. By dividing the distance by the corresponding travel time, the shear wave velocity can be determined. The First Arrival Method provides a relatively straightforward and efficient approach to estimating V_s, allowing for quick and practical assessment of soil stiffness and dynamic properties. To calculate the shear wave velocity for layers between each depth the difference in travel time between two depths is calculated and the thickness of that layer is divided by that time. The sketch in Figure 8 shows a general representation of the measurement and the calculations used to calculate the shear wave velocity.

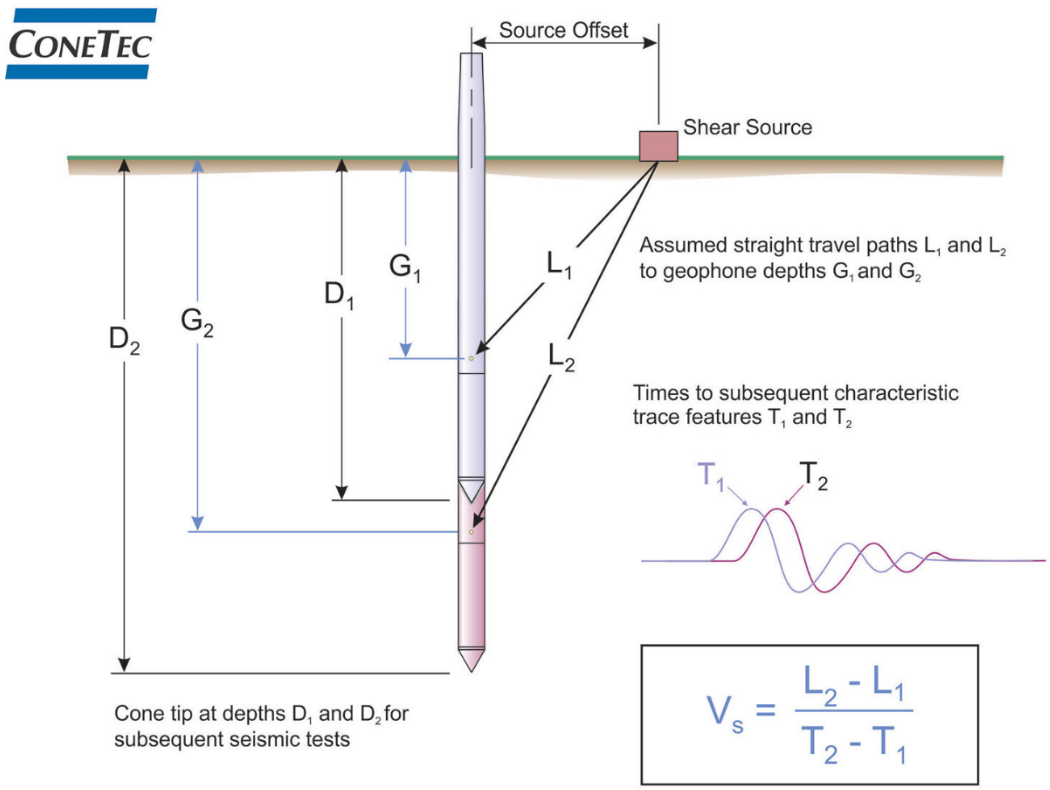

Figure 8. Shear wave measurements using SCPTu in the field (Conetec.com).

3.3.4 Undisturbed Soil Sampling

Undisturbed sampling was performed according to the American Society for Testing and Materials (ASTM) D1587-15 “Standard Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes” (ASTM 2015). For each site, continuous thin wall tube sampling was performed to collect soil samples from the top 3 to 4 meters along the soil profile. The depths were chosen to represent the active zone where the most significant moisture content changes happen during wet and dry seasons. These samples were carefully transported back to the laboratory for suction and shear wave velocity testing under confining stresses simulating those in situ. Samples were immediately extruded at the laboratory and trimmed to a 1:1 diameter to height ratio. Samples were covered in plastic wraps and placed in plastic bags to help preserve the original moisture content before testing.

3.3.5 Laboratory Shear Wave Velocity Measurements

For shear wave velocity testing, soil specimens were placed in the triaxial cell mentioned in Section **3.2.4** and shear wave velocity measurements were taken at the applied confining stress. Shelby tube samples were extruded and trimmed into a 1:1 diameter to height ratio. Specimens were subjected to a confining stress equal to the estimated overburden pressure in the field and shear wave velocity measurements were taken. Additionally, the shear wave velocity was taken at dry and wet conditions to observe the changes in the shear wave velocity with changes in saturation. To do so, the trimmed Shelby tube soil samples were placed in the vapor equilibrium glass chambers to modify the water content of the samples. For each site, two samples were taken at similar depths; one sample was placed in a wetting glass chamber, and one was placed in a drying glass chamber. Samples were tested before placing them in the chambers to verify the moisture contents and suction values of both samples before starting the test. Samples were left in the chamber for two weeks and tested at wet and dry conditions. The soil suction, water content, and shear wave velocity were measured at the end of the two weeks and data were plotted to show the changes in shear wave velocity as water content and suction changed.

3.4 Investigation of Seasonal Variations in Moisture Content on SCPTu Shear Wave Velocity Measurements

3.4.1 Seismic Cone Penetration Testing (SCPTu) During Wet and Dry Seasons

The seismic cone penetration test was conducted at four sites with various soil stratigraphy. For each site, an attempt was made to conduct the SCPTu once during a wet season and once during a dry season. As mentioned in Section 3.3.3**,** testing was performed in general accordance to ASTM standard D5778-12 “Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils” and ASTM standard D7400/D7400M-19 “Standard Test Methods for Downhole Seismic Testing”.

For this phase a light weight Vertek CPTu rig designed for Seismic Cone Penetration Testing (SCPTu) was used. This versatile rig features a hydraulic push system that enables precise control and penetration of the cone into the ground. The seismic cone used in the Vertek SCPTu rig is a specialized instrument designed to measure seismic wave properties in soils during Cone Penetration Testing (CPTu). The seismic cone features a durable construction and is equipped with high-quality geophones that capture and record seismic waves generated at the ground surface. The cone is designed to accurately measure shear wave velocity (V_s) in the soil layers, providing valuable information about the soil's dynamic properties and stiffness. Figure 9 shows an example of the Vertek SCPTu rig used in the field.

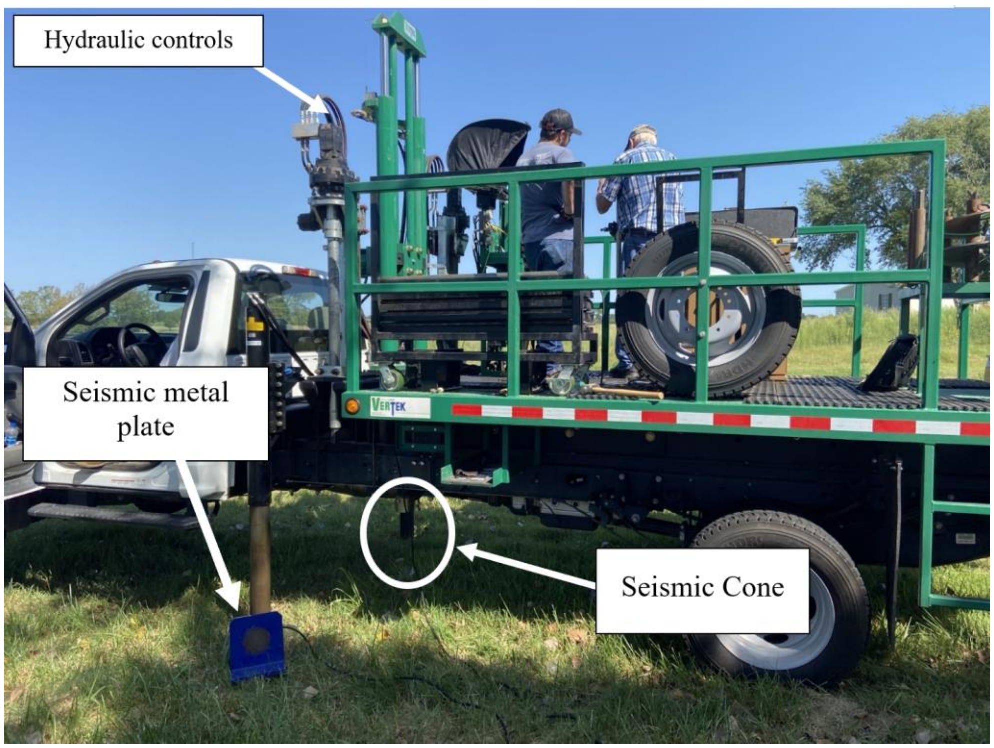

Figure 9. Light weight Vertek SCPTu truck.

For each site visit, four soundings were performed in close proximity to each other (around 2 to 3 meters apart) but separated enough to avoid interference between test locations. For each sounding the cone tests were conducted by pushing through the active zone of the soil profile or to refusal. Shear wave velocity measurements were taken by halting the cone penetration every 1-meter during penetration as described previously. For each sounding, the data were analyzed and the shear wave velocity was calculated for each layer of soil between each cone position where the measurements were made.

3.4.2 Disturbed Soil Sampling and Laboratory Testing

Disturbed samples were collected in a borehole adjacent to the SCPTu testing locations. Disturbed samples were taken to the lab for soil property testing. At each test site soil samples were collected in general accordance with the American Society for Testing and Materials (ASTM) D1452-16 "Standard Practice for Soil Exploration and Sampling by Auger Borings" ASTM (2009) or (ASTM) D6282-14 "Standard Guide for Direct Push Soil Sampling for Environmental Site Characterizations" (ASTM 2014).

Disturbed samples were used to determine the suction and water content of the tested soil along the soil profile. Suction testing was done in general accordance with the "WP4 and WP4-T operator's manual" (Version 5, 2007) provided by the Decagon device, Inc. The gravimetric water content of the soil was determined in general accordance with the American Society for Testing and Materials (ASTM) D 2216-19 "Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass".

Chapter 4: Results of Laboratory Investigation of Shear Wave Velocity in Unsaturated Soil

4.1 Overview

In this chapter, the results of the laboratory investigation of shear wave velocity in unsaturated soil are presented and discussed. Specifically, this section presents and discusses the observed relationships between measured shear wave velocity, moisture content, suction, confining stress, and density along the wetting and drying paths. Additionally, the effects of fines content and soil structure due to compaction wet and dry of the OMC are discussed. Before showing shear wave velocity data, results of testing to investigate the uniformity of moisture contents in specimens subjected to suction control via vapor equilibrium are presented. Soil water characteristic curve data for the three test soils are presented as well.

4.2 Soil Water Characteristic Curves

The soil water characteristic curves (SWCCs) for this study were determined using the chilled mirror dew point technique (WP4-T). SWCC graphs were plotted for each of the test soils using results from the companion specimens tested in the glass chambers. The total suction was measured using the WP4-T, which was also used to measure the osmotic suction of the soils using the method proposed by Wei and Miller (2019). The osmotic suction was negligible and total suction was assumed to be equal to the matric suction.

Additionally, the SWCC was developed using the empirical method of Zapata et al. (2000). This procedure estimates the fitting parameters for the Fredlund and Xing (1994) SWCC equation using Weighted Plasticity Index (*wPI*). The *wPI* is calculated by multiplying the plasticity index and percentage of soil passing a #200 sieve for the soil of interest. The saturated volumetric water content used in establishing the SWCCs was determined by utilizing the pre-established measurement of the weight of water and volume of the soil samples determined during the specimen preparation. Using the saturated water content the drying and wetting curves were established using the Zapata et al. (2000) method. Figures 10 and 11 show the estimated SWCCs and the measured suction data versus the volumetric water content for soils prepared at maximum dry density (MDD) and 95% maximum dry density. Three curves are plotted starting at various volumetric water content, which represents the variation in soil types. The plotted lines represent the estimated suction using the Zapata et al. (2000) method, while the symbols represent the data collected using the WP4-T device.

The measured data portray a wide range of suction along the drying and wetting paths. For Soil-1 the suction ranges between 80 and 1100 kPa, for Soil-2 the suction ranges between around 300 and 5000 kPa, and for Soil-3 the suction ranges between 450 and 6500 kPa. It is noticed that the variation between wetting and drying curves decreases as the plasticity and percent of fines decreases.

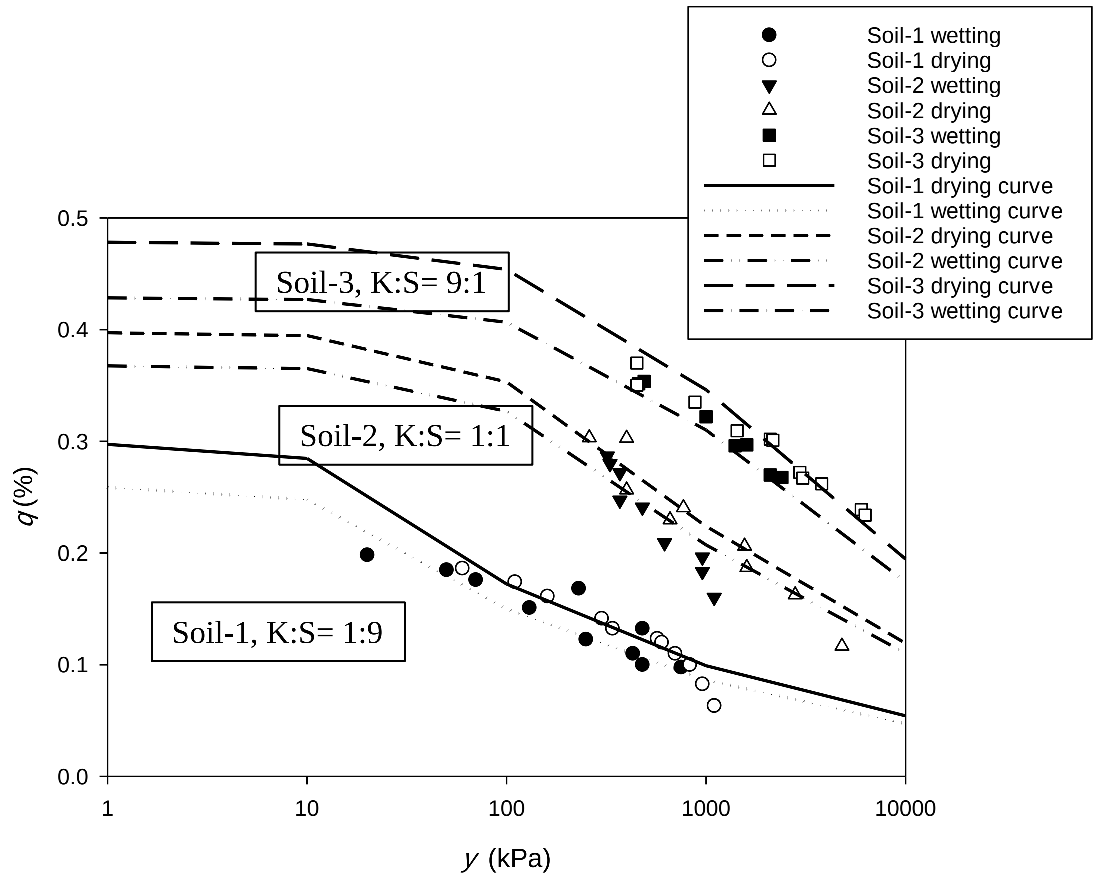

Figure 10. Soil Water Characteristic Curves for soils 1,2, &3 along the wetting and drying paths for soils compacted at maximum dry density. Symbols represent laboratory measurements while the lines represent the empirically determined SWCC based on the method of Zapata et al. (2000).

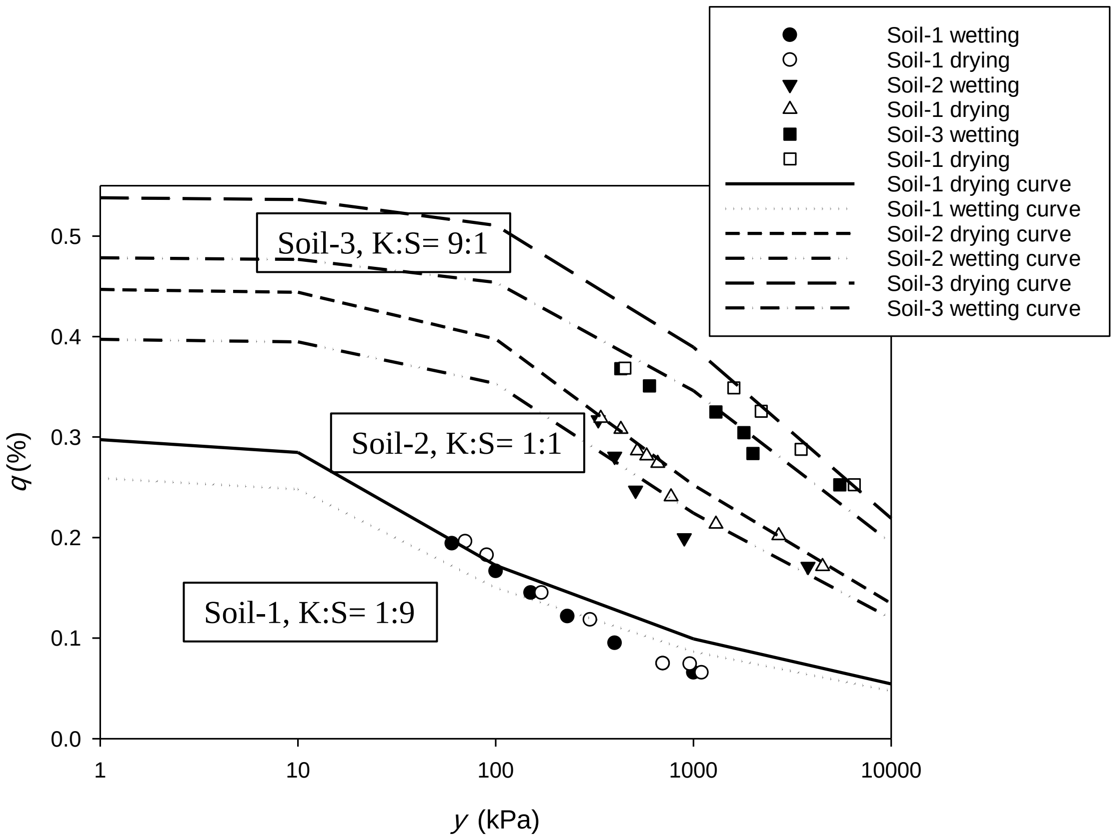

Figure 11. Soil Water Characteristic Curves for soils 1,2, &3 along the wetting and drying paths for soils compacted at 95% maximum dry density. Symbols represent laboratory measurements while the lines represent the empirically determined SWCC based on the method.

4.3 Influence of Moisture Content and Soil Structure on Shear Wave Velocity

The shear wave velocity versus water content for soils compacted wet and dry of OMC at MDD are plotted in Figures 12 a-f. The measured data portray a wide range of shear wave velocity along the wetting and drying paths. Specimens compacted wet of optimum were assumed to have a more dispersed structure while samples compacted dry of optimum were assumed to have a more flocculated structure.

For Soil-1 (Fig. 12 a & b) the water content ranged from 4% to 12% and the shear wave velocity ranged between 126 m/s to 173 m/s for specimens compacted wet of optimum and from 126 m/s to 163 m/s for specimens compacted dry of optimum. For Soil-2 (Figs. 12 c & d) the water content ranged between 9% to 17% and the shear wave velocity ranged from 153 m/s to 343 m/s for specimens compacted wet of optimum and from 153 m/s to 275 m/s for specimens compacted dry of optimum. For Soil-3 (Figs. 12 e & f) the water content ranged between 17% to 25% and the shear wave velocity ranged from 176 m/s to 510 m/s for specimens compacted wet of optimum and from 176 m/s to 320 m/s for specimens compacted dry of optimum. It is observed that the initial structure of the soil has an impact on the shear wave velocity measurement; higher shear wave velocity is noticed for soils that have a more dispersed structure due to compaction wet of optimum. Similar observations were made by Oslon and Langfelder (1965), and Sawangsuriya et al (2008).

In general, results from Figure 12 a-f showed that the increase in the water content leads to a decrease in the shear wave velocity. Also, it is noticed that the shear wave velocity along the drying and wetting paths varies. For instance, Fig. 12 d) show that for Soil-2 at the same water content of 9% the shear wave velocity along the drying path is higher than the wetting path; from 215 m/s for wetting to 275 m/s for drying. Finally, the shear wave velocity is shown to be higher as the plasticity and percent of fines increase. For example, the highest shear wave velocity measured for Soil-1 (Fig 12. a)) was 173 m/s at a water content of 8% while the highest shear wave velocity measured for Soil-3 (Fig 12. e)) was 510 m/s at water content of 17%.

4.4 Influence of Dry Density on Shear Wave Velocity

The plot of shear wave velocity versus water content at various initial dry densities is shown in Figure 13. For each soil, the data were plotted for samples compacted at maximum dry density and 95% of maximum dry density.

Results in Figure 13 reveal that higher dry density generally results in higher shear wave velocity. This suggests that the ratio of shear modulus to density (G/ρ) in Equation 1 increases due to the increase in density, which indicates the increase in shear modulus outweighs the increase in density in this relationship.

With the exception of Soil 3, which contains 10% sand, the difference in shear wave velocities between soils compacted at MDD and 95% MDD is relatively small for soil compacted wet of optimum. Furthermore, for all soils, as the water content increases the differences in shear wave velocity decreases.

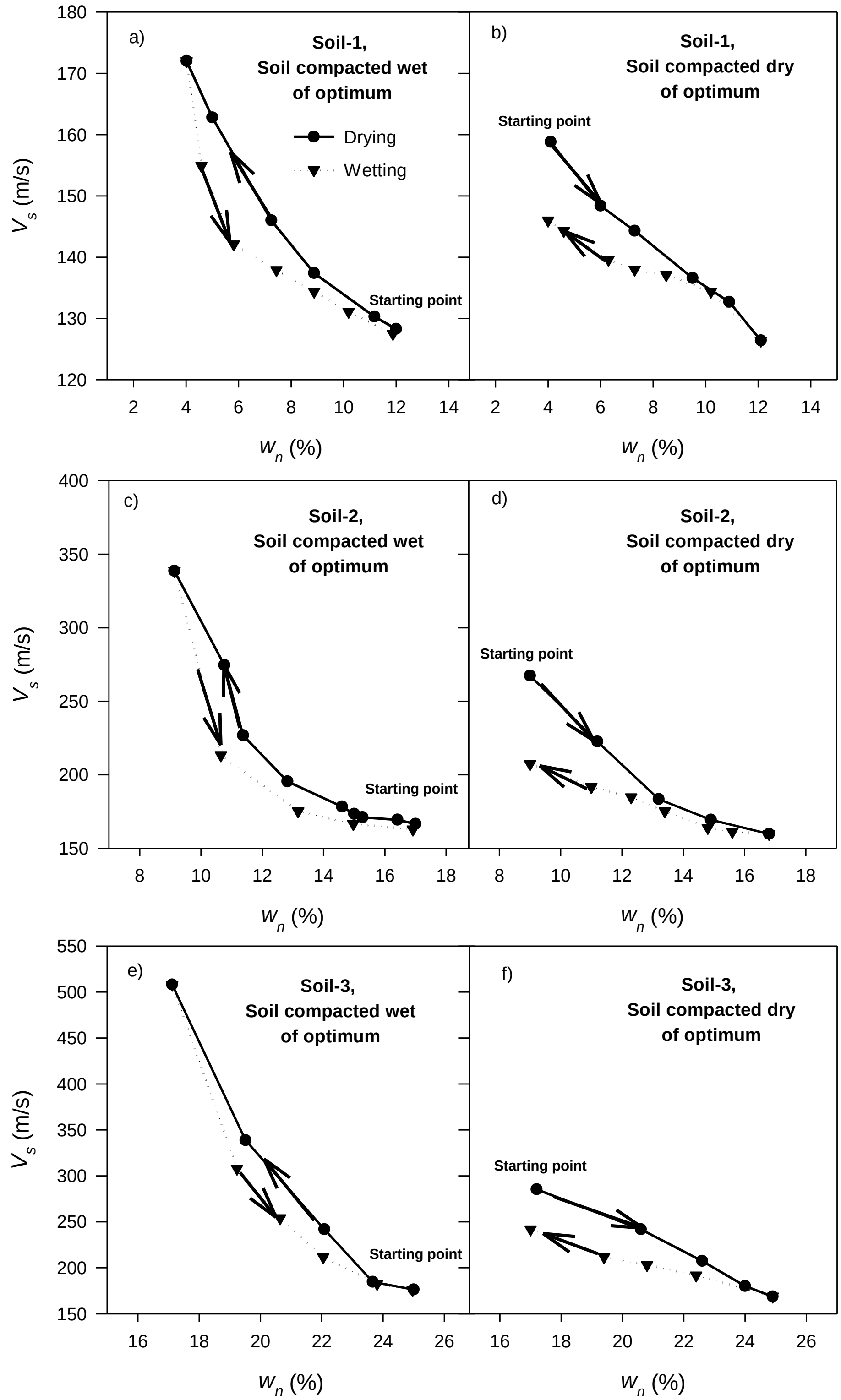

Figure 12. Shear wave velocity versus water content for Soils 1, 2, & 3 along the wetting and drying paths for samples compacted at MDD: a), c), and e) represent soils compacted wet of optimum; b), d), and f) represent soils compacted dry of optimum.

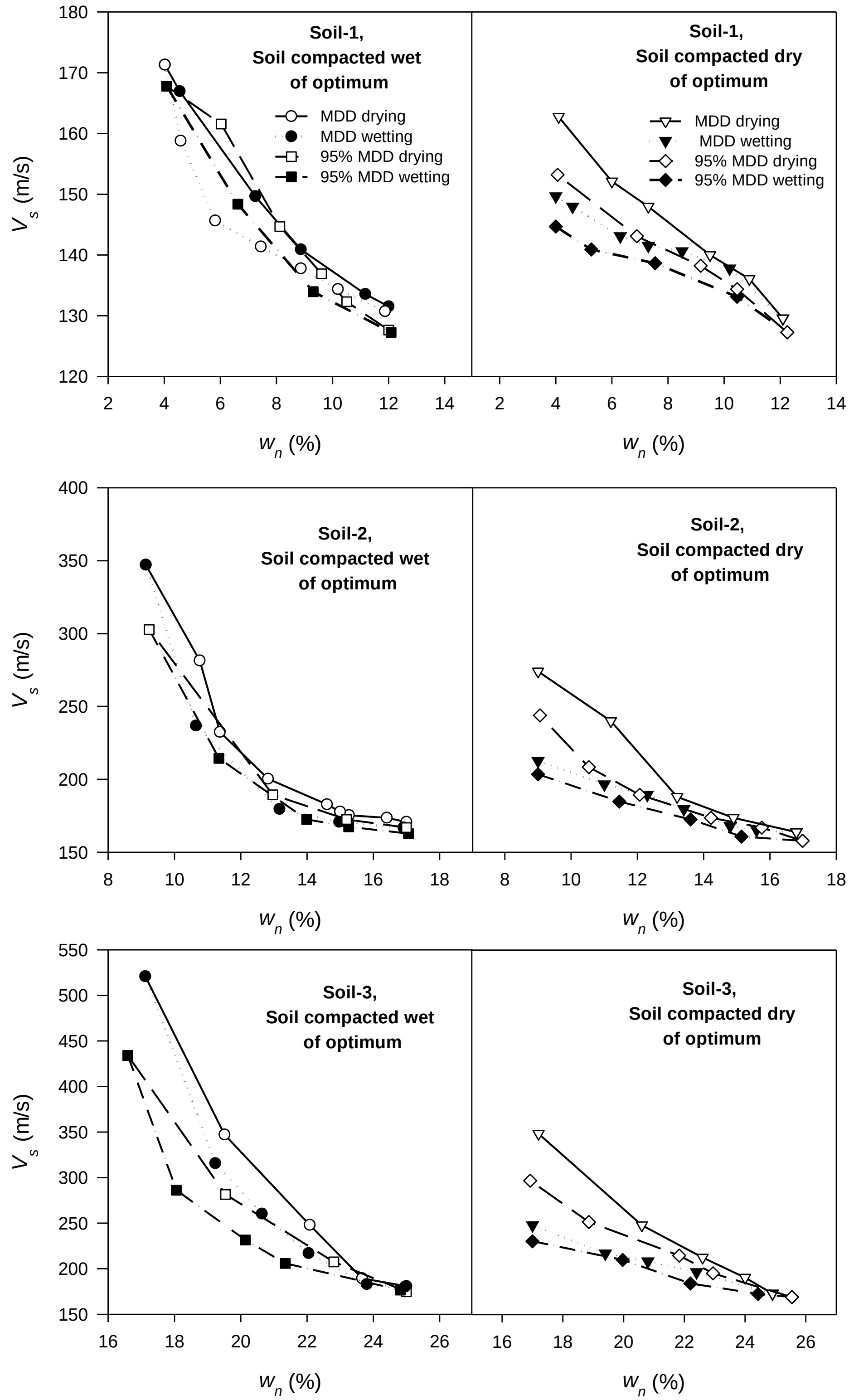

Figure 13. Shear wave velocity versus water content for Soils 1, 2, & 3 along the wetting and drying paths for samples compacted at MDD and 95% MDD: a), c), and e) represent soils compacted wet of optimum; b), d), and f) represent soils compacted dry of optimum.

4.5 Influence of Suction on Shear Wave Velocity

Soil suction was plotted against shear wave velocity for each soil as shown in Figure 14 a-f. Plots on the left-hand side (Figs. a, c, e) represent samples compacted at maximum dry density while plots on the right-hand side (Figs. b, d, f) represent the sample compacted at 95% maximum dry density. A linear regression analysis was conducted for the plotted data to represent the relationship between suction and shear wave velocity as shown in Figure 14. As expected, results show an increase in shear wave velocity as soil suction increases along both the wetting and drying paths and, steeper trend lines were found in soils compacted at maximum dry density compared to 95% of MDD.

An important observation in Figure 14 is that the relationship between suction and shear wave velocity does not exhibit obvious hysteresis. While there is some scatter of data points relative to the trends shown in Figure 14, there is no consistent pattern relative to the location of points representing drying and wetting paths. This is in stark contrast to Figures 3 and 4, where hysteretic behavior is clearly evident in the water content-shear wave velocity relationship.

On the other hand, the soil structure as determined by compacting soils wet or dry of optimum moisture content did appear to have some small influence on the behavior as shown in Figure 15. The trend lines for the shear wave velocity versus suction data for soils initially compacted wet and dry of optimum moisture content are shown in Figure 15 a-f. The trendlines indicate that for Soils 1, 2, and 3, slight variations are observed between the soils compacted wet and dry of optimum at low suction levels. However, as the suction increases, the disparities in shear wave velocity become more pronounced. Soils compacted wet of optimum exhibit higher shear wave velocities compared to those compacted dry of optimum. This is due to the differences in soil structures between soils compacted wet and dry of optimum. Soils compacted wet of optimum have a more dispersed structure while soils compacted dry of optimum have a more flocculated structure. Dispersed structures tend to exhibit a higher suction force because particles are more uniformly distributed which results in smaller pore spaces and increased capillary forces while in flocculated structures the particles are aggregated which increases pore spaces and reduces capillary forces resulting in lower suction forces (Vanapalli et al. 1999).

Additionally, it is noticed that soils with higher plasticity had a higher range of suction, which contributed to higher shear wave velocity measurements. Soil-1 (Figs. 15 a & b), which contains 90% sand, has the lowest shear wave velocities, the lowest suction, and the lowest plasticity while Soil-3 (Figs. 15 e & f), which contains 10% sand, has the highest shear wave velocities, the highest suction, and the highest plasticity. Moreover, the graph trends show that the increase in soil suction leads to an increase in the shear wave velocity. Similar observations were made by researchers for shear wave velocity measurements taken along the drying path (Sawangsuriya et al. 2006, Sawangsuriya et al. 2008, Whalley et al. 2012).

The coefficient of determination (r^2) values of the first order trend lines shown in Figure 15 were found to be high as listed in Table 8. Generally, r^2 values are around 0.9 or above, except for Soil-3 had values slightly below 0.9. Scatter in the data is expected since the suction measurement using the WP4-T chilled mirror hygrometer has an accuracy of around ±100 kPa and due to natural variations in the sacrificial samples used to determine suction. Furthermore, slight differences between moisture content and structure of sacrificial samples used to measure suction and nominally identical specimens used for shear wave velocity testing will contribute to the scatter. However, in spite of these potential sources of scatter, the trends in the data are quite strong. Table 8 below shows the results of the r^2 values for Soils 1, 2, & 3 compacted wet and dry of optimum at maximum dry density and 95% maximum dry density.

Table 8. r-squared values for soils compacted wet and dry of optimum.

Figure number	Soil	Dry Density	r^2 wet of optimum	r^2 dry of optimum
14 a)	Soil-1	MDD	0.902	0.897
14 b)	Soil-1	95% MDD	0.935	0.978
14 c)	Soil-2	MDD	0.924	0.911
14 d)	Soil-2	95% MDD	0.988	0.988
14 e)	Soil-3	MDD	0.871	0.864
14 f)	Soil-3	95% MDD	0.993	0.982

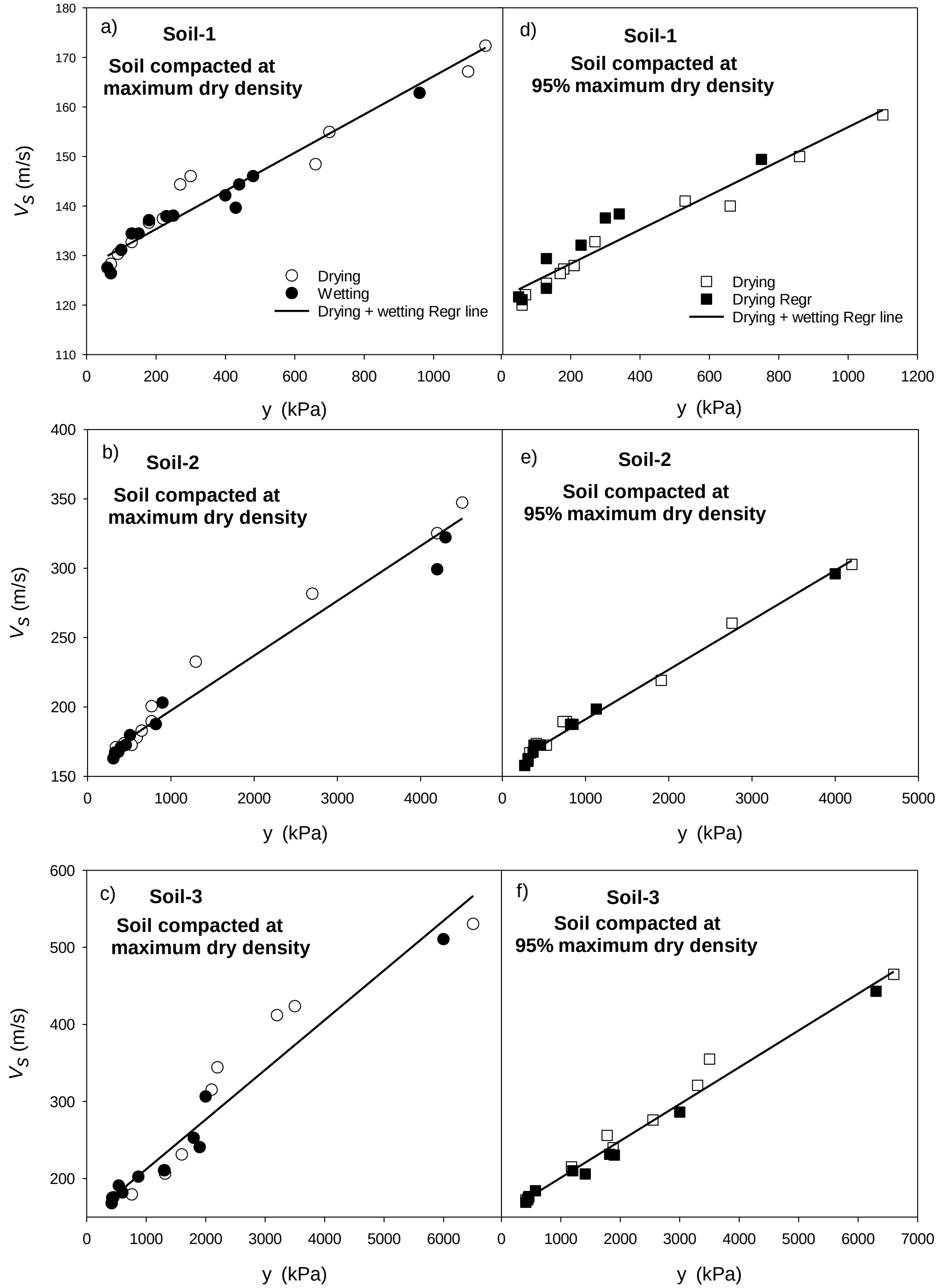

Figure 14. Shear wave velocity versus suction for Soils 1,2, & 3 along the wetting and drying paths: a), b), and c), show results for soils compacted at maximum dry density and d), e), and f) show results for soils compacted at 95% maximum dry density.

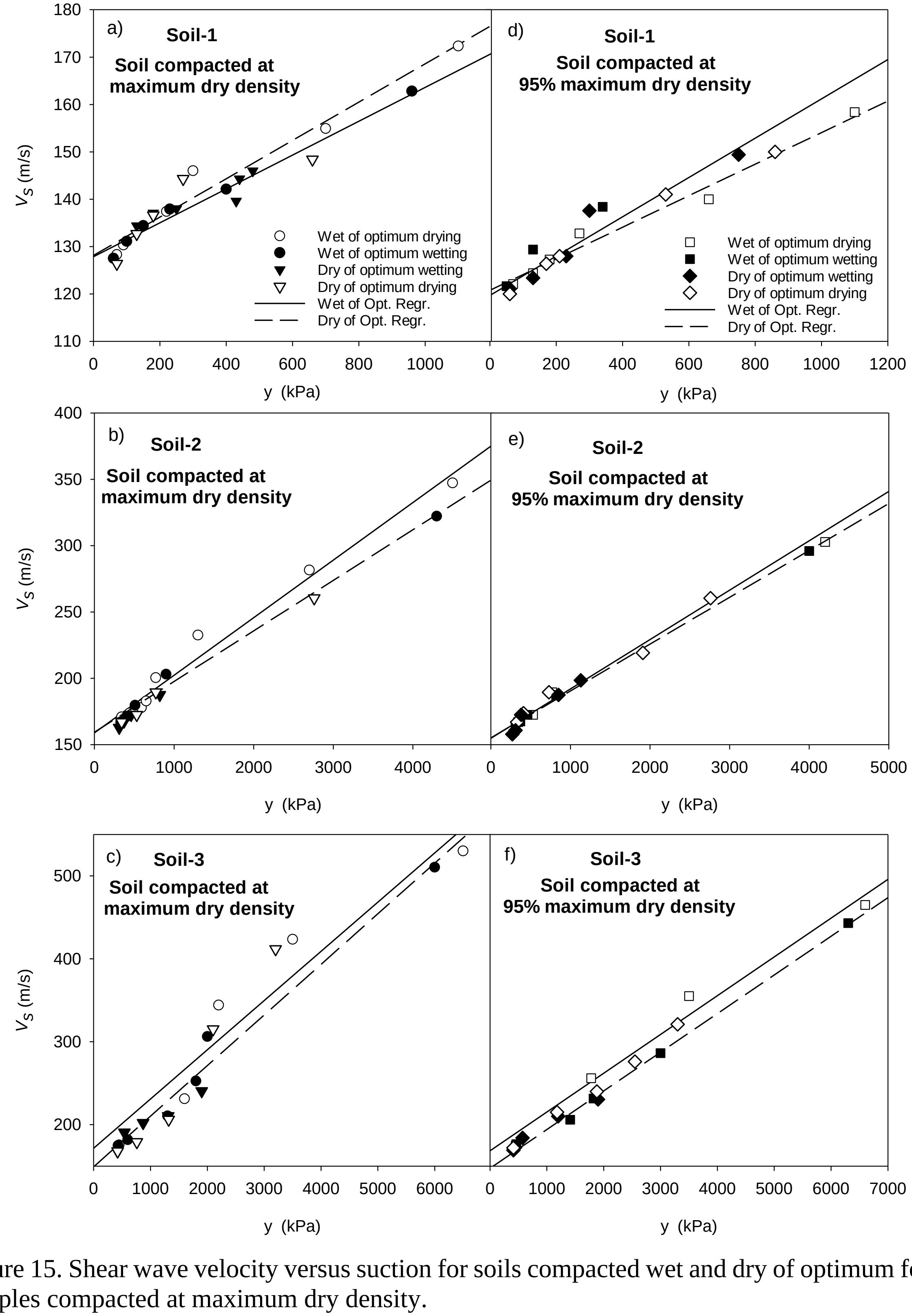

Figure 15. Shear wave velocity versus suction for soils compacted wet and dry of optimum for soil samples compacted at maximum dry density.

4.6 Influence of Confining Stress on Shear Wave Velocity

The relationships between shear wave velocity and water content for different confining stresses along the wetting and drying paths are shown in Figures 16 and 17. Soil-2 was used during testing; two specimens were prepared at initial compaction wet and dry of optimum at maximum dry density. As expected, results show that increases in confining stress correspond to increases in shear wave velocity along the wetting and drying paths. Also, samples prepared wet of optimum generated higher shear wave velocity when compared to samples prepared dry of optimum. This observation aligns with the results shown in previous sections.

For the same soil specimens, the shear wave velocity versus suction was plotted for different confining stresses as shown in Figures 18 and 19. Similar to the relationship between shear wave velocity and water content, results show that as confining stress increases the shear wave velocity increases for different suction values. Moreover, as mentioned in the previous section, Figures 18 and 19 show that the relationship between suction and shear wave velocity is not affected by the wetting and drying process, i.e., it appears not to exhibit hysteresis.

It is important to note that as the stress state increases via increasing suction and confining stress, the volume of the samples decrease. These changes in the volume of the samples cause an increase in the dry densities that will influence the shear wave velocity.

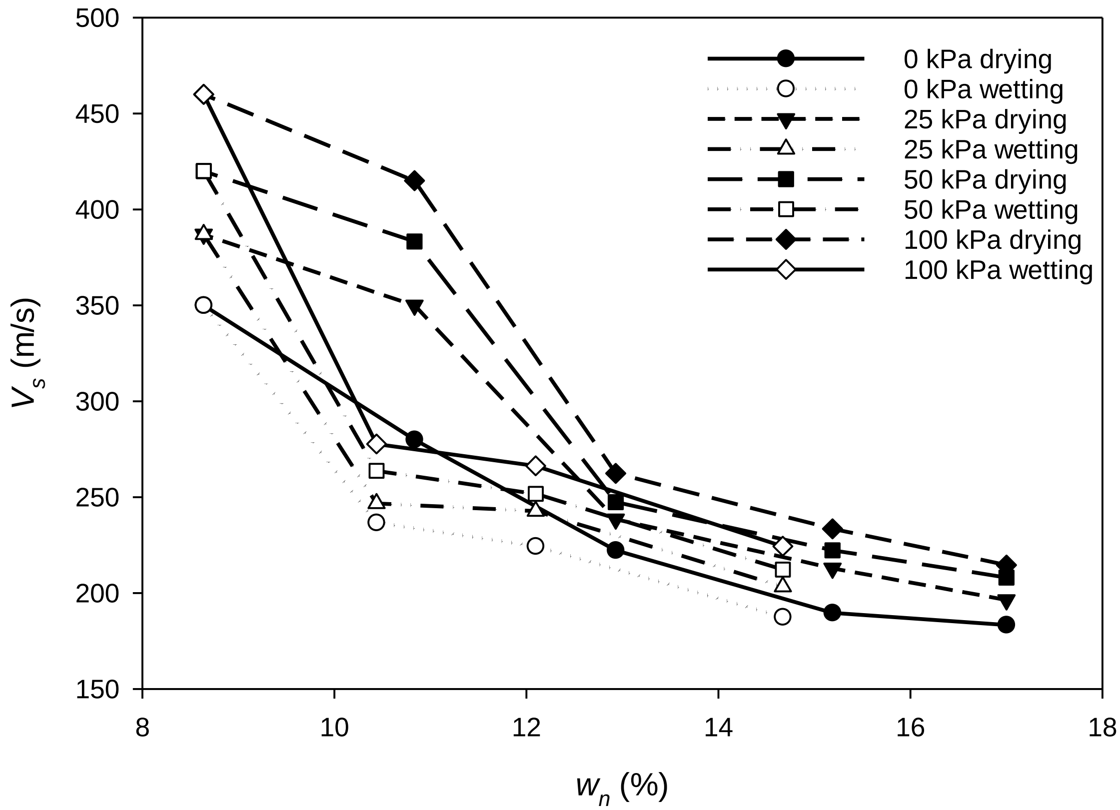

Figure 16. Shear wave velocity versus water content for the specimen containing 50% kaolin and 50% fine sand prepared wet of optimum at maximum dry density. Soil was tested at 0 kPa, 25 kPa, 50 kPa, and 100 kPa confining stresses along the wetting and drying paths.

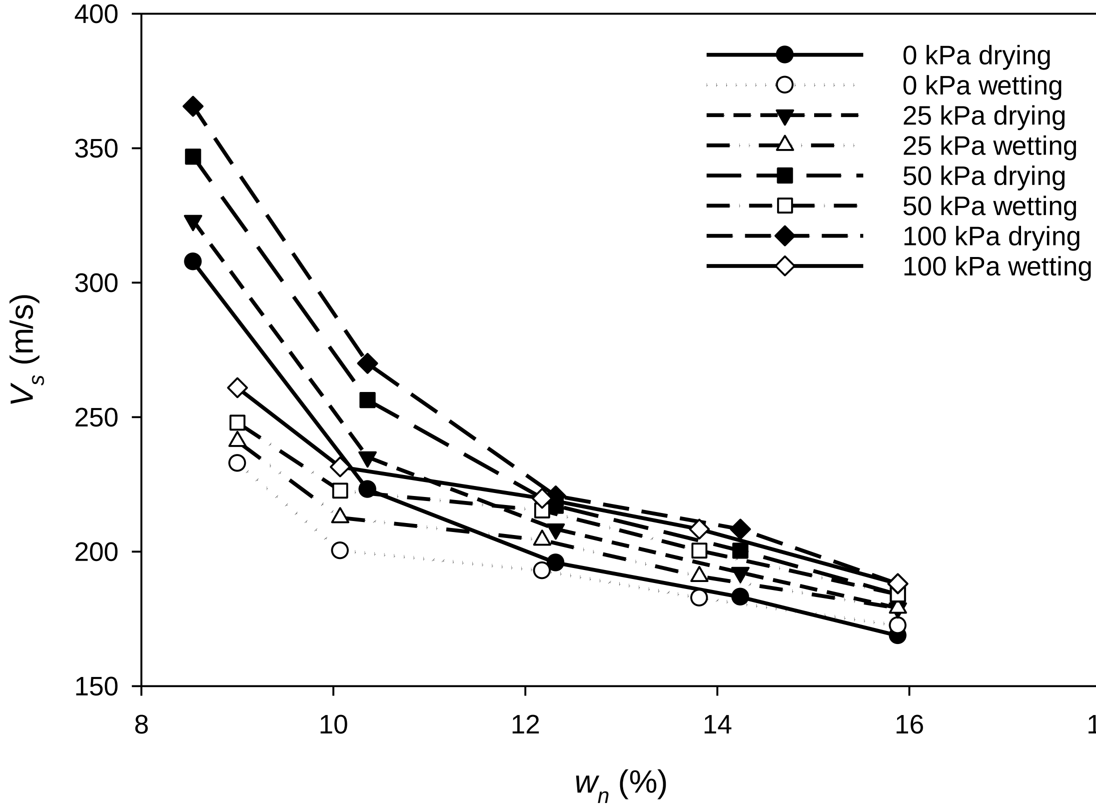

Figure 17. Shear wave velocity versus water content for the specimen containing 50% kaolin and 50% fine sand prepared dry of optimum at maximum dry density. Soil was tested at 0 kPa, 25 kPa, 50 kPa, and 100 kPa confining stresses along the wetting and drying paths.

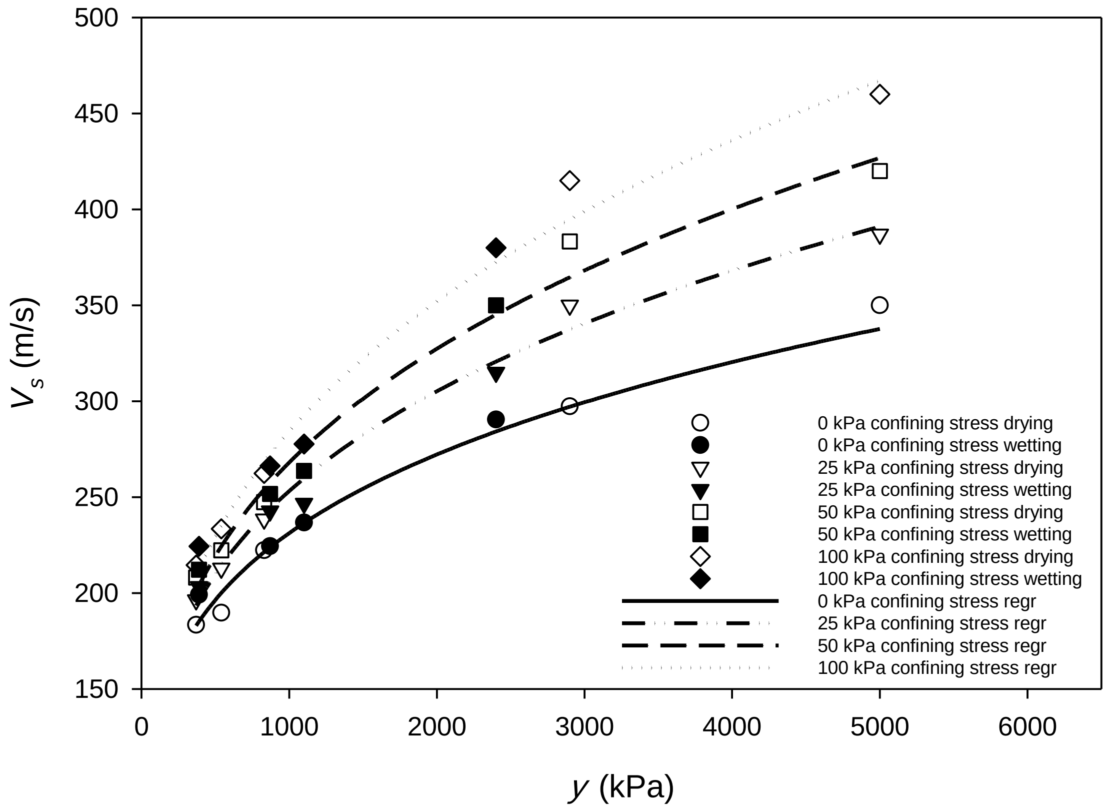

Figure 18. Shear wave velocity versus suction for the specimen containing 50% kaolin and 50% fine sand prepared wet of optimum at maximum dry density. Soil was tested at 0 kPa, 25 kPa, 50 kPa, and 100 kPa confining stresses along the wetting and drying paths.

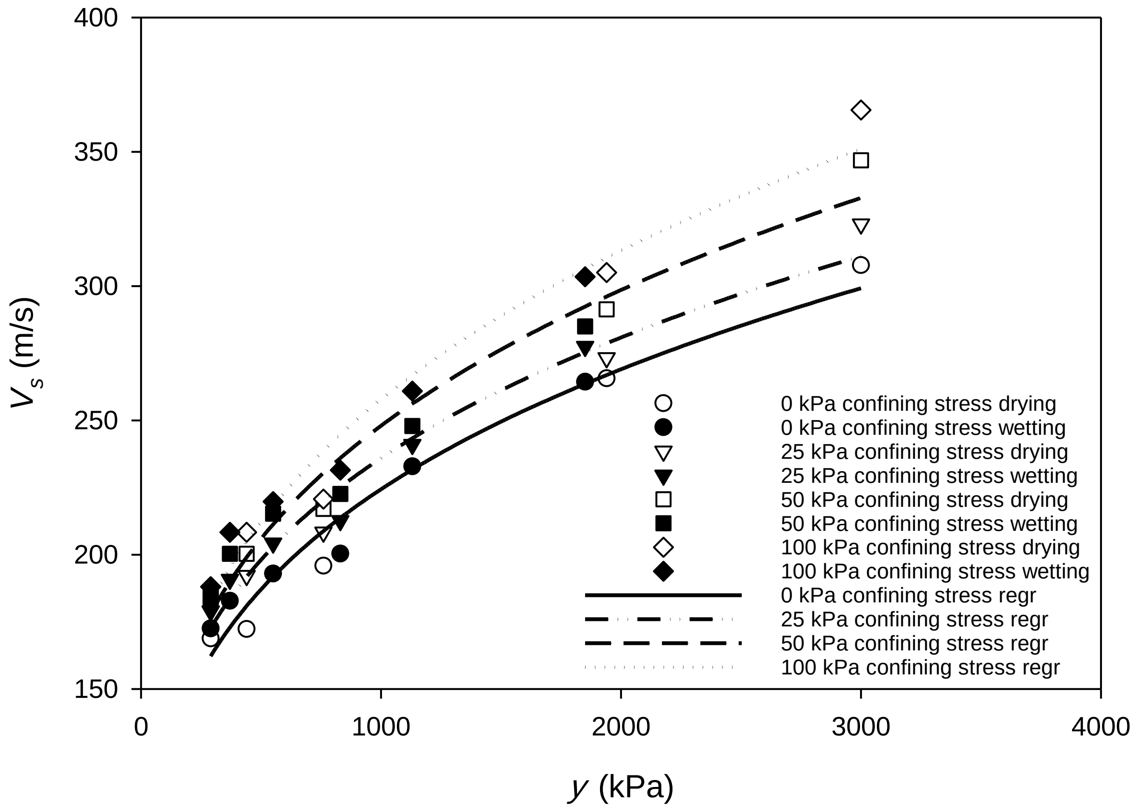

Figure 19. Shear wave velocity versus suction for specimen tested with 50% kaolin:50% fine sand prepared dry of optimum at maximum dry density. Soil was tested at 0 kPa, 25 kPa, 50 kPa, and 100 kPa confining stresses along the wetting and drying paths.

To further investigate the effect of changes in density during testing on shear wave velocity, the density, water content, and suction variations determined during testing were plotted in Figure 20 against shear wave velocity. Additionally, the effective stress calculated using Lu and Likos (2006) definition of suction stress, discussed in Chapter 7, is plotted against shear wave velocity. These results are from tests on the Soil-2 specimen during (insert drying or wetting). The volume was determined at different water contents before subjecting the specimen to confining stress. Table 9 shows tabulated results of the water content, wet density, dry density, suction, effective stress (using suction stress definition) and shear wave velocity of the test specimen. The results indicate that an increase in the wet and dry densities of the soil, due to changes in water content and corresponding changes in sample volume, led to an increase in the shear wave velocity. This contradicts the definition of shear wave velocity shown in Equation 1, where shear wave velocity decreases as density increases. This contradiction may be attributed to the fact that the suction and effective stress have a predominant influence on shear wave velocity. Increases in effective stress will increase the shear modulus, which increases the shear wave velocity according to Equation 1. It appears that increases in shear modulus due to increasing effective stress are more important than corresponding increases in density.

Additionally, as portraied by the Figure 20, the linear regression lines show that the relationship between suction and effective stress with shear wave velocity is strong while there is a lot of scatter observed in the relationship between density and shear wave velocity.

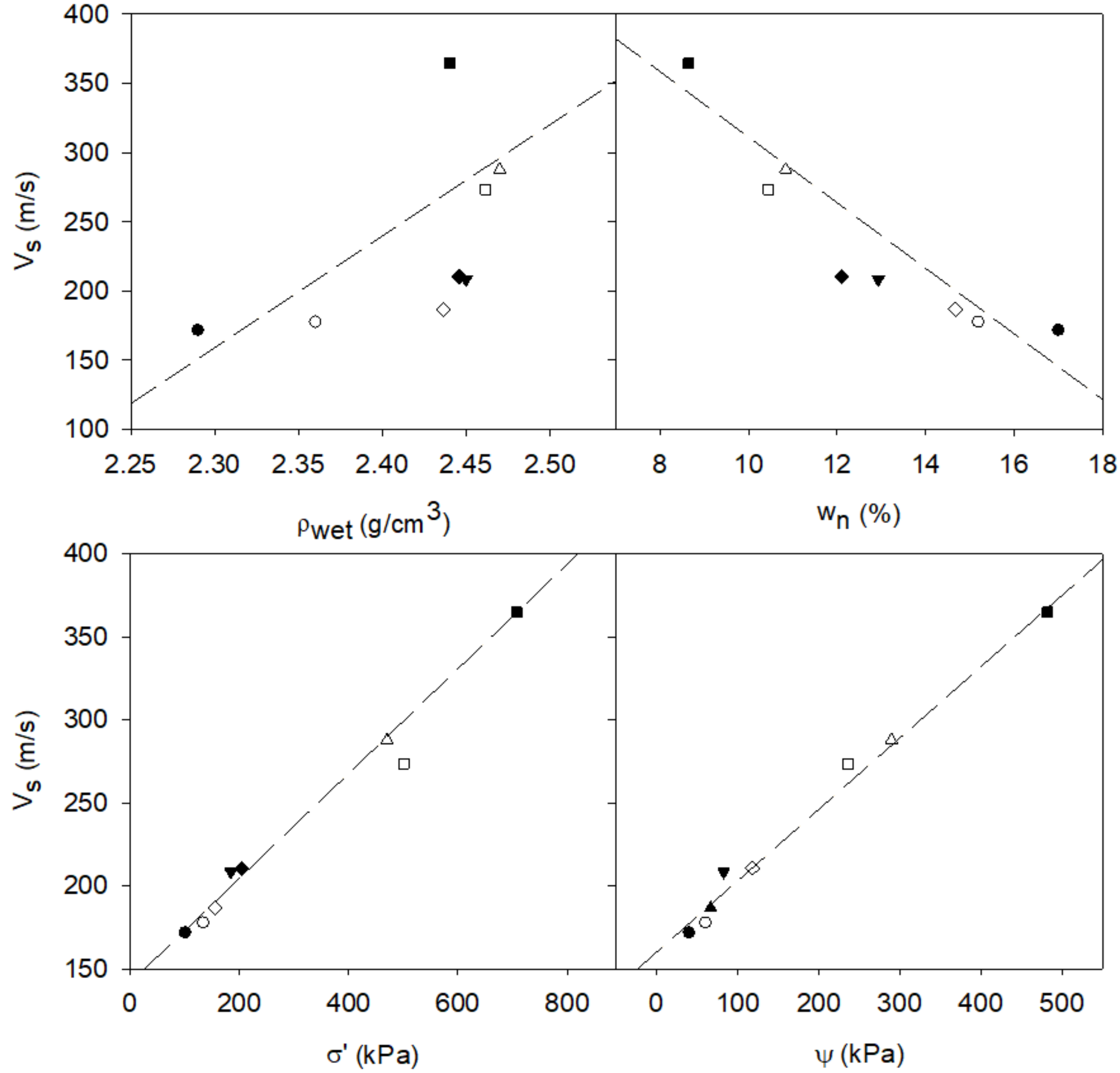

Figure 20. Shear wave velocity versus various soil properties: a) density, b) water content, c) effective stress (using Lu and Likos (2006), d) suction for Soil-2.

Table 9. Water content, density, suction, effective stress, and shear wave velocity results for Soil-2.

Water content (%)	Wet density (g/cm3)	Dry density (g/cm3)	Suction (kPa)	Effective stress (kPa)	Shear wave velocity (m/s)
17.0	2.29	1.96	40.0	100.3	550.1
15.1	2.36	2.05	60.0	133.2	568.8
12.9	2.45	2.17	82.5	183.9	666.7
10.8	2.47	2.21	289.4	470.0	921.1
8.6	2.44	2.25	482.4	707.1	1166.7

Chapter 5: Field Investigation of Shear Wave Velocity in Unsaturated Soils

5.1 Overview

This chapter presents and discusses the results of shear wave velocity measurements at nine test sites that were conducted to investigate the influence of seasonal variations in moisture content on the shear wave velocity. Shear wave velocity measurements with the SCPTu on different dates were compared to assess the influence of natural variations in moisture conditions and suction on the measurements.

5.2 Soil Properties and Soil Profiles

Test results from nine test sites located across the state of Oklahoma are presented and discussed below. For each site, the site number, the soil type, and site location in Oklahoma are shown in Table 10. A summary of the soil types (AASHTO and USCS), percent of fines, plasticity index, plastic limit and liquid limit are shown in Tables 11 to 19. The soil property profiles including USCS group symbol, water contents during the first and second visits, plastic limit, liquid limit and percent of fines against depth are shown in Figures 18 to 26. Also shown in these figures are the measured total suction and shear wave velocity.

Table 10. Location number, soil types, location of the tested sites, and the study associated with the tested site.

Location Number	Soil Types	Location
1	Wind blown silts and silty sands (SPT Calibration Site)	Curtis
2	Clay soils	Lake Hefner
3	Mixed clay soils	Muskogee
4	Clay soils	Wagoner
5	Clay soils	Hobart
6	Paleoterrace, clayey and loamy colluvium or alluvium over clayey residuum weathered from shale	Wewoka
7	Fine sand	Norman
8	Mixed clay soils	Fairview
9	Mixed clays, sands and silty clays	Fears Lab-University of Oklahoma

5.3 Index Properties

The soils investigated in this study were tested to determine physical and index properties including grain size distribution (ASTM D 6913-17) and Atterberg Limits (ASTM D 4318-00). The results of these tests are presented in Tables 2 through 10. For each site the AASHTO and USCS classification, grain size distribution and Atterberg limits through the active zone are shown. The data shown in the tables for Sites 1, 2, 3, 4, 5, 6, and 8 were obtained from records of previous studies by ODOT. The results were obtained from soils collected in the same location the CPT tests were conducted. For Sites 7 and 9, tests were conducted in the University of Oklahoma laboratory to determine soil properties needed for classification. The results showed that the soil profiles include various types of soils such as clays and clayey mixtures, silts and silty mixtures, and sand and sandy mixtures.

Site # 1 Curtis

This site consists of eolian silts and silty sands. As shown in the Table 11, the top 4 feet of the soil profile is composed of non-plastic silts while the bottom 6 feet is composed of slightly plastic silts and silty sands mixtures.

Table 11. Soil index properties and classification for Site 1 (Curtis).

Depth (m)	**AASHTO Group Class.**	**USC Group Class.**	**Percent Fines (%)**	**Liquid Limit (%)**	**Plastic Limit (%)**	**Plasticity Index (%)**
0.30	A-2-4	SM	18	NP	NP	NP
0.61	A-2-4	SM	22	NP	NP	NP
0.91	A-2-4	SM	18	NP	NP	NP
1.22	A-2-4	SM	15	NP	NP	NP
1.52	A-4	SC	40	23	13	10
1.82	A-6	CL	63	40	16	24
2.13	A-6	CL	51	29	12	17
2.43	A-2-4	SM	25	NP	NP	NP
2.74	A-4	SC	34	22	14	8
3.04	A-6	SC	43	22	10	12

Site #2 Lake Hefner

This site is composed of a shallow residual clay soil profile underline by shale. The first few feet consist of fat clay soils while the lower part consists of lean clay. The water table was not encountered at this site.

Table 12. Soil index properties and classification for Site 2 (Lake Hefner).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-7-6	CL	92	46	18	28
0.61	A-7-6	CH	95	56	15	41
0.91	A-7-6	CH	95	59	17	42
1.22	A-7-6	CH	97	67	19	48
1.52	A-6	CL	96	37	19	18
1.82	A-6	CL	95	34	19	15
2.13	A-6	CL	96	36	18	18

Site # 3 Muskogee

This site consists of alluvial mixed clay, the profile is uniformly composed of lean clay soil with a change at 2 feet to fat clay.

Table 13. Soil index properties and classification for Site 3 (Muskogee).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-7-6	CL	86	46	19	27
0.61	A-7-6	CH	87	61	22	39
0.91	A-7-6	CL	86	47	25	22
1.22	A-6	CL	72	34	22	12
1.52	A-6	CL	87	38	21	17
1.82	A-6	CL	80	32	19	13
2.13	A-6	CL	82	34	19	15
2.43	A-6	CL	87	38	20	18
2.74	A-6	CL	86	37	20	17

Site # 4 Wagoner

A uniform profile of alluvial fat clay soil is shown in the table below. The plasticity index ranges from 49% at the highest and 40% at the lowest.

Table 14. Soil index properties and classification for Site 4 (Wagoner).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-7-6	CH	89	66	26	40
0.61	A-7-6	CH	99	72	26	46
0.91	A-7-6	CH	99	73	28	45
1.22	A-7-6	CH	98	66	25	41
1.52	A-7-6	CH	98	74	26	48
1.82	A-7-6	CH	99	75	26	49
2.13	A-7-6	CH	98	71	24	47
2.43	A-7-6	CH	98	67	24	43
2.74	A-7-6	CH	98	68	24	44
3.04	A-7-6	CH	98	68	23	45
3.34	A-7-6	CH	99	65	23	42
3.65	A-7-6	CH	99	66	23	43
3.95	A-7-6	CH	98	64	23	41

Site # 5 Hobart

This site is composed of a mixture of residual clays, the soil varies between lean and fat clay throughout the soil profile.

Table 15. Soil index properties and classification for Site 5 (Hobart).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-6	CL	96	37	19	18
0.61	A-7-6	CH	98	57	20	37
0.91	A-7-6	CH	95	58	26	32
1.22	A-7-6	CH	96	53	18	31
1.52	A-7-6	CH	93	52	20	32
1.82	A-7-6	CH	93	52	24	28
2.13	A-7-6	CL	94	46	18	28
2.43	A-7-6	CL	97	47	17	30
2.74	A-7-6	CL	98	49	25	24
3.04	A-7-6	CL	96	44	21	23
3.34	A-7-6	CL	97	42	21	21

Site # 6 Wewoka

The alluvial soil in this profile is a mixture of non-plastic sand, silty sand and fat clay.

Table 16. Soil index properties and classification for Site 6 (Wewoka).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-2-4	SM	33	NP	NP	NP
0.61	A-4	ML	40	19	16	3
0.91	A-6	SC-SM	48	26	14	12
1.22	A-6	CL	52	30	14	16
1.52	A-6	SC-SM	47	35	15	20
1.82	A-2-4	SM	21	NP	NP	NP
2.13	A-6	SC	49	37	18	19
2.43	A-7-6	CH	98	69	24	45
2.74	A-7-6	CH	98	57	27	30
3.04	A-7-6	CH	99	59	25	34
3.34	A-7-6	CH	95	52	23	29
3.65	A-7-6	CL	98	49	26	23
3.95	A-7-6	CH	99	60	26	34

Site # 7 Norman Maintenance Yard

In this site the profile consists of alluvial fine sands mixtures. As the depth increases the plasticity of the soil changes from non-plastic to low plasticity as shown below.

Table 17. Soil index properties and classification for Site 7 (Norman MY).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-3	SM	8	NP	NP	NP
1.52	A-3	SM	9	NP	NP	NP
2.13	A-2-4	SC	30	20	15	5
3.04	A-2-4	SC	32	20	16	4

Site # 8 Fairview

The top 3 feet of this site are composed of fat clay which then changes to lean clay for the depths of 4-11 feet. This soil is classified as a residual clay soil.

Table 18. Soil index properties and classification for Site 8 (Fairview).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-7-6	CH	95	58	16	42
0.61	A-7-6	CH	92	58	18	40
0.91	A-7-6	CH	95	52	16	36
1.22	A-7-6	CL	94	46	17	29
1.52	A-7-6	CL	91	43	16	27
1.82	A-7-6	CL	91	45	17	28
2.13	A-7-6	CL	99	45	18	27
2.43	A-7-6	CL	91	40	17	23
2.74	A-7-6	CL	90	41	14	27
3.04	A-7-6	CL	93	42	20	22
3.34	A-7-6	CL	97	44	26	19

Site # 9 Fears Lab

This site consists of a diverse profile composed of a mixture of silts, silty clay and silty sands.

Table 19. Soil index properties and classification for Site 9 (Fears Lab).

Depth (m)	AASHTO Group Class.	USC Group Class.	Percent Fines (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
0.30	A-4	ML	57	NP	NP	NP
0.61	A-4	CL	70	26	16	10
0.91	A-4	ML	63	NP	NP	NP
1.22	A-4	ML	64	NP	NP	NP
1.52	A-4	ML	62	NP	NP	NP
1.82	A-6	CL	60	24	11	13
2.13	A-4	ML	61	NP	NP	NP
2.43	A-4	ML	55	NP	NP	NP
2.74	A-4	CL	58	22	14	8

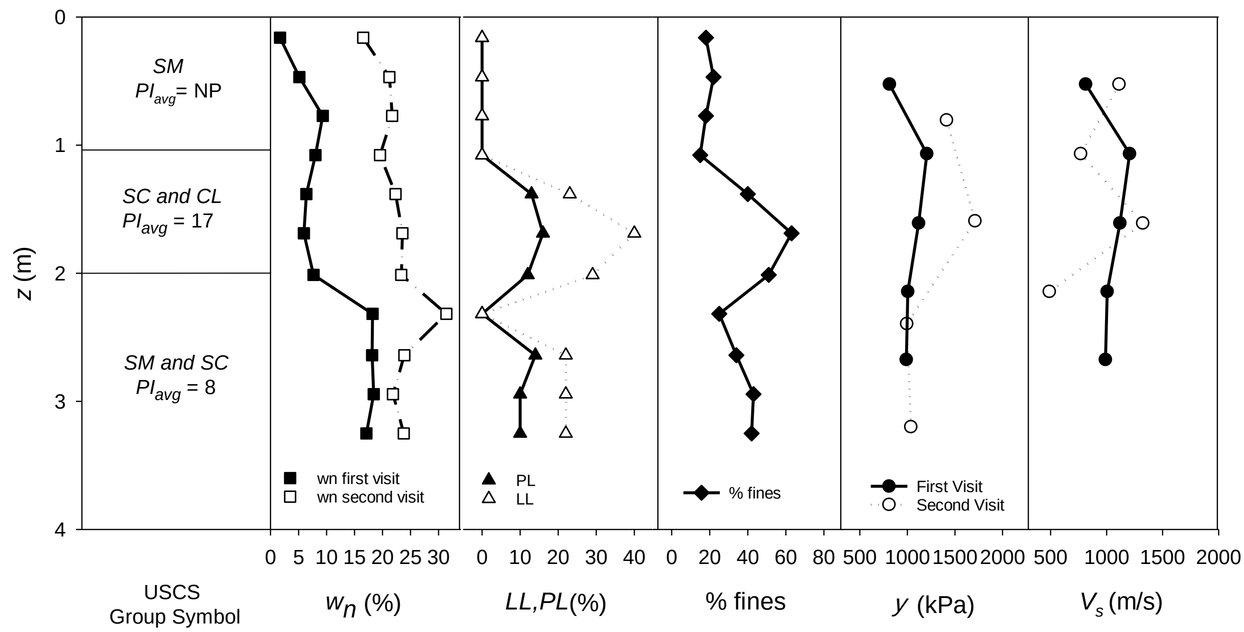

Figure 21. Soil profile for Site 1 including USCS, water content, plastic limit, liquid limit, percent of fines, suction, and shear wave velocity.

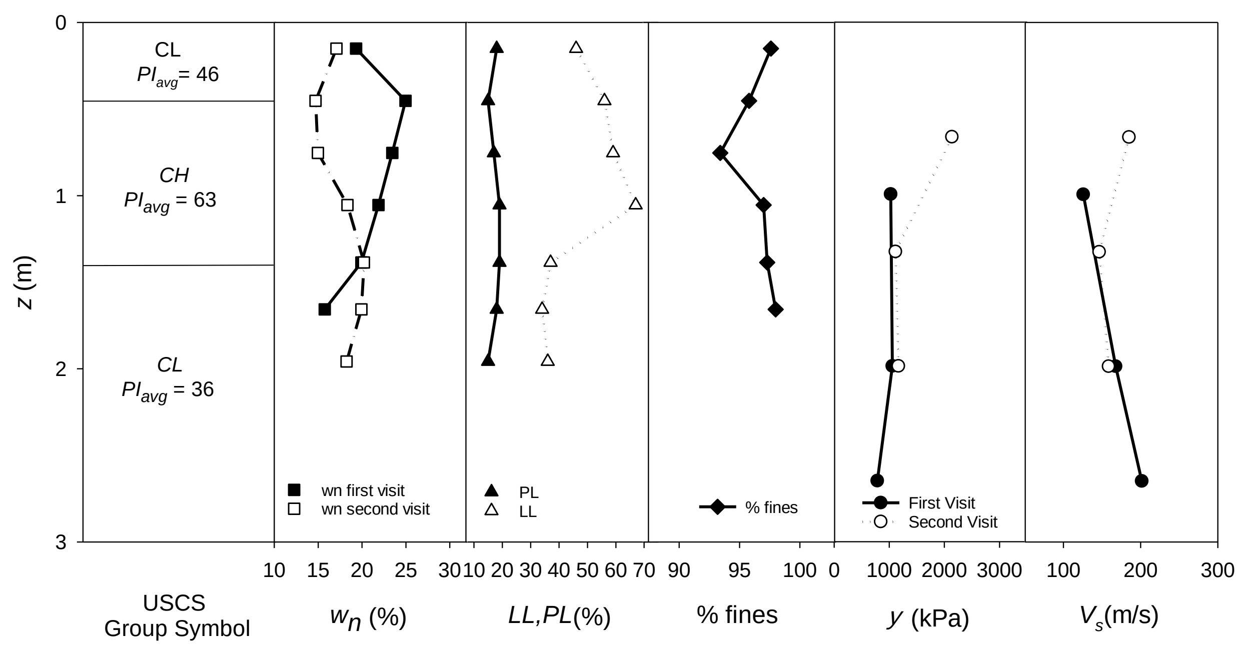

Figure 22. Soil profile for Site 2 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

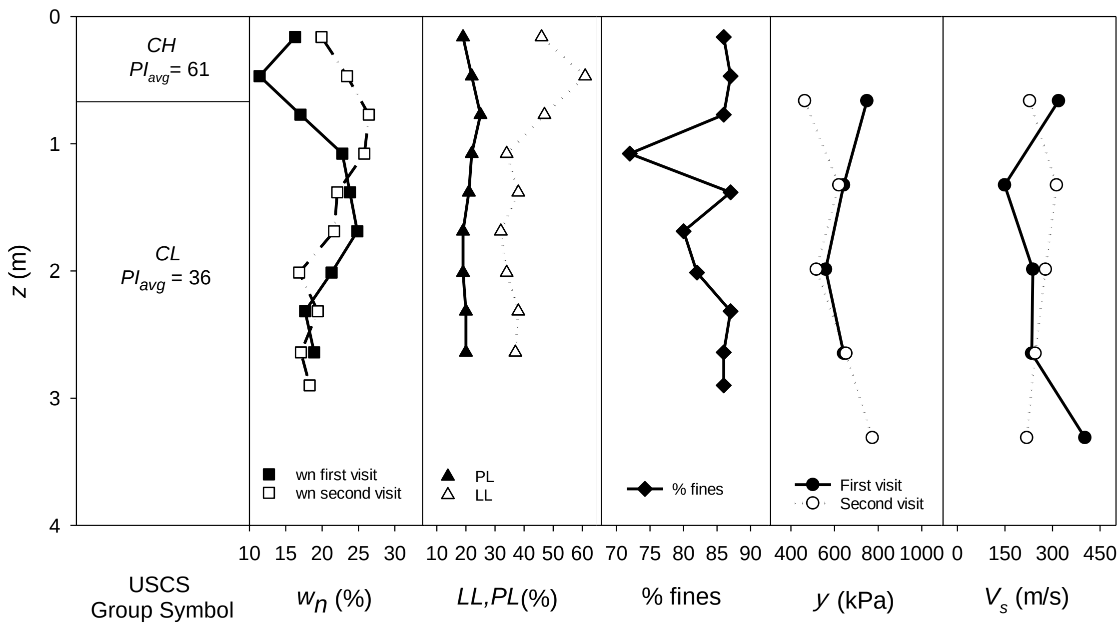

Figure 23. Soil profile for Site 3 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

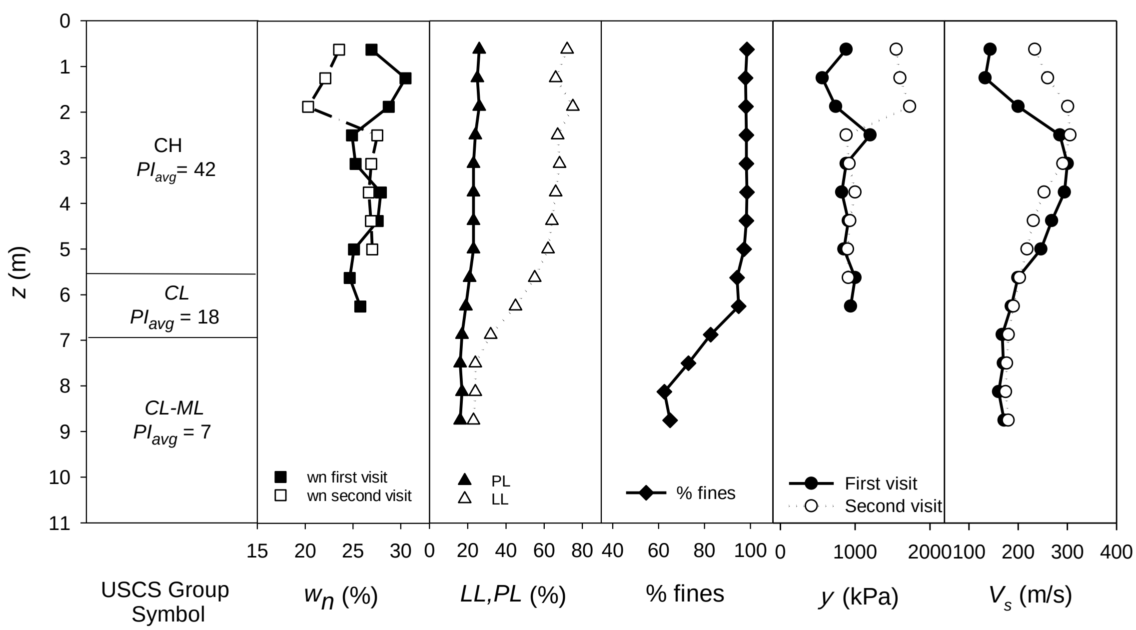

Figure 24. Soil profile for Site 4 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

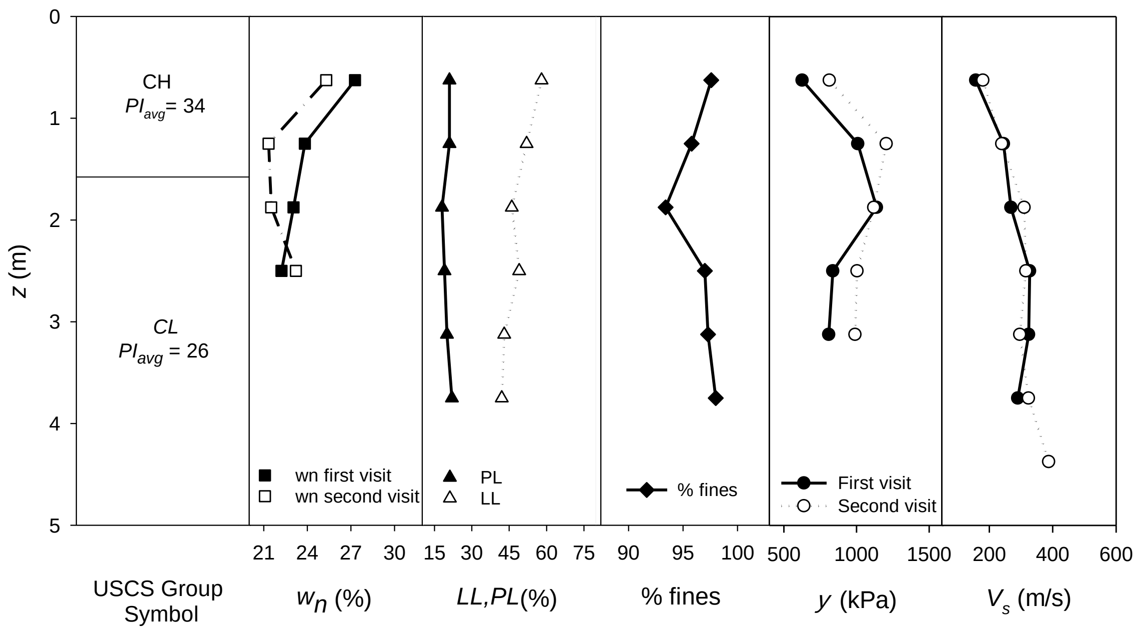

Figure 25. Soil profile for Site 5 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

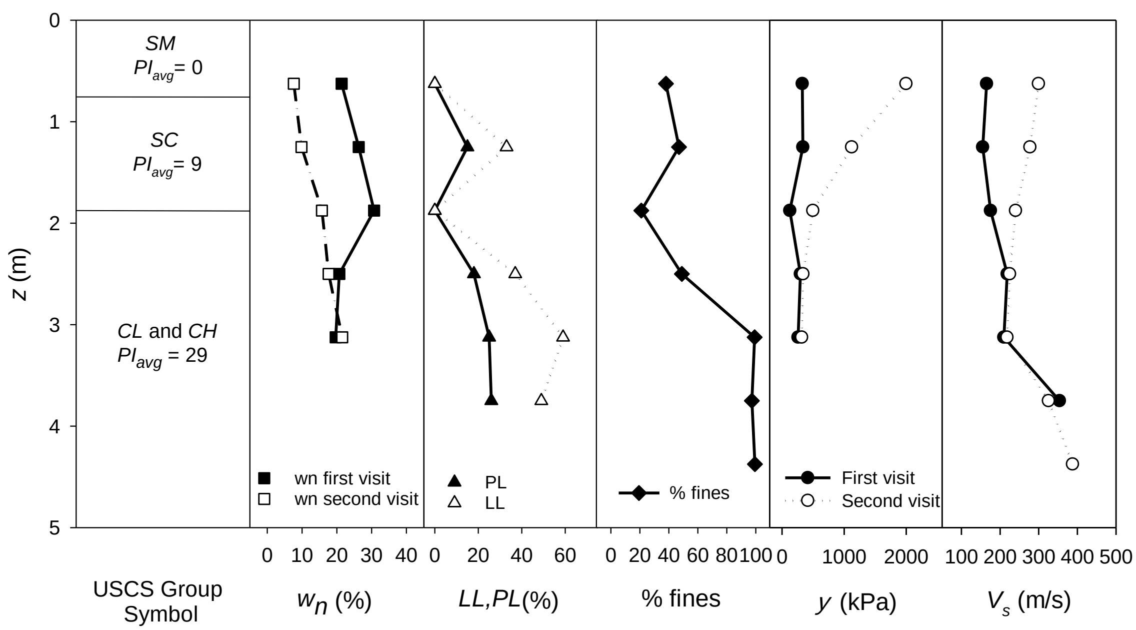

Figure 26. Soil profile for Site 6 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

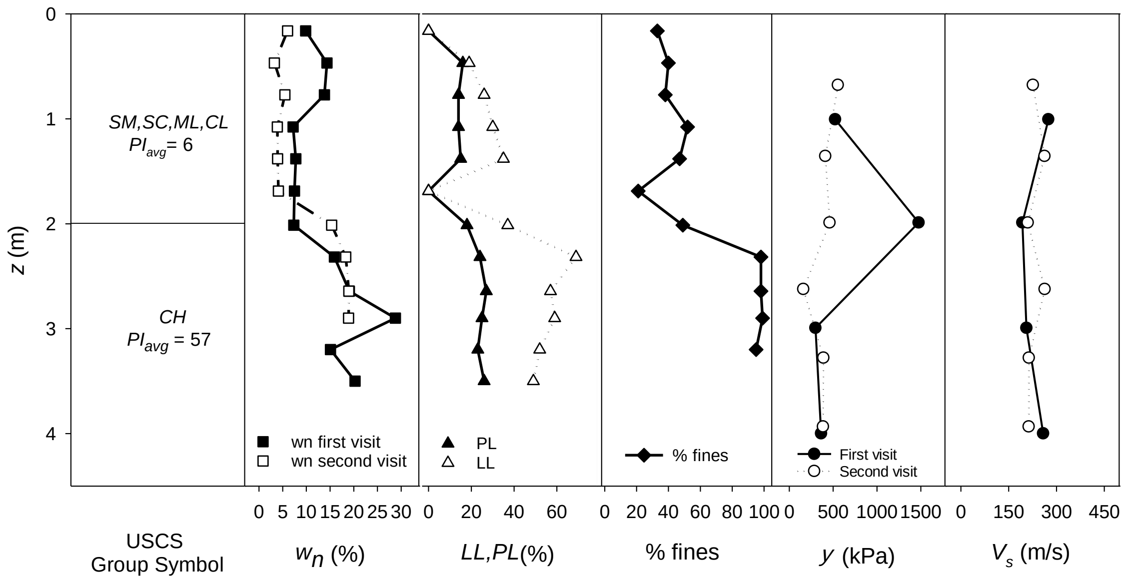

Figure 27. Soil profile for Site 7 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

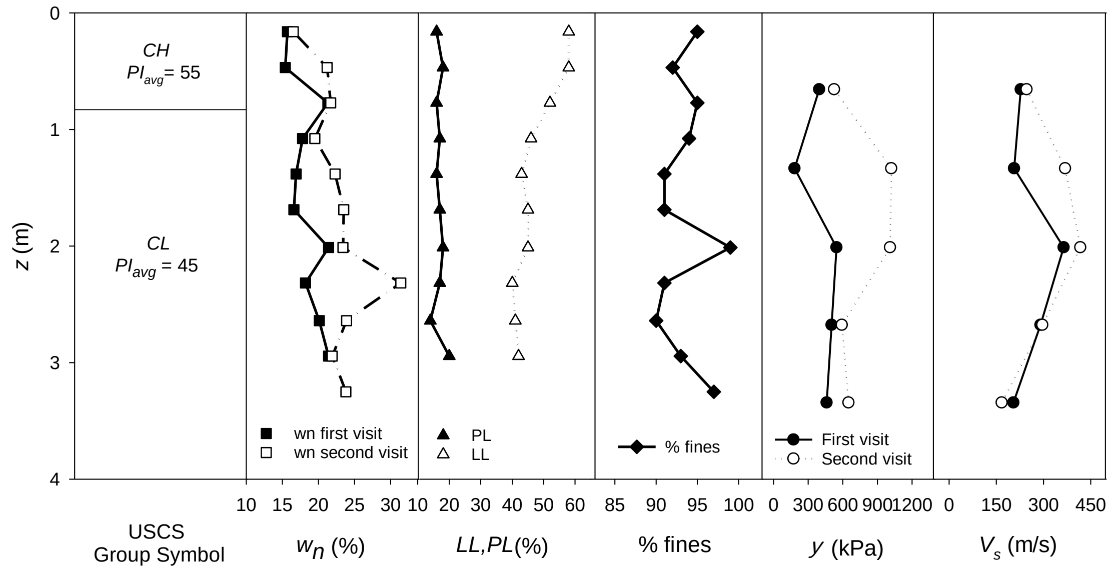

Figure 28. Soil profile for Site 8 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

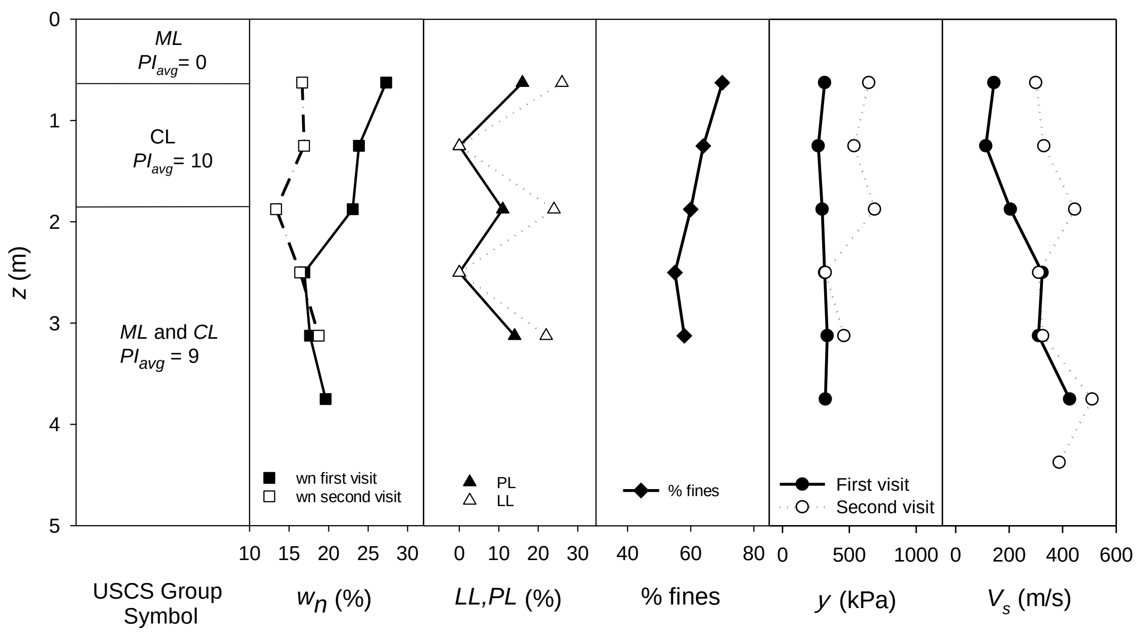

Figure 29. Soil profile for Site 9 including USCS, water content, plastic limit, liquid limit, and percent of fines, suction, and shear wave velocity.

As depicted in Figures 21 to 29, the soil profiles at the tested sites revealed a diverse array of soil types present within the subsurface. The soil profiles displayed a range of liquid limits, plastic limits, and percent of fines that varied significantly across the different sites, indicating a varied subsurface environment. Lean and fat clays, silty and sandy soils were encountered in the tested soils.

At each site the water content profile was determined for the two testing dates as shown in Figures 21 to 29. In general, during the first visit, the water content in the soil profiles for the first 2 to 3 meters was relatively high. However, during the second visit, the water content in the same depth range had decreased. Beyond the first 2 to 3 meters below the ground surface, the water content generally remained fairly constant between the two visits at most sites. Overall, the water content in the soil profiles varied between the first and second visit at shallow depths but remained relatively stable at deeper depths.

Suction measurement profiles determined for the two testing dates showed that the suction results are consistent with the water contents results (i.e. when water content increases the suction decreases). In general, during the first visit, the suction in the soil profiles for the first 2 to 3 meters was relatively lower than the second visit for the same depth range. On the other hand, water content and suction measurements varied with the shear wave velocity measurements for each site. For site 1, 3, and 7 the results from water content, suction, and shear wave velocity are not consistent, in some cases the shear wave velocity increases with increasing water content and in some it decreases. Sites 2, 4, 5, 6, 8, and 9 show a consistent trend between suction, water content, and shear wave velocity where shear wave velocity increases as water content decreases and suction increases.

5.4 Shear Wave Velocity Results as Affected by Seasonal Variations in Moisture Content

The results from five of the nine sites examined using the SCPT during both the wet and dry seasons are analyzed and discussed in this section. These five sites consisted of a soil stratigraphy of mostly lean clay and fat clay soil (CL and CH). The field data, including measurements of shear wave velocity, water content and suction, were collected and analyzed to gain insights into behavior at each site. The trends and patterns observed at five of the nine sites in the data are discussed in detail, and the implications of these findings for understanding the soil properties and behavior at each site are considered. Five sites were chosen for analysis (Sites 4, 5, 6, 8 and 9) in this section based on the results observed between all the sites. Generally, the four sites not included in the analysis did not exhibit consistent trends between water content, suction and shear wave velocity. This could be attributed to natural variability in the soil profiles at these sites as well as variability in the wetting-drying process the soil was experiencing at the time of testing. Soil water content and suction are dependent on whether soil is experiencing wetting or drying depending on the hysteretic behavior in the SWCC.

Figures 24, 25, 26, 28 and 29 present the results from the site visits conducted on different dates, with the water content, suction, and shear wave velocity being plotted as a function of depth for the wet and dry season testing. A visual inspection of the data reveals some variability in the shear wave velocity measurements at each site. However, upon closer examination, a trend emerges. Specifically, the results show that the higher shear wave velocity values tend to correspond to drier soil conditions. This is particularly evident for Test Sites 4, 6, 8 and 9, but for Site 5 the seasonal change in moisture content did seemingly not have a large influence on the shear wave velocity. Possibly, the observed differences in water content and suction were not significant enough to cause a difference in shear wave velocity.

In general, shear wave velocity increases as the soil becomes drier, due to the increase in soil stiffness that typically accompanies a reduction in water content. Conversely, shear wave velocity decreases as the soil becomes wetter, due to the decrease in soil stiffness that typically results from an increase in water content. Additionally, the water content in the soil profiles for the first 2-3 meters was relatively different with higher water content observed during the wet season when compared to the dry season. Beyond the first 2-3 meters below the surface level, the water content generally remained relatively constant between the two visits. Overall, the water content in the soil profiles varied between the first and second visit at shallow depths but remained relatively stable at deeper depths.

Figure 30 presents shear wave velocity from the five sites plotted against the moisture content and suction. Trends observed in the data reveal the relationship between shear wave velocity, moisture content and suction. Specifically, the trend lines indicate that shear wave velocity decreases with increasing water content and increases with increasing suction.

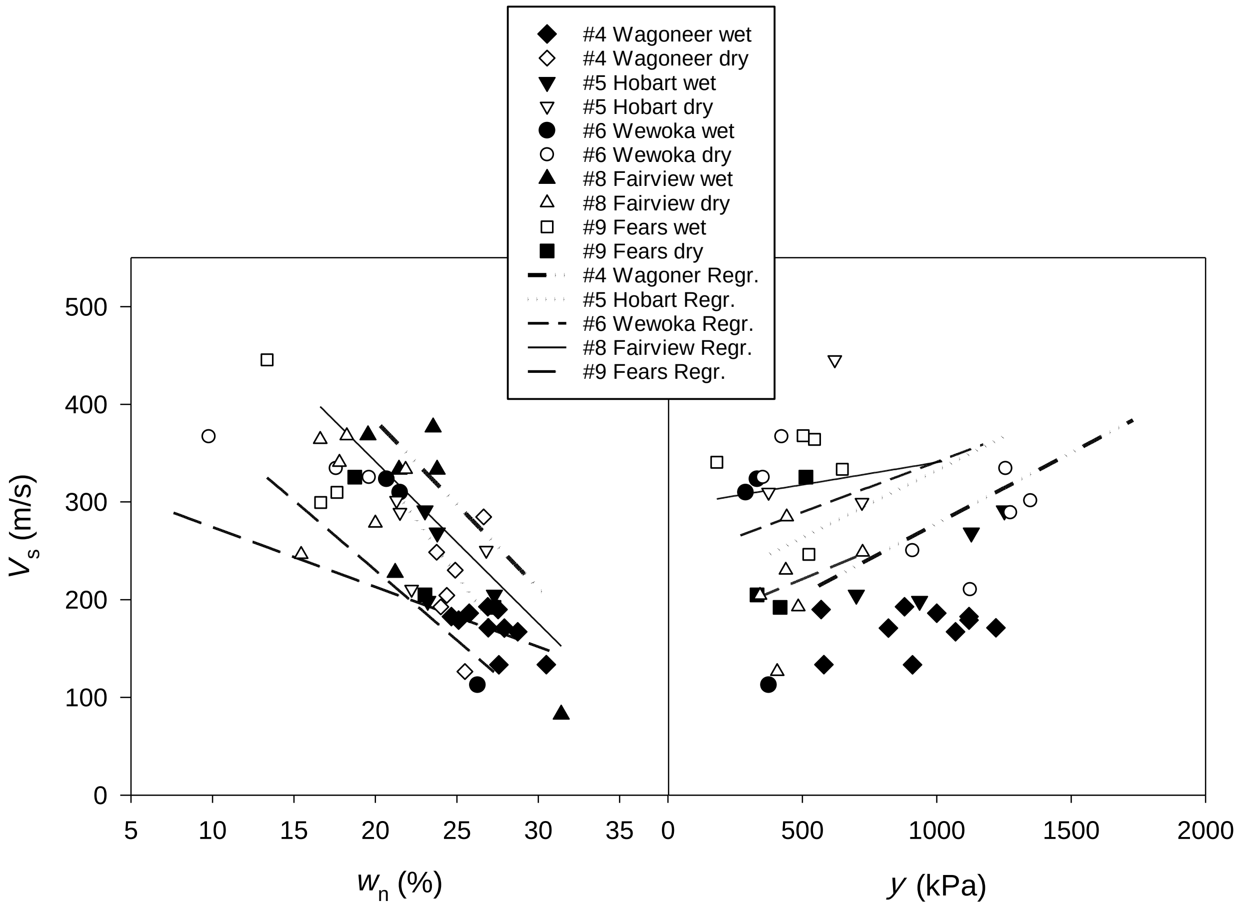

Figure 30. Shear wave velocity versus water content (left), and shear wave velocity versus suction (right) for Sites 4,5,6, 8 and 9.

To further quantify these relationships, regression lines were fitted to the data. These lines show the general direction and strength of the correlations between shear wave velocity and water content, as well as between shear wave velocity and suction. Results from the regression analysis including the equations and the coefficients of determination are shown in Table 20. Overall, although a lot of scatter in the data was observed, the results suggest that shear wave velocity is sensitive to changes in both water content and suction, with the direction and magnitude of the changes being determined by the specific soil conditions and types at each site. The scatter observed in the results could be attributed in part to the fact that in some sites there is a variation in soil type with depth.

Table 20. Regression analysis data for shear wave velocity versus water content and suction.

Site No.	Site Name	(V_s-w_n) r^2	(V_s-ψ) r^2	Equations w_n	Equations ψ
4	Wagoner	0.315	0.374	$Vs=726.9 - 17.1w_n$	$V_s=132.7+0.14\psi$
5	Hobart	0.107	0.322	$Vs= 580.2 - 7.1w_n$	$V_s=194.2+0.13\psi$
6	Wewoka	0.534	0.167	$Vs=474.1 - 9.9w_n$	$V_s=237.8+0.10\psi$
8	Fairview	0.646	0.019	$Vs= 673.3 - 16.6w_n$	$V_s=294.7+0.046\psi$
9	Fears Lab	0.958	0.700	$Vs= 302.9-4.1w_n$	$V_s=163.7+0.11\psi$

Table 21 below shows the variation in shear wave velocity for each site during wet and dry seasons as selected depths. These results demonstrate the significant changes in shear wave velocity that can occur when water content and suction change due to seasonal wetting and drying.

The results of this field study emphasize the importance of considering the influence of seasonal variations in moisture content on shear wave velocity in the active zone of the soil profile. For using shear wave velocity measurements in geotechnical analysis and design, a method of interpretation is needed to account for expected changes in moisture content and suction, particularly if the site has experienced dry conditions leading up to the time of testing. Chapter 7 presents a framework for interpreting shear wave velocity measurements in the field with consideration of changing moisture conditions.

Table 21. Variation in shear wave velocity at tested sites during wet and dry season for particular depths.

Site Number	Depth (m)	Shear wave velocity wet (m/s)	Shear wave velocity dry (m/s)	Water content wet (%)	Water content dry (%)	Suction wet (kPa)	Suction dry (kPa)
4	0.6	120	380	27	12	400	1200
5	2.0	190	250	29	22	500	1400
6	2.0	280	460	28	14	400	700
9	1.2	130	430	26	20	600	1700

Chapter 6: Comparison of Field and Laboratory Measurements of Shear Wave Velocity in Unsaturated Soils

6.1 Overview

This chapter presents and discusses the comparison of shear wave velocity measurements obtained by field and laboratory testing. Field measurements were made using the SCPTu and lab measurements were made using bender element testing on Shelby tube samples obtained from discrete depths within the soil profile.

6.2 Soil Properties and Soil Profiles

Sites 10-12 shown in Table 7 were tested by conducting the SCPT and retrieving disturbed and undisturbed samples from the field. These three sites are listed in Table 22. The soil property profiles including USCS group symbol, water content, plastic limit, liquid limit and percent of fines are shown in Figures 31-33. As depicted in Figures 31-33, the soils at these three sites were primarily low to moderately plastic silt and clay soils with varying amounts of sand.

Table 22. Location number, soil types, and location of the tested sites in Oklahoma.

Location Number	Soil Types	Location
10	Mixed clays, and silty clays	Oklahoma City
11	Mixed clays, and silty clays	Tuttle
12	Mixed clays, and silty clays	Norman

6.3 SCPT and Bender Element Comparison Results

Shear wave velocity results and water content measurements are shown in Figures 31-33. Shear wave velocity determinations from the SCPT and the bender element method are plotted side by side for comparison. Values from the SCPT represent the average shear wave velocity value for the 1-meter layer above the plotted point, whereas the values from the lab were determined on a 75-mm long sample from the test depth. Thus, the comparison is not exact in that it involved averages over different soil depths. For each site, SCPT measurements are shown using closed triangle symbols and bender element measurements are shown using open triangle symbols. Water content data correspond to the values at the test depths on the SCPT testing date, which was determined using soil samples collected in the field on the testing date. Results in Figures 31-33 show that there was a variation in the water content along the soil profile. Also, shear wave velocities measured using the SCPT varied along the tested soil profiles in a manner that mirrored the water content profile.

Moreover, SCPT and bender element shear wave velocity measurements were nearly identical along the soil profile for Sites 10 and 11. For Site 12 small differences were found in the results between SCPT measurements and bender element measurements, where the first measurement was higher using the SCPT while the rest of the measurements were slightly higher using the bender element method. For the shallowest depth, this is likely due to fact that SCPT values represent the average for the first 1-m of soil where water content variations were probably relatively larger in the case of Site 12. The remaining differences may also be attributed to the differences in measurement depth ranges involved in each of the test methods, and natural variability in the soil profile.

The results of the comparison of field and laboratory measurements are important in that they suggest the shear wave velocity determined from SCPT testing provides meaningful accurate measurements of shear wave velocity relative to those measured under controlled laboratory conditions. This is important because it suggests that shear wave velocities can be reliably determined using different methods and lends credibility to the use of SCPT and bender element testing for determination of shear velocity for geotechnical engineering applications.

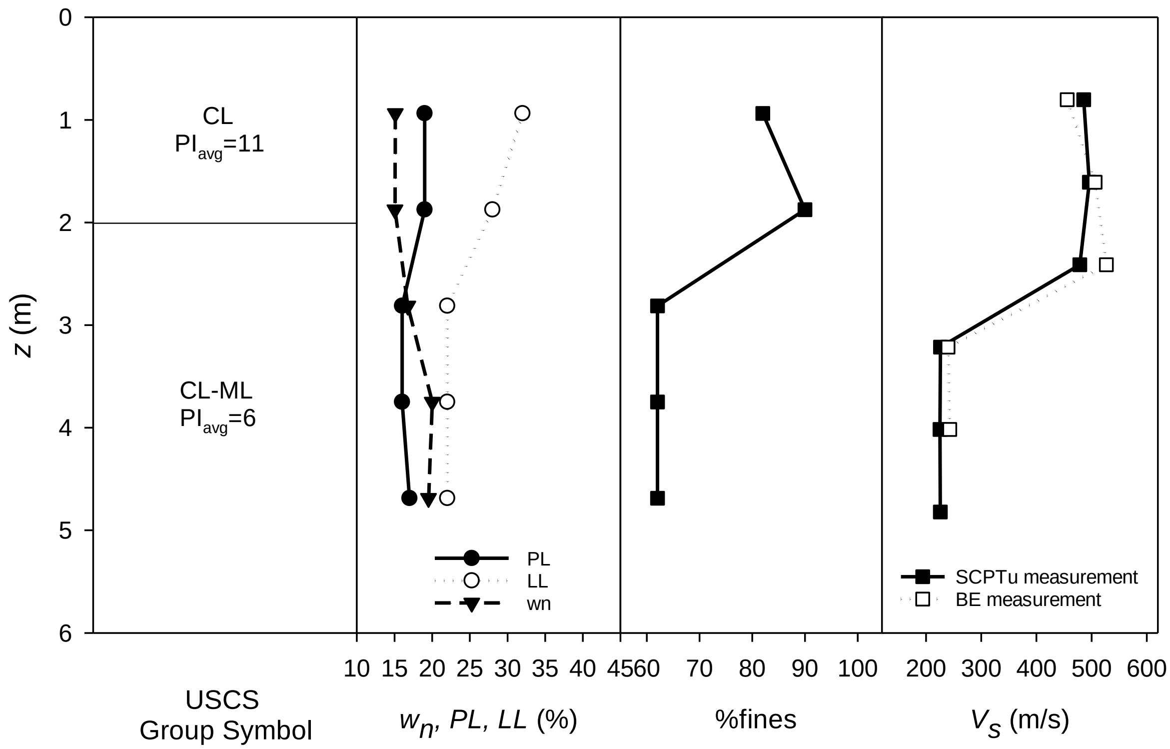

Figure 31. Water content and shear wave velocity results for tests conducted at Site 10. The figure shows shear wave velocity measurements using both the SCPT and bender element methods.

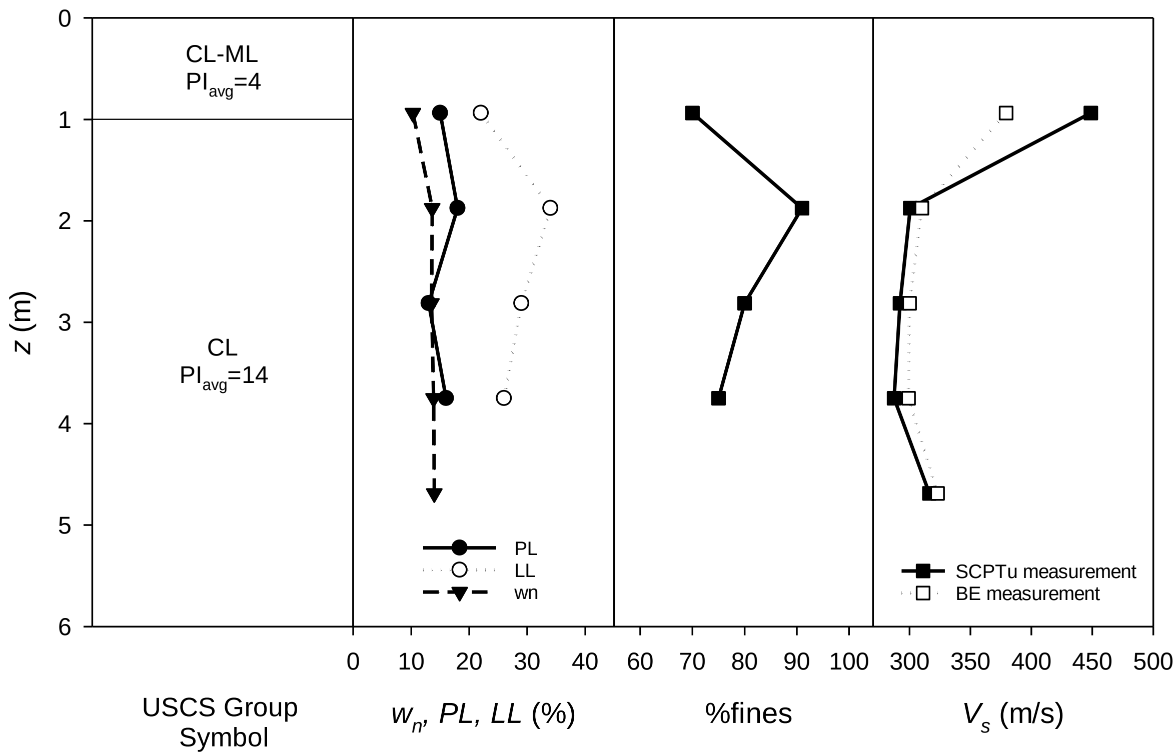

Figure 32. Water content and shear wave velocity results for tests conducted at Site 11. The figure shows shear wave velocity measurements using both the SCPT and bender element methods.

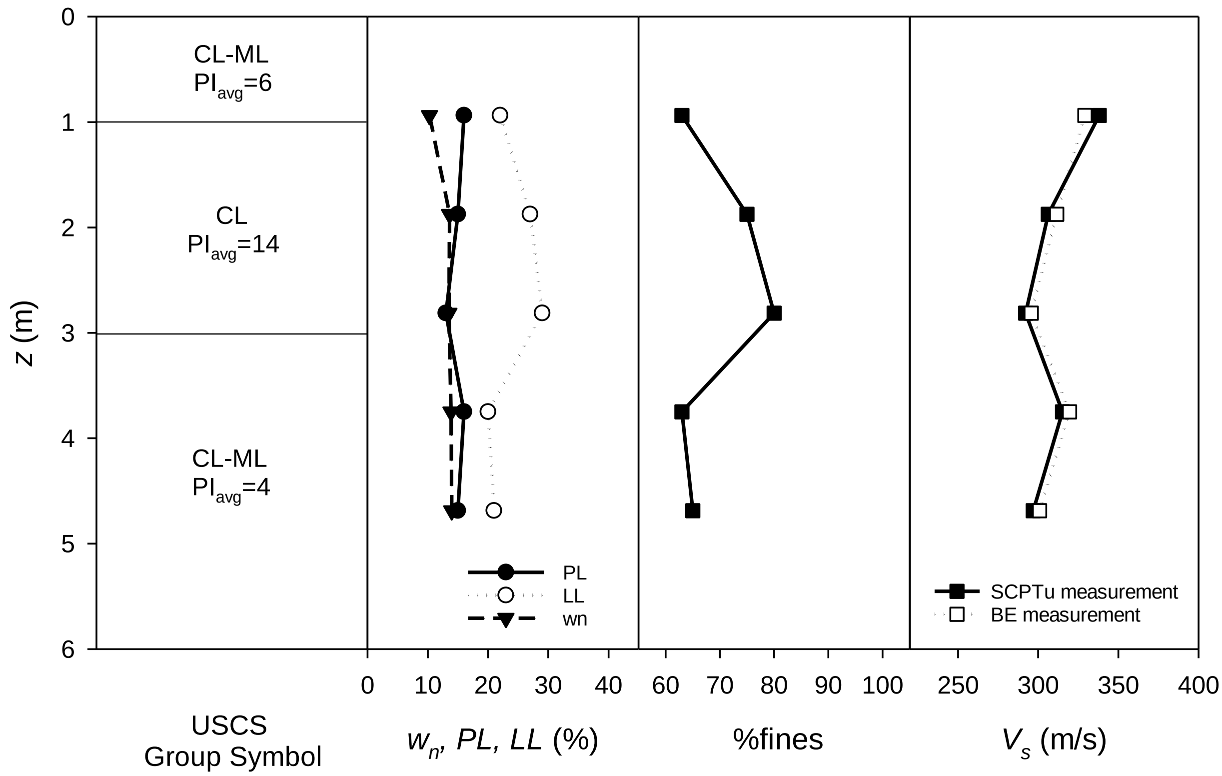

Figure 33. Water content and shear wave velocity results for tests conducted at Site 12. The figure shows shear wave velocity measurements using both the SCPT and bender element methods.

6.4 Bender Element Results for Wet and Dry Samples

Water content, suction, and shear wave velocity measurements for soil samples tested at various moisture conditions are shown in Figures 34-36. Closed circles, open circles, and closed triangles were used to represent in-situ, dry, and wet conditions, respectively.

Results show a variation in water content, suction, and shear wave velocity as degree of saturation changes. For all three sites, the shear wave velocities under dry conditions were higher than in-situ and near saturated conditions. Hence, as water content decreases and suction increases, shear wave velocity increases. Additionally, results show that in-situ conditions were closer to wet conditions, which indicates that the SCPTs were conducted during a wetter season.

It was noticed that there was a major difference between measurements taken during wet and dry conditions. For example, for Site 11 the wet shear wave velocity was around 280 m/s along the soil profile while dry shear wave velocity was around 630 m/s. This is an important observation since the change between wet and dry conditions may affect the seismic site class of the tested soil, i.e., soil moved from class D to class C as soil dried. However, the actual seismic site class would depend on the shear wave velocity in the upper 30.5 m of the soil profile. Thus, the seismic site class may not change from D to C due to drying, but it could, depending on the average seismic velocity for the 25.5 m of soil underneath the 5 m deep profile considered here. Thus, it is important to consider the moisture conditions when investigating the shear wave velocity using the SCPT in unsaturated soil profiles.

Additionally, the dry unit weight of the soil samples was obtained by determining their volume and computing the unit weight based on the total weight and measured water content. It's worth noting that the changes in water content could impact dry unit weight due to shrinking and swelling. These results verify the investigated behavior of shear wave velocity versus density which was mentioned in chapter 4. Changes in dry unit weight, in turn, can have a significant effect on the shear wave velocity of the soil. As dry unit weight increases, the stiffness of the soil also increases, leading to a corresponding increase in the shear wave velocity. Conversely, as dry unit weight decreases, the soil becomes less stiff, resulting in a decrease in the shear wave velocity. Table 23 presents the results of the measurements of the dry unit weight of the soil tested for Site 10. Similar results were observed for the other test site soils.

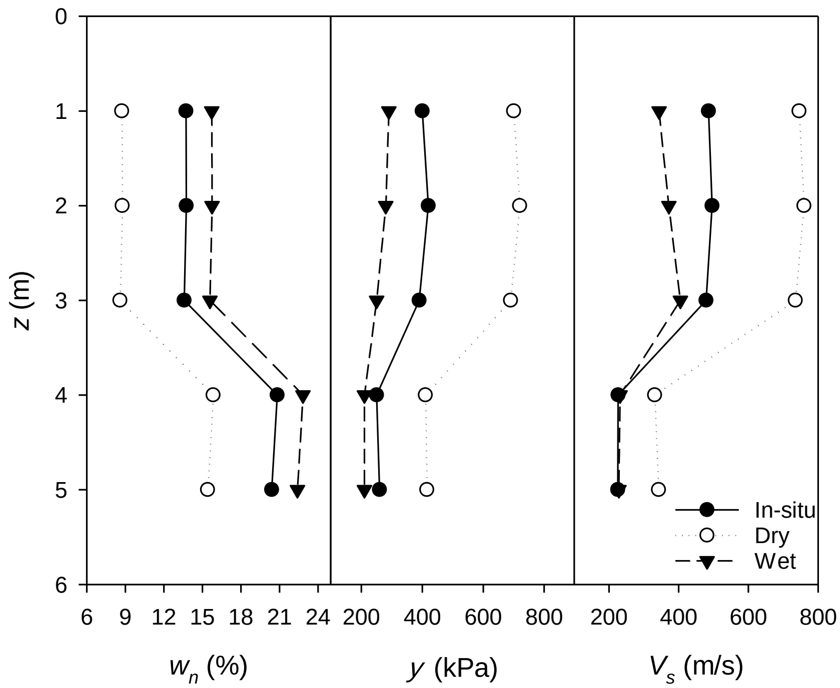

Figure 34. Soil profile showing water content, suction, and shear wave velocity results for Site 10 under in-situ, dry, and wet saturation conditions.

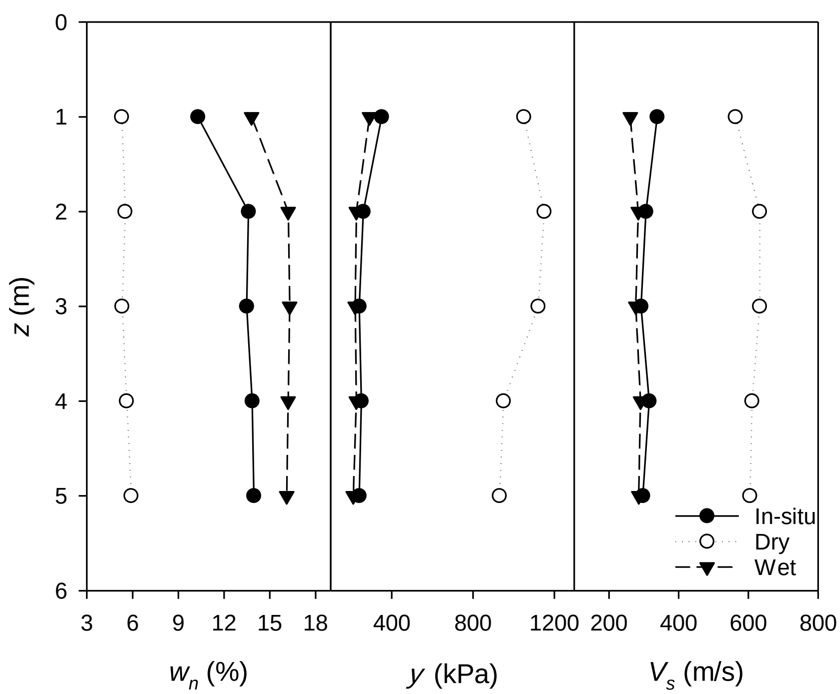

Figure 35. Soil profile showing water content, suction, and shear wave velocity results for Site 11 under in-situ, dry, and wet saturation conditions.

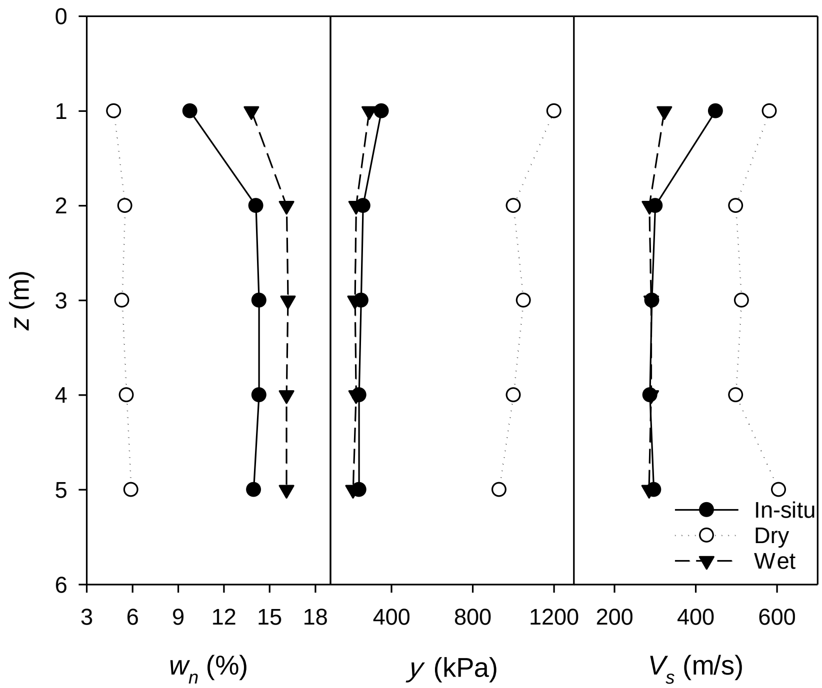

Figure 36. Soil profile showing water content, suction, and shear wave velocity results for Site 12 under in-situ, dry, and wet saturation conditions.

Table 23. Dry unit weight for soils tested at Site 11 at in situ, dry, and wet conditions.

Depth (m)	Soil type	Dry unit weight (in situ condition) (kN/m^3)	Dry unit weight (Dry condition) (kN/m^3)	Dry unit weight (Wet condition) (kN/m^3)
1	CL-ML	15.44	15.99	15.06
2	CL	14.94	15.21	14.58
3	CL	15.04	15.29	14.67
4	CL	14.87	15.54	14.28

Chapter 7: Proposed Model

7.1 Model Theory and Analysis

By analyzing the relationships mentioned in the previous sections, it is noticed that in general, changes in soil suction and confining stresses control the behavior of shear wave velocity. In this chapter a model is developed to predict shear wave velocity in unsaturated soils taking into consideration the soil properties studied previously. The aim of this model is to predict the changes in shear wave velocity in the field in a soil profile due to changes in water content and suction.

Multiple formulations have been proposed to calculate the dynamic properties of soils. For shear wave velocity, Santamarina et al. (2001) proposed a power relationship to define shear wave velocity using effective stress for saturated soils as shown in Equation 14.

$$V = A\left(\frac{\sigma'_o}{1\ \text{kPa}}\right)^{\beta} \tag{14}$$

Where A and β are experimentally determined fitting parameters.

Similarly, factors affecting shear modulus, *G*, were studied by some researchers (Hardin and Black 1968, Marinho et al. 1995, Mancuso et al. 2002, Inci et al. 2003, Kim et al. 2003, Mendoza et al.2005, Sawangsuriya et al. 2009, Ng et al. 2009, Khosravi and McCartney 2012, Oh and Vanapalli 2014). A power relationship was established for saturated and dry soils by Hardin and Richart (1963) and Hardin and Drnevich (1972), as shown in Equation 15.

$$G = A\text{f}(e)(\sigma')^{n} \tag{15}$$

where *A* and *n* are fitting parameters, f(*e*) is a function of the void ratio defined by $\text{f}(e) = \frac{1}{0.3+0.7e^2}$, and σ' is the effective stress.

By comparing the shear wave velocity and the small-strain shear modulus *G*, it was observed that both properties have similar stress dependencies, and are affected by similar factors (saturation, density, type of soil, suction, and confining stresses), hence, using a power equation to define shear wave velocity is a reasonable assumption. The model proposed by Hardin and Richart (1963) and Hardin and Drnevich (1972) was used to estimate changes in the shear wave velocity in unsaturated soils by Sawangsuryia (2006). Equation 16 shows the power model used by Sawangsuriya to measure shear wave velocity in unsaturated soils, this model uses the power model proposed by Hardin and Richart (1963). For unsaturated soils, Bishop's effective stress equation was incorporated in the model. Bishop's definition of effective stress is shown in Equation 17.

$$V_s = \mathrm{A}((\sigma_o - u_a) + \chi(u_a - u_w))^{\beta} \qquad (16)$$

$$\sigma' = (\sigma_o - u_a) + \chi(u_a - u_w) \qquad (17)$$

Where A and β are fitting parameters and χ is the effective stress parameter.

Bishop (1958) proposed parameter χ was equal to the degree of saturation *S*. Although this assumption is acceptable, it does not accurately describe the soil behavior near dry conditions and for fine soils (Lu and Likos 2006). Figure 37 below shows the results of shear wave velocity versus effective stress for the data measured in this study. The shear wave velocity measured in the lab was plotted against the effective stress calculated using the Bishops's definition of effective stress in unsaturated soils. Additionally, the power regression lines were plotted to show the accuracy and variability of the power model using Bishop's effective stress definition. This graph indicates that the shear wave velocity is not uniquely related to the Bishop effective stress because it is also dependent on the suction. Hence, a different model for effective stress may be needed to uniquely correlate shear wave velocity to effective stress. Table 24 shows the r-squared values and the parameters A and β extracted from the plots in Figure 37.

Table 24. Power regression results for shear wave velocity versus confining stress.

Figure No.	Confining pressure (kPa)	r^2 value	Parameter A	Parameter β
36 a)	0	0.980	36.7	0.29
36 a)	25	0.983	37.8	0.28
36 a)	50	0.988	40.2	0.26
36 a)	100	0.954	41.1	0.24
36 b)	0	0.971	30.2	0.36
36 b)	25	0.978	42.2	0.31
36 b)	50	0.977	52.2	0.27
36 b)	100	0.894	64.1	0.22

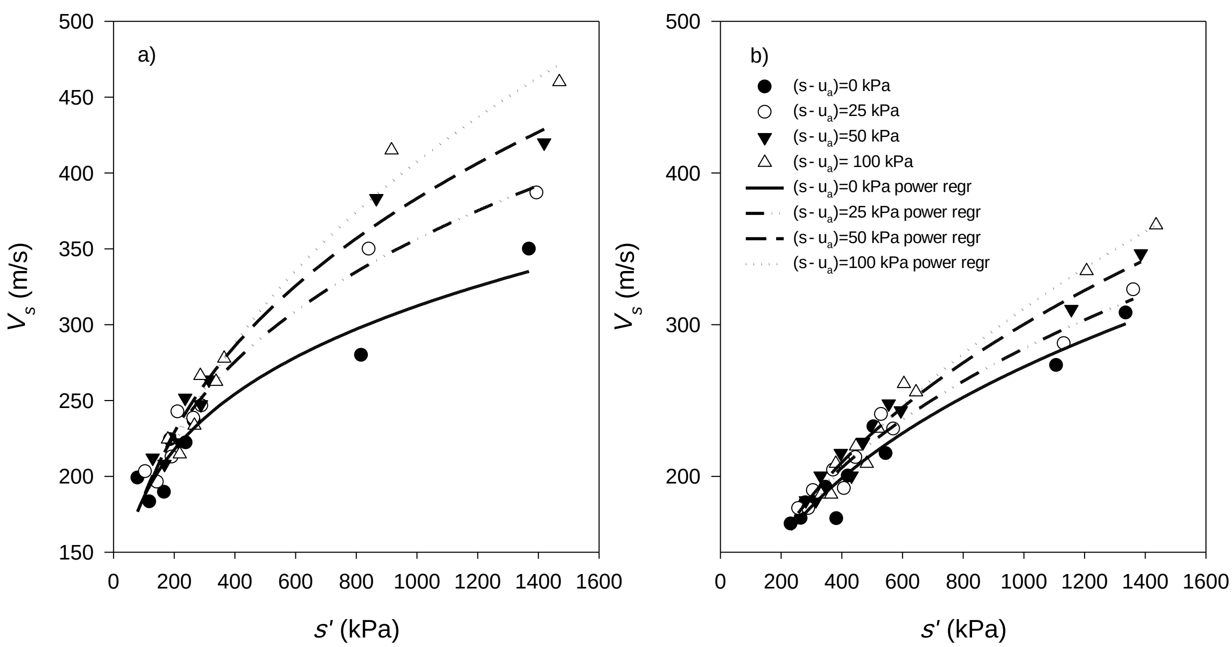

Figure 37. Shear wave velocity versus effective stress using Bishop's (1956) definition of stress parameter χ: a) results from specimens compacted at +4% OMC and b) results from specimens compacted at -4% OMC. Regression lines represent a power equation having the same form as Eq. 16.

The challenge of defining the effective stress parameter χ has been a problem addressed by many researchers, multiple definitions have been proposed (e.g. Vanapalli et al. 1996 b, Oberg and Sallfors 1997, Khalili and Khabbaz 1998, Lu and Likos, 2006, Lu et al., 2009, 2010, Oh et al., 2012). To distinguish between the contributions of matric suction and confining stresses on the effective stress, the suction stress σ_s concept was proposed by Lu and Likos (2006). Additionally, Lu et al. (2009, 2010), and Oh et al. (2012, 2013) implemented this concept in their studies. The suction stress is used to describe the changes that happen in the effective stress due to changes in soil saturation, as shown in Equations 18 and 19:

$$\sigma' = (\sigma - u_a) + \sigma_s \tag{18}$$

where σ_s is as

$$\sigma_s = -(u_a - u_w)\theta_e \tag{19}$$

where the effective saturation $\theta_e = \frac{1}{1+[\alpha(u_a-u_w)]^n}^{1-\frac{1}{n}}$. Parameters α and n are fitting parameters related to unsaturated soil properties, with $\alpha = 1/u_b$, where u_b is the air entry pressure for saturated soil, and n is a parameter related to the pore size of the soil.

This definition of the suction stress generalizes the effective stress proposed by Bishop (1958). The suction stress is used to define the contribution of matric suction to the effective stress, which considers the interparticle stress mechanism in unsaturated soils. Using this definition of effective stress based on suction stress, the shear wave velocity can be represented by the power model shown in Equation 20.

$$V_s = A((\sigma_o - \mathrm{u}_a) + (\mathrm{u}_a - \mathrm{u}_w)\left[\left(\frac{1}{1+[\alpha(u_a-u_w)]^n}\right)^{\left(1-\frac{1}{n}\right)}\right]^\beta \tag{20}$$

Where A and β are fitting parameters.

The fitting parameters A and β used in Equations 20 were defined in the literature (Sawangsuriya 2006). Parameter A reflects the soil structure or the fabric of the soil (which is unique for every soil type) and parameter β represents the contact effect between the soil particles, which reflects the porosity, void ratio, and shape of the particles.

To calculate the suction stress, parameters α and *n* were assumed based on the properties of the soil. For the data presented in Figure 38, parameter α was estimated using the air entry pressure u_b determined using the Zapata et al. (2000) SWCC. Parameter *n* was chosen based on the data mentioned in the literature for various types of soil (Lu et al. 2010, Oh and Lu 2013); the value of *n* was found to range between 1.05-1.65. Using data found in the literature for parameter *n*, two graphs were developed to estimate the value of *n* using either the void ratio (*e*) or the plasticity index (PI). Figure 39 shows the graphs and equations developed to estimate parameter *n*. A summary of soil properties and parameter *n* found in the literature is shown in Table 25.

Table 25. Parameter *n* found in the literature.

Type of soil	**PI (%)**	**Parameter u_b (kPa)**	**Parameter *n***	**Void ratio (*e*)**	**Author (s)**
Kaolin	33	395	1.2	-	Lu et al
Jossigny Silt	18	182	1.54	-	Lu et al
Yellow Colluvium	22	54	1.62	-	Lu et al
Hume Dam Clay	12	77	1.37	-	Lu et al
Barcelona Silt	16	15	1.13	-	Lu et al
Glacial till	18	41	1.46	-	Lu et al
Mature residual soil	18	38	1.63	-	Lu et al
Esperance Sand	-	-	1.05	-	Lu et al
Hopi Silt	13	-	1.58	0.72	Oh and Lu
Bonny Silt	4	-	1.52	0.9	Oh and Lu
BALT silt	6	-	1.65	0.67	Oh and Lu
Missouri Clay	-	-	1.44	0.67	Oh and Lu
Denver Claystone	18	-	1.38	-	Oh and Lu

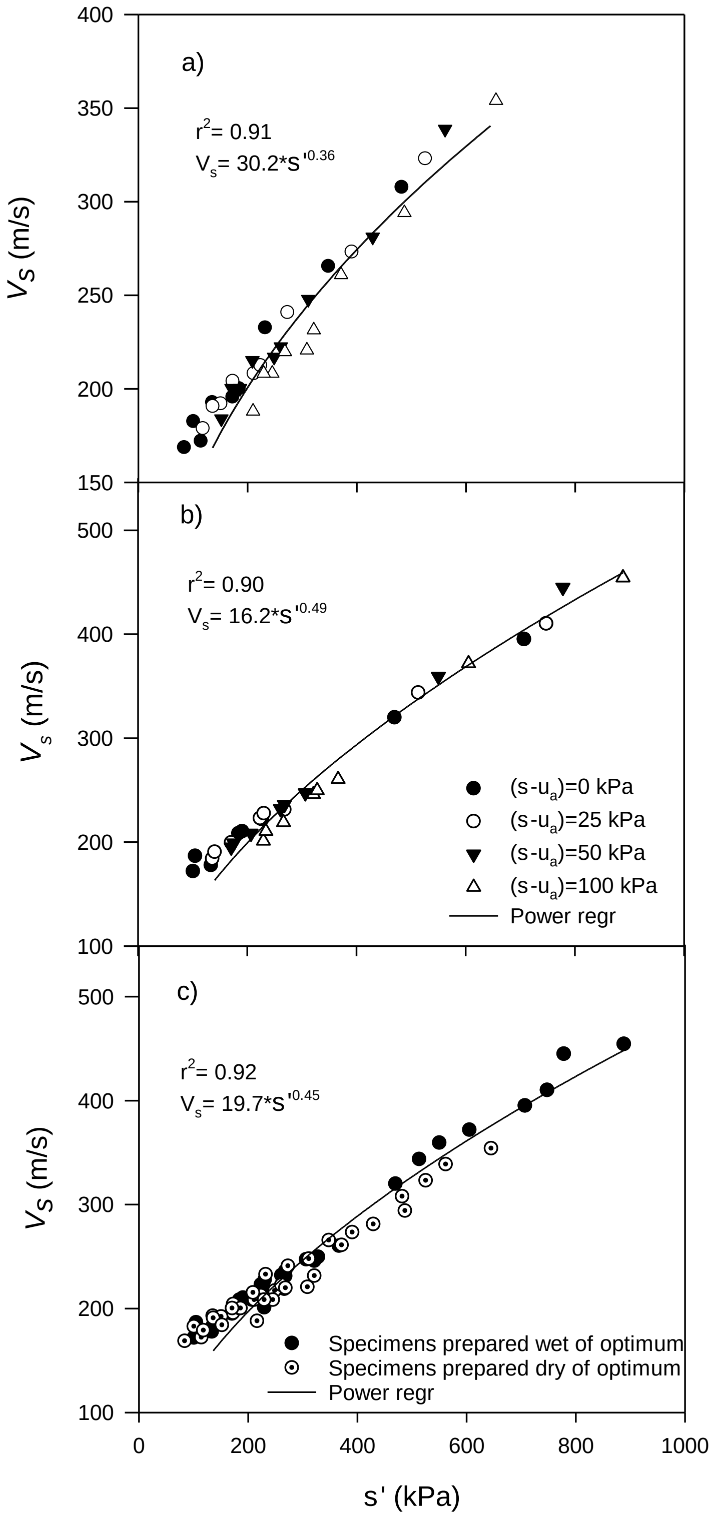

Figure 38. Shear wave velocity versus effective stress using Lu et al. (2006) definition of suction stress σ_s: a) results from specimens compacted at -4 OMC, b) results from specimens compacted at +4 OMC and c) combined results.

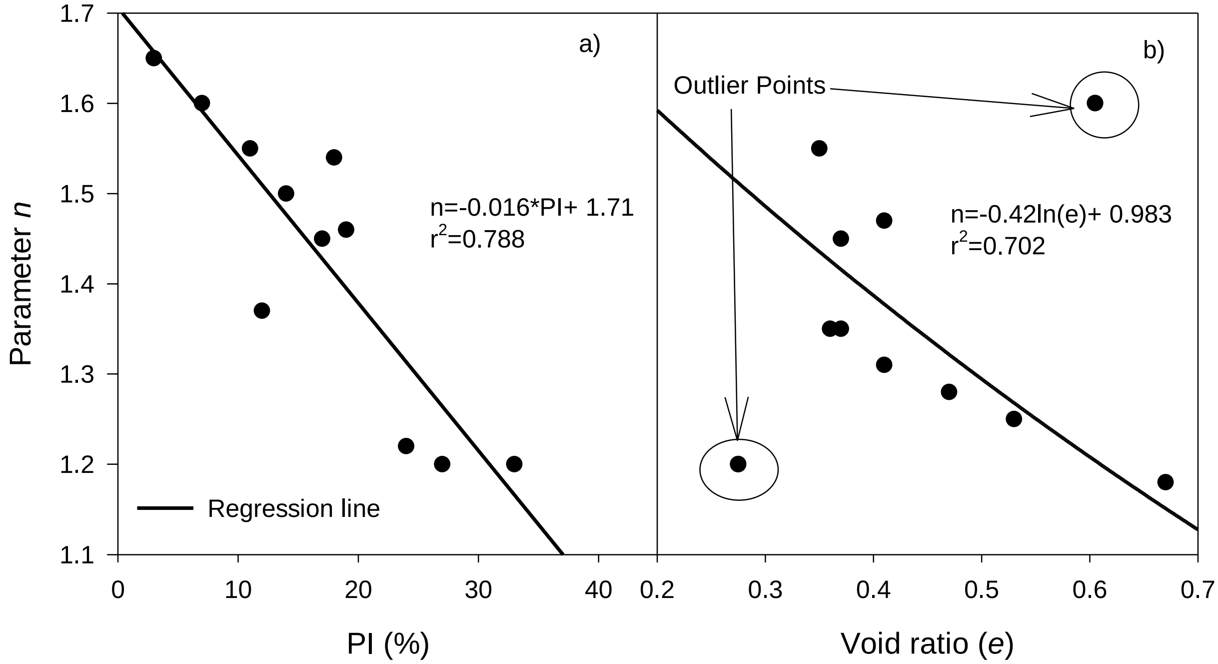

Figure 39. Correlations between different soil properties and parameter *n* based on data extracted from the literature: a) results for *n* versus plasticity index (PI), and b) results for *n* versus void ratio (*e*).

A stronger correlation was observed between the plasticity index and parameter *n* when compared to the void ratio. The relationship between *n* and PI is assumed to be linearly decreasing where parameter *n* decreases as PI increases. For the void ratio, parameter *n* decreases nonlinearly as the void ratio increases. Table 24 shows the values used for α (estimated using the SWCC) and *n* (estimated using the results found in the literature) at different void ratios during testing.

Table 26. Parameters α and *n* for different confining stresses as found in the literature (Lu et al. 2010).

Confining stress (kPa)	Air entry pressure u_b (kPa)	Estimated α using SWCC results	Estimated *n* using (Lu et al. 2010)	Void ratio
0	2	0.5	1.25	0.531
25	5	0.2	1.28	0.471
50	10	0.1	1.31	0.412
100	17	0.06	1.34	0.367

Using the Lu and Likos (2006) definition of effective stress via Equation 18 to model the relationship between shear wave velocity and effective stress it is seen that the shear wave velocity versus effective stress curves collapsed onto a single curve that could be used to uniquely define the shear wave velocity as shown in Figure 38. The model appears to follow the trend of the measured data; however, further examinations reveals that the model tends to be less accurate at relatively low effective stresses. As a result, an alternative model may be more appropriate to fit the data represented.

Although the proposed power model based on the Lu and Likos (2006) effective stress concept is a satisfactory model for the measured data, a closer correlation was observed when utilizing a linear model instead. The definition of effective stress put forward by Lu and Likos (2006) was employed in Equations 21 and 22, as illustrated below.

$$V_s = m * \sigma' + V_{so}, \qquad (21)$$

$$V_s = m\left((\sigma_o - u_a) + (u_a - u_w)\left[\left(\frac{1}{1+[\alpha(u_a-u_w)]^n}\right)^{\left(1-\frac{1}{n}\right)}\right]\right) + V_{so} \qquad (22)$$

Where m and V_{so} are fitting parameters.

Parameter m is the slope of the graph which portrays the influence of changing effective stress on shear wave velocity. The parameter V_{so} is defined as the intercept of the y-axis (shear wave velocity-axis) which corresponds to the shear wave velocity at near zero effective stress. These parameters are dependent on the soil type and soil properties.

As depicted in Figure 40, the shear wave velocity data are fitted with a linear model using linear regression. Utilizing the parameters of α and n outlined in Table 26, effective stress was calculated during the analysis. The linear relationship seemingly is a better fit to the data in comparison to the power relationship, as demonstrated by the graphical representation in the figure and the calculated r-squared values of the proposed regressions as shown in Table 27.

Table 27. r-squared comparison between linear and power regression for Lu et al. (2006).

Compaction method	r^2- Linear regression	r^2- Power regression
Wet of optimum	0.987	0.984
Dry of optimum	0.967	0.926
Combined	0.977	0.957

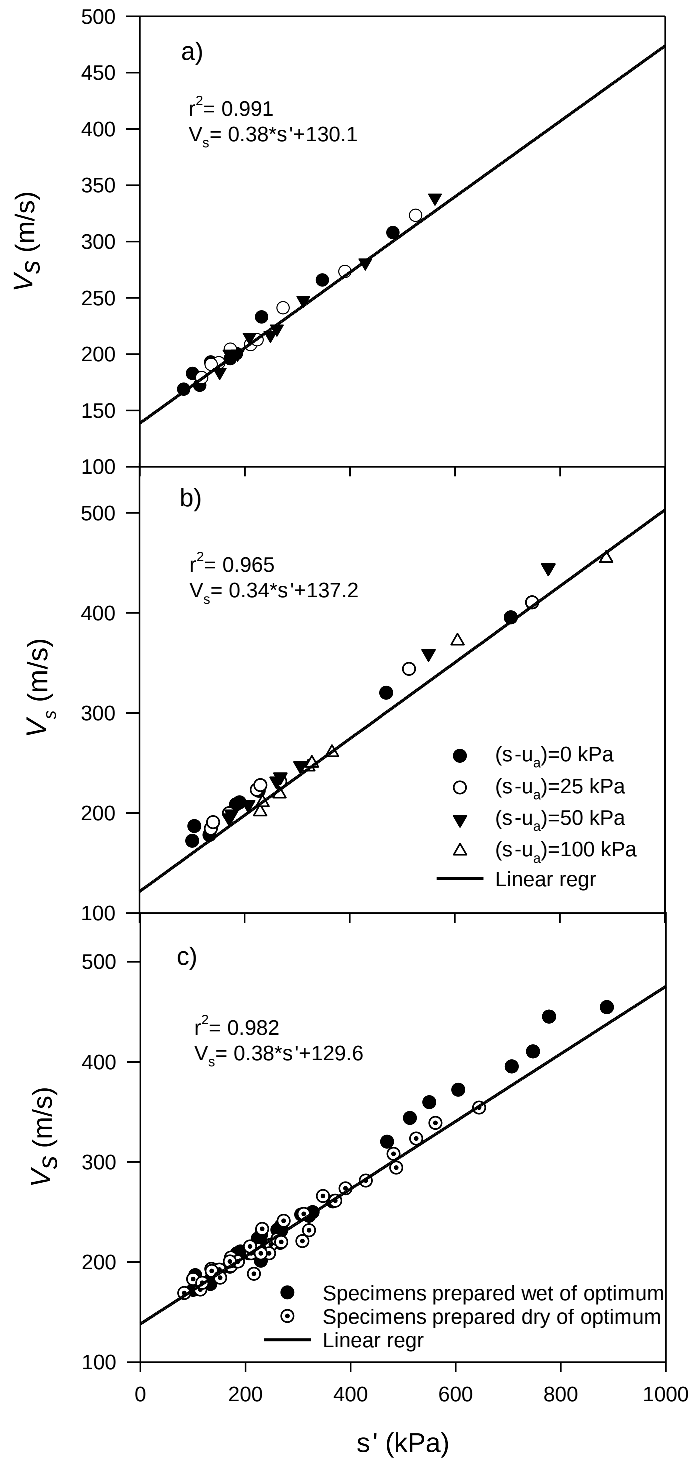

Figure 40. Shear wave velocity versus effective stress using Lu and Likos (2006) definition of suction stress σ_s: a) results from specimens compacted at -4 OMC, b) results from specimens compacted at +4 OMC and c) combined results.

7.2 Development of the Linear Model

Data collected in the lab during this study and data found in the literature were used to develop and validate the proposed model. Results from laboratory testing were best fitted with a linear model as shown in Figures 41-43. Additionally, the best fit power regression curves are shown for comparison. The parameters chosen for calculating the effective stress parameters α and n were determined using the SWCC estimated using Zapata et al. (2000) and results proposed in Figure 39 based on PI.

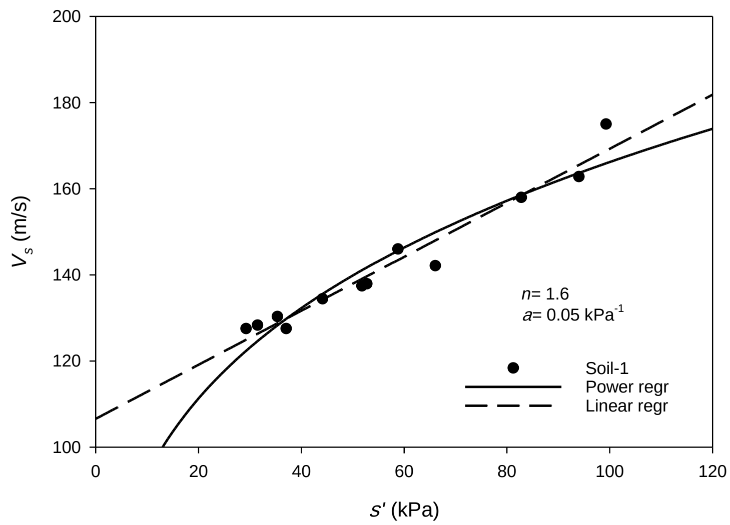

Figure 41. Shear wave velocity versus effective stress (solid points) for Soil-1 using Lu and Likos (2006) definition of effective stress along with the linear and power best fit regression lines.

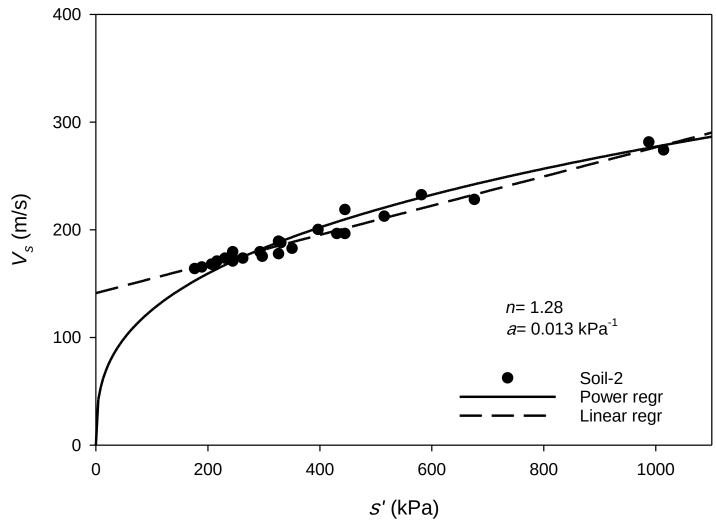

Figure 42. Shear wave velocity versus effective stress (solid points) for Soil-2 using Lu and Likos (2006) definition of effective stress along with the linear and power best fit regression lines.

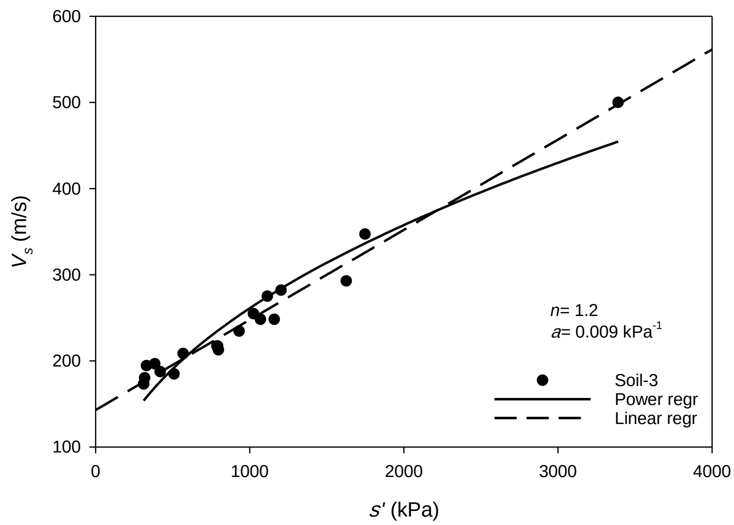

Figure 43. Shear wave velocity versus effective stress (solid points) for Soil-3 using Lu and Likos (2006) definition of effective stress along with the linear and power best fit regression lines.

Results presented in Figures 41-43 show the variation between the power and linear approach to modeling the shear wave velocity. The linear regression line tends to estimate the changes in shear wave velocity more precisely than the power regression.

Shear wave velocity data found in the literature (Sawangsuriya 2006, and Dong and Lu 2016) were used to further develop and test the proposed model. Sawangsuriya (2006) and Dong and Lu (2010) conducted bender element testing on various soil types; properties of the tested soils are shown in Table 28. Figures 44 and 45 show the measured shear wave velocity data (solid points) and the best fit linear and power regression lines. The parameters extracted from the analysis are shown in Table 29.

Table 28. Soil properties found in the literature including USCS classification, Liquid limit, Plasticity Index, and percent of fines for studies conducted by Sawangsuriya 2006 and Dong and Lu 2016.

Sawangsuriya 2006					
Soil type	Figure Number	USCS	Liquid limit (%)	Plasticity index (%)	Fines (%)
Clayey sand	44 a)	SC	28	11	41
Silt	44 b)	ML	28	14	88.1
Lean clay	44 c)	CL	42	24	91.1
Dong and Lu 2016					
Soil type	Figure Number	USCS	Liquid limit (%)	Plasticity index (%)	Fines (%)
Claystone	45 a)	CH	63	18	-
Hopi Silt	45 b)	SC	36	13	-

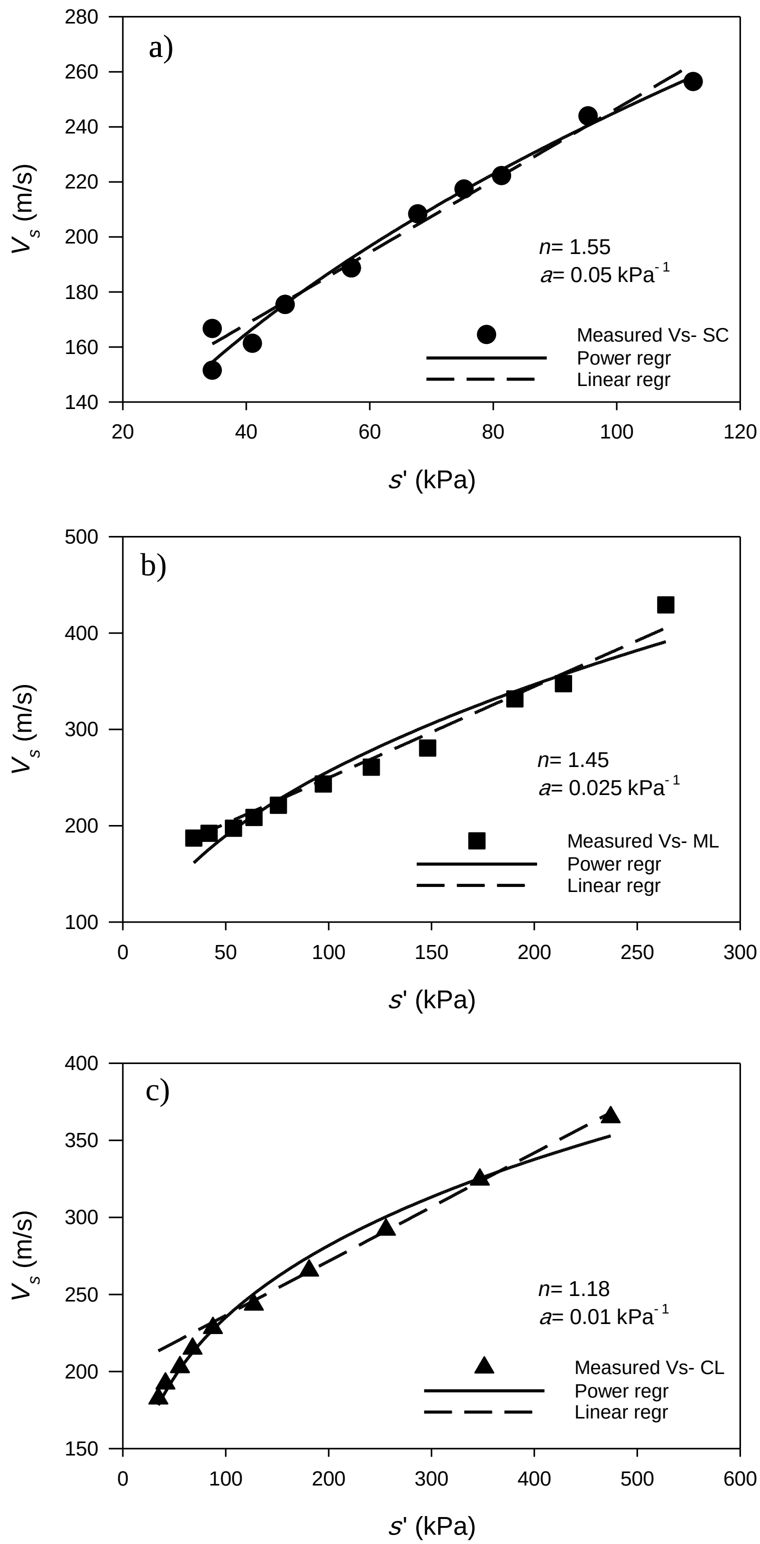

Figure 44. Measured shear wave velocity data from Sawangsuriya 2006 fitted along with the linear and power best fit regression lines for various soils. Parameters *n*, and α are shown on the graphs.

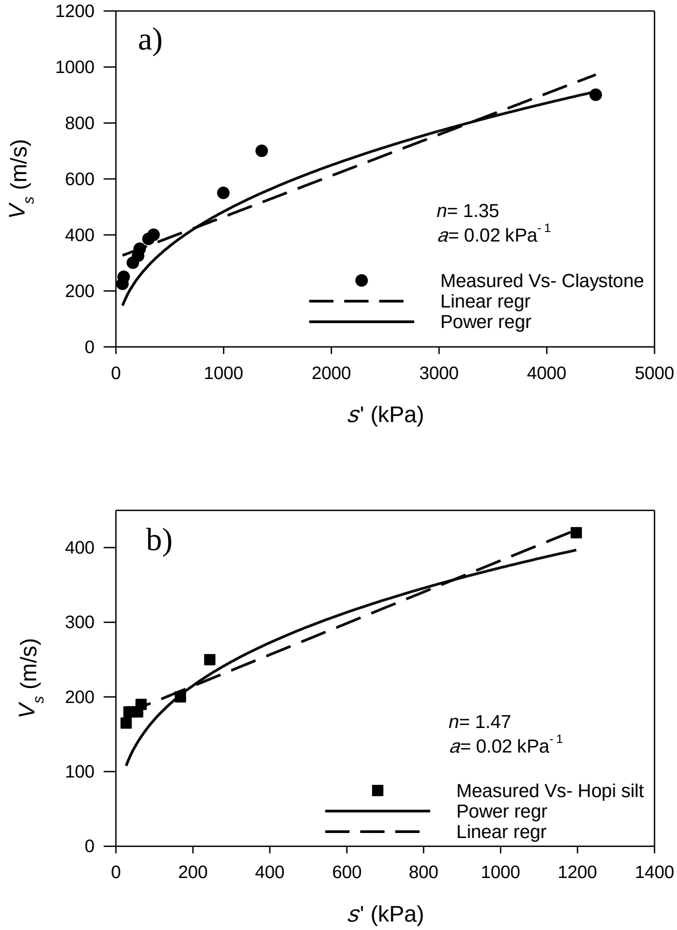

Figure 45. Measured shear wave velocity data from Dong and Lu 2016 along with the linear and power best fit regression lines for various soils. Parameters *n*, and α are shown on the graphs.

For the Sawangsuriya (2006), the linear regression appears better for SC and ML soils while the power regression appears to be better for the CL soil. Similar results were found for Dong and Lu (2011) where the linear regression is better fitted with the SC soil and the power regression is better fitted for the CL soil.

Table 29 illustrates the variations in the goodness of fit between power regression and linear regression through the presentation of r^2 values. It is worth noting that the power model estimates that the shear wave velocity is very close to zero as the effective stress approaches zero, whereas the linear model does not exhibit this behavior. This is an important point since test results showed that the measured shear wave velocity is not equal to zero even near zero effective stresses (Kwon and Cho 2005, Dong and Lu 2011). This is attributed to the dependency of shear wave velocity on multiple microscale factors including effective stress, suction, and stiffness of the soil. When the effective stress is close to zero, it means that the pore water pressure is nearly equal to the total stress applied to the soil. However, this does not imply that the shear wave velocity is zero because the material properties of the soil still play a significant role in determining the velocity of shear waves. Shear wave velocity depends on the stiffness and density of the soil material. Even in cases where the effective stress is close to zero, the soil particles still have some inherent stiffness and density, and this contributes to the propagation of shear waves. In other words, the material itself has a natural resistance to shearing forces, which allows shear waves to travel through the soil.

Additionally, the presence of soil particles and their interlocking nature creates a certain degree of internal friction and cohesion, which also contributes to the shear wave velocity. These properties are not solely dependent on the effective stress but are intrinsic to the soil material. Hence it may be better to use the proposed linear model in place of the power model in some cases. An exploration into the variability of models reveals the possibility of the influence of clay mineralogy on shear wave velocity. Limited research has been dedicated to understanding the impact of clay mineralogy on shear wave velocity. Initial findings suggest that different clay types (such as kaolinite, illite, montmorillonite, among others) have different effects on shear wave velocity owing to their distinct crystal structures and elastic properties (Wood and Wightman 1972, Hayashi and Inoue 2007). However, a conclusive understanding is yet to be established.

Table 29. r-squared values for data plotted in Figures 41-45 for the power regression and linear regression analyses.

Soil Type	Power Regression, r^2	Linear Regression, r^2	Power Equation	Linear Equation
Soil-1	0.90	0.95	$V_s=16.2*\sigma'^{0.49}$	$V_s=0.39*\sigma'+130.1$
Soil-2	0.91	0.97	$V_s=30.2*\sigma'^{0.36}$	$V_s=0.34*\sigma'+137.2$
Soil-3	0.92	0.98	$V_s=19.7*\sigma'^{0.45}$	$V_s=0.38*\sigma'+129.6$
Sawangsuriya (SC)	0.97	0.99	$V_s=33.8*\sigma'^{0.43}$	$V_s=1.3*\sigma'+112.5$
Sawangsuriya (ML)	0.93	0.97	$V_s=42.9*\sigma'^{0.39}$	$V_s=1.0*\sigma'+144.6$
Sawangsuriya (CL)	0.98	0.94	$V_s=73.8*\sigma'^{0.25}$	$V_s=0.4*\sigma'+183.9$
Dong and Lu (Claystone)	0.98	0.84	$V_s=58.5*\sigma'^{0.32}$	$V_s=0.14*\sigma'+318.4$
Dong and Lu (Hopi silt)	0.92	0.98	$V_s=74.8*\sigma'^{0.22}$	$V_s=0.21*\sigma'+172.6$

The fitting parameters *m* and V_{so} were plotted against different soil properties for the tested soils; Soil-1, 2 & 3 from this study, and soil tested by Sawangsuriya (2006), and Dong and Lu (2011). Figure 46 presents parameters m and V_{so} plotted against plasticity index and percent of fines. A general trend observed is that parameter V_{so} increases linearly with the plasticity index and percent of fines, while the parameter *m* decreases exponentially as the plasticity index and percent of fines increase.

In the case of parameter V_{so}, an increase in plasticity and the percentage of fines results in an upward trend in V_{so}. This can be attributed to the presence of higher stiffness and suction forces at lower effective stresses for soils with higher plasticity compared to lower plasticity soils. Regarding parameter *m*, as plasticity increases, the slope of the graph undergoes significant variation within the range of 0 to 15 before reaching a relatively stable point where changes in plasticity index (PI) no longer significantly affect *m*. This behavior is also linked to the higher suction forces observed in soils with higher plasticity when compared to soils with lower plasticity which results in higher changes in the shear wave velocity. It should be noted that the correlation between parameter *m* and plasticity index shows a better fit for the data.

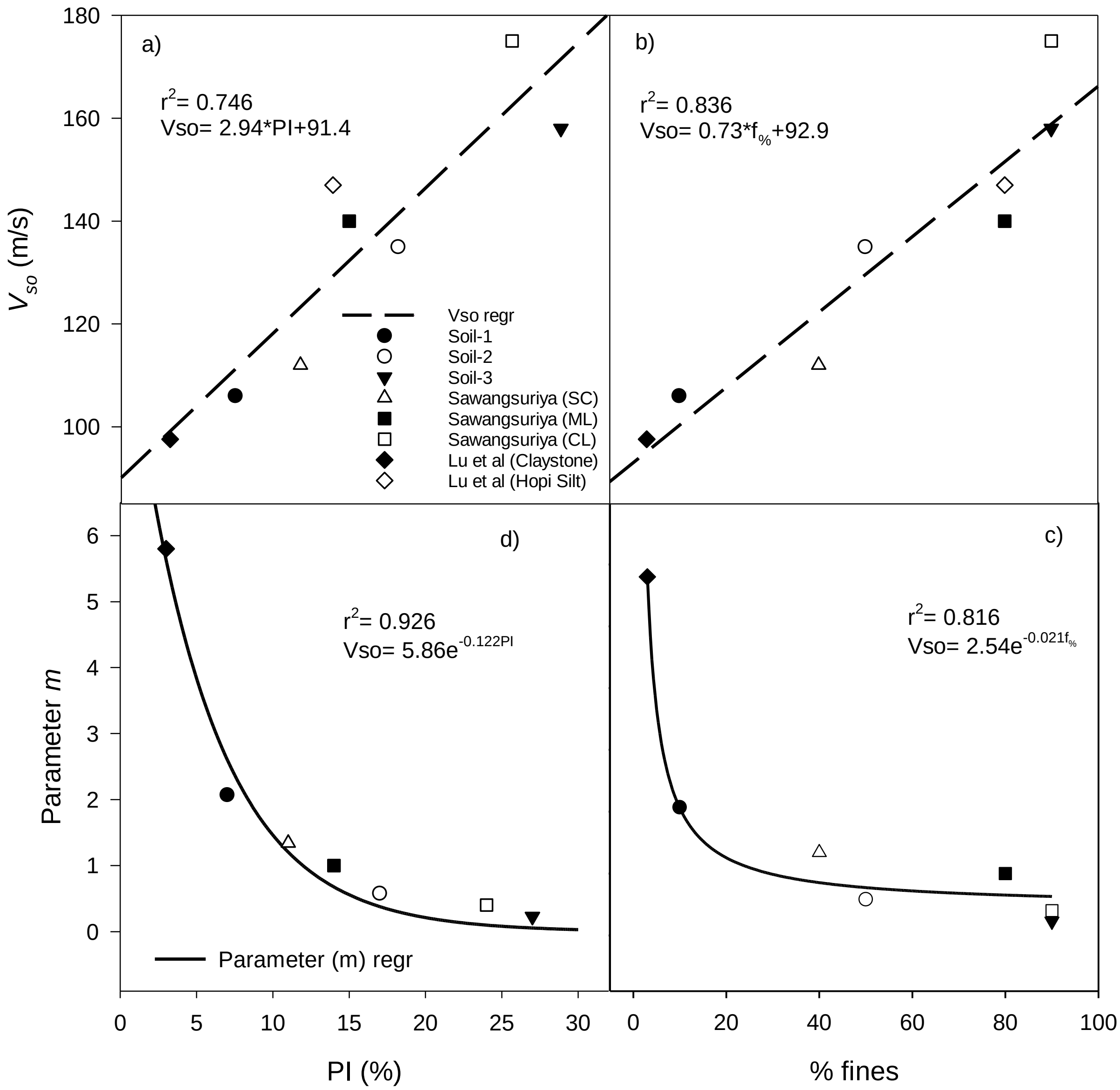

Figure 46. Parameters m and V_{so} relationship with Plasticity Index (%), and percent of fines (%). Figure a) shows PI vs V_{so}, Figure b) shows % fines vs V_{so}, Figure c) shows PI vs *m*, and Figure d) shows % fines vs *m*.

7.3 Practical Implications of the Model

The purpose of the model proposed in this study is to estimate the shear wave velocity in the field due to seasonal changes in soil conditions. Changes in shear wave velocity due to seasonal changes in moisture content (and hence suction) from dry to wet could lead to poor performance or failures of structures if analysis and design of these structures is based on shear wave velocity or properties derived there from. The following steps could be used to estimate the range of shear wave velocity for a particular test site. First, soil properties are used to interpret parameters m and V_{so} from Figure 46. Second, the effective stress is calculated at various suction values using the suction stress concept proposed by Lu and Likos (2006); parameters α and n are determined from the Zapata et al. (2000) or measured SWCC and Figure 39. Finally, Equation 22 is used to calculate the shear wave velocity for the desired soil at moisture contents of interest, such as near saturated or saturated conditions.

Using the procedure described above, the shear wave velocity field data from sites 4, 5, 6, 8 and 9 were plotted against effective stress based on the Lu and Likos (2006) suction stress concept. Soils were split into two groups (CL and CH), which define the majority of the tested soil profiles and for each group a value of n and α were estimated using Figure 39 and the Zapata et al. (2000) method. Figure 47 shows the results for the shear wave velocity versus effective stress. Additionally, the figure shows the r-squared value and the parameters used for the effective stress for each soil type. The effective stress was calculated using the measured total suction from the WP4-T and by estimating the total stress. The measured total suction was assumed to be equal to the matric suction and was used to calculate the suction stress. The total stress was calculated by assuming the unit weight of the soil and that the horizontal and vertical stresses are equal. Also, for the purpose of this study, the pore air pressure was assumed to be zero. Then using the definition of effective stress proposed by Likos and Lu (2006) the effective stress was calculated. The results indicate that the shear wave velocity is more strongly correlated with effective stress than suction. This can be seen by noting that the scatter observed in Figure 30 was reduced by using the suction stress to define the effective stress. This is an important observation showing the applicability of the proposed model. Additionally, the shear wave velocity was calculated using the proposed model, parameters *m* and V_{so} estimated using Figure 46 by using the measured PIs of the tested soils. These shear wave velocities were plotted against versus measured shear wave velocity in the field as shown in Figure 48. Considering the natural variability in the data set, and the necessary estimation of soil parameters involved, the results show a good agreement between measured and estimated shear wave velocity results.

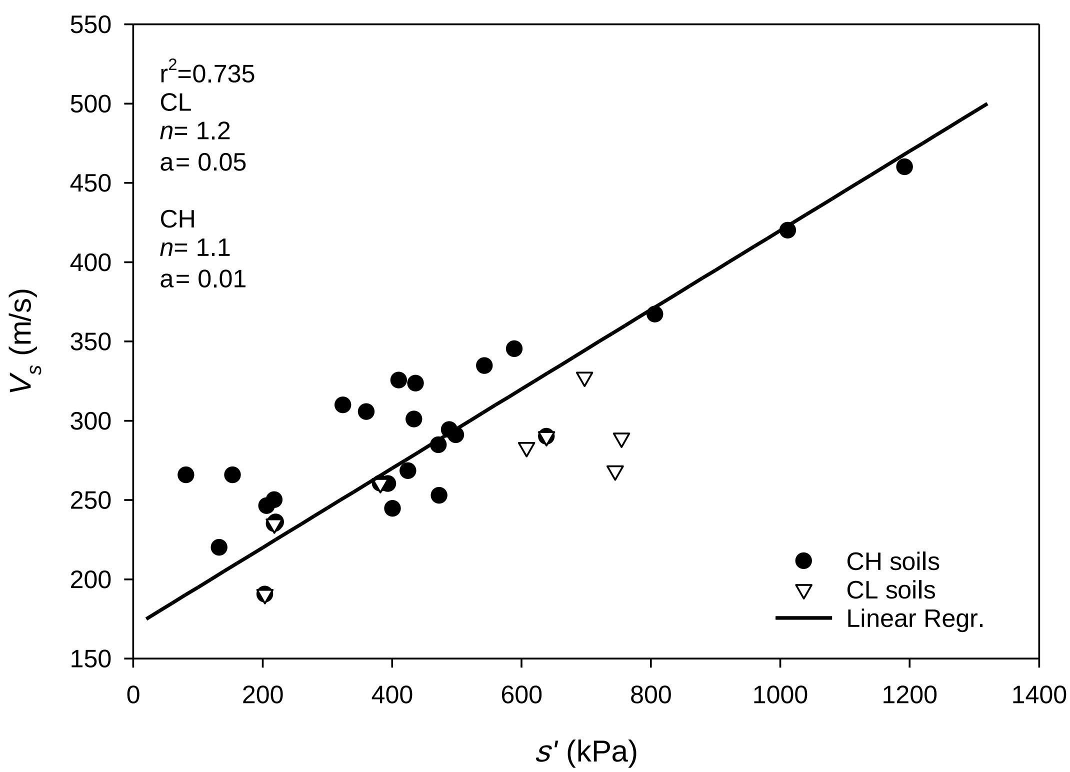

Figure 47. Shear wave velocity versus effective stress for field data from Sites 4, 5, 6, 8 and 9.

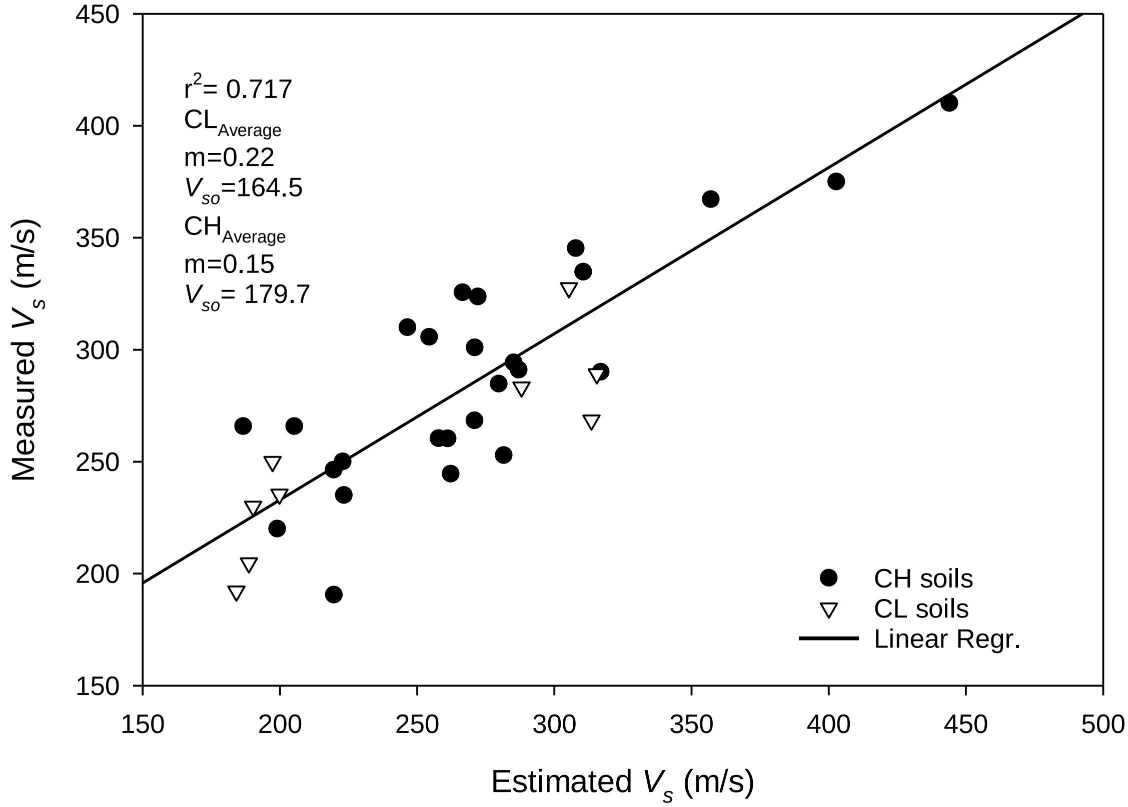

Figure 48. Measured shear wave velocity in the field (Sites 4, 5, 6, 8 and 9) versus estimated shear wave velocity using the proposed model.

Chapter 8: Conclusions and Recommendations

8.1 Overview

The goal of the research work described in this dissertation was to improve the interpretation and analysis of shear wave velocity in unsaturated soils. The work included four primary objectives:

1) Investigate the effect of various soil properties on the behavior of shear wave velocity in unsaturated soils. This included a laboratory study on the effects of soil type, moisture content, suction, confining stress, wetting-drying hysteresis, density, and soil structure on shear wave velocity.

2) Compare and analyze shear wave velocity measurements taken in the field using the seismic cone penetrometer and the laboratory.

3) Investigate the effect of seasonal changes in the field on shear wave velocity measurements from seismic cone tests.

4) Develop a mathematical model that uses the physical and mechanical properties of the soil to estimate the shear wave velocity under various saturation conditions. The following sections outline the major conclusions associated with the work performed to address each of these objectives.

8.2 Conclusions

8.2.1 Conclusions from Laboratory Investigation on the Effect of Various Soil Properties on Shear Wave Velocity

Major conclusions from the laboratory study to investigate the influence of various factors on shear wave velocity in unsaturated soils are as follows.

1) Shear wave velocity was observed to increase as water content decreased and suction increased. This is consistent with other studies reported in the literature (e.g. Cho and

Santamarina 2001, Claira and Rinaldi 2006, Youn et al. 2008, Lu and Sabatier 2009, Asslan and Wuttke 2012, Dong and Lu 2016).

2) Along drying and wetting paths, shear wave velocity exhibited hysteretic behavior with respect to water content. For similar water content, shear wave velocity along the drying path was higher than on the wetting path. This is consistent with other studies reported in the literature (e.g. Khosravi and McCartney 2012, Dong and Lu 2016, Khosravi et al. 2018).

3) When shear wave velocity along drying and wetting paths was plotted against matric suction, hysteretic behavior was not apparent. That is, the shear wave velocity appeared to be primarily dependent on suction and not on the water content.

4) Shear wave velocity was observed to increase as the dry density of the soil increased. However, the increase in shear wave velocity appears to result from increases in shear modulus associated with increased density, since density and shear wave velocity are theoretically inversely related. Other factors, such as suction and confining stress, that influence the shear modulus are important to consider as well.

5) For soils compacted wet and dry of the optimum moisture content, shear wave velocity at a similar water content was higher for soils compacted wet of optimum than soils compacted dry of optimum. This suggests that shear wave velocity was influenced by the soil structure with respect to water content. That is, the shear wave velocity in a more dispersed soil structure, for soils compacted wet of optimum, was higher than in a more flocculated soil structure, for soils compacted dry of optimum.

7) Results show that increases in confining stress correspond to increases in shear wave velocity along the wetting and drying paths.

8) Similar to what was stated before, under confining stresses, samples prepared wet of optimum generated higher shear wave velocity when compared to samples prepared dry of optimum.

9) Differences in shear wave velocity were observed for different soil types. Shear wave velocity increased as percent of fines and the plasticity index increased.

8.2.2 Conclusions from the Investigation Comparing Shear Wave Velocity Determined in the Field and the Laboratory

Major conclusions from the field and laboratory studies to investigate the variation of shear wave velocity measurements taken in the field and the laboratory are as follows:

1) Shear wave velocity measurements from seismic cone penetration testing during "wet" and "dry" periods were different depending on changes in water content and suction. Generally, shear wave velocity increased as moisture content decreased and suction increased in the upper portion of the soil profile.

2) Shear wave velocity measurements taken in the field and the laboratory appeared to be in good agreement for soils under similar moisture and stress conditions.

3) Shear wave velocity measurements conducted on undisturbed samples collected from the field showed that as water content increases and suction decreases, the shear wave velocity decreases.

4) Additionally, shear wave velocity measurements on undisturbed samples showed that high variation in shear wave velocities are observed for soils tested at wet and dry states.

8.2.3 Conclusions from the Field Investigation of the Effect of Seasonal Changes in Moisture Content on Shear Wave Velocity

1) Seismic cone penetration testing in the field revealed that shear wave velocity measured during the wet season is lower than shear wave velocity measured during the dry season for the same soil profile where moisture content variations occur.

2) Shear wave velocity was influenced by the soil type variation along the site profile, where soils with higher plasticity generally exhibited higher shear wave velocity than soils with lower plasticity.

4) Shear wave velocity changes are most predominant in the first 2-3 meters of depth in the active zone of the soil profile. At greater depths, changes in shear wave velocity were generally less significant between wet and dry seasons.

8.2.4 Conclusions from Development of a Proposed Model for Predicting Shear Wave Velocity in Unsaturated Soils

1) When shear wave velocity measurements obtained from the laboratory study were plotted against Bishop's effective stress, the relationship observed was not unique and exhibited a strong dependence on the confining stress used during testing. A power model was used to fit the relationships, and provided a good fit to the data representing different confining stresses; however, different model parameters were required to represent each confining stress. This indicates that Bishop's effective stress cannot be uniquely related to shear wave velocity.

2) When shear wave velocity measurements obtained from the laboratory study were plotted against effective stress based on the suction stress concept proposed by Lu and Likos (2006), the relationship was observed to be unique. A power model was used to fit

the relationships, and provided a good fit to the data representing different confining stresses and a unique set of model parameters provided a good representation of the data trend. This indicates that effective stress based on the suction stress concept is uniquely related to shear wave velocity.

3) A linear model for the relationship between shear wave velocity and effective stress based on the suction stress concept proposed by Lu and Likos (2006) was found to provide a better fit to the data from this study compared to the power model. The linear model was also compared to the power model for data sets obtained from the literature and proved to be better than the power model in two of the four cases examined.

4) New model parameters for the linear model were introduced: slope *m* and intercept V_{so}, and were shown to be dependent on readily obtainable soil properties (plasticity index, void ratio, and percent of fines). Relationship between model parameters and soil properties were provided.

8.3 Contributions to the Knowledge gaps

In this study the behavior of shear wave velocity in unsaturated soils was examined under various physical and mechanical conditions. The following are the major contributions to the knowledge gaps in the literature:

1) Shear wave velocity was tested under various conditions where soil type, water content, suction, density, confining stress, and soil structure were varied and the combined effect of changing these parameters was assessed. Some previous studies addressed some aspects of this work, but no single study has examined all the factors investigated in the current study.

2) A comprehensive set of test results was produced that examines the influence of soil structure on shear wave velocity during wetting and drying for three different soils.

3) An investigation of shear wave velocity with the seismic cone penetrometer in the field at several test sites during wet and dry seasons demonstrates the importance of considering changes in shear wave velocity due to changes in moisture content and suction in the active zone of the soil profile. This has important implications for determination of soil dynamic properties and seismic site class based on field measurements of shear wave velocity in unsaturated soils.

4) A systematic comparison of shear wave velocity determined using SCPT in the field and bender element testing in the laboratory on Shelby tube samples obtained on the same day was accomplished for three different test sites. The study revealed that field measurements were nearly the same as lab measurements made under similar confining stress. Relatively limited data of this type has been reported in the literature. These results indicate that measurements of shear wave velocity, whether in the field or lab, are robust and reliable provided good techniques are employed. It is particularly important during laboratory testing to utilize representative samples from the field with similar confining stress and suction (water content) to conditions found in the field.

5) Existing power models for predicting shear wave velocity with effective stress were examined and a new linear model was developed and found to provide better predictive capability than the power model for 6 out 8 data sets examined, including 3 from the current study and 5 from the literature. Relationships between the linear model parameters and readily obtainable soil properties were developed.

6) The proposed linear model was found to provide reasonable estimates of shear wave velocity when compared to field measurements of shear wave velocity obtained at several of the test sites using the SCPT. This observation indicates the model provides a tool for

estimating changes in shear wave velocity for moisture conditions other than those encountered during field testing.

8.4 Recommendations

This study focused on the behavior of shear wave velocity in unsaturated soils in the lab under controlled environments and in the field. Based on the results from the study the conclusions mentioned above were made; however, unsaturated soils are very widespread and vary significantly. Therefore, experimental research should be carried out to establish whether the proposed model and conclusions made can be applied to soils from different regions. Based on the findings of this study, the following recommendations are proposed:

8.4.1 Recommendation for Practice

1) Consider Suction in Seismic Site Characterization: When assessing seismic site classification or determining seismic soil parameters from shear wave velocity measurements in the field, it is essential to incorporate suction measurements alongside traditional measures of water content. This will provide essential information to calculate the shear wave velocity during wet and dry conditions that may occur after the time of field testing. At a minimum, water contents obtained at various depths during the field investigation on the same day can be used to estimate suction based on measured or estimated soil water characteristic curves. This will provide a more accurate representation of soil response to seismic loading.

2) Account for Initial Soil Structure: Researchers and practitioners should account for the initial soil structure when predicting shear wave velocity by measuring shear wave velocity using bender elements wet and dry of optimum moisture content for compacted soils. This is particularly relevant when dealing with fine-grained soils that exhibit varying degrees of flocculation or dispersion.

3) Account for confining stresses: Given the observed results of the variation of shear wave velocity measured in the field and the lab, it is extremely important to apply confining stresses to shear wave velocity testing in the laboratory. Applying confining stresses to the tested samples in the lab allows for shear wave velocity determinations that are to better represent the field conditions.

4) Utilize the Linear Prediction Model: For practical applications involving shear wave velocity prediction, the linear predictive model proposed in this study is recommended due to its better performance compared to the power-law model. However, further validation and refinement of the model may be necessary for specific soil types and conditions.

8.4.2 Recommendations for Research

1) Use broader variation in soil properties: Using wider ranges of suctions, water contents, confining stresses and densities during research will give a wider perspective of the behavior of unsaturated soils. For example, a range of 90-6600 kPa suction and a confining stress of 0-100 kPa was used in this study. Soils with higher suctions and confining stresses were not fully represented. Additionally, conducting an in depth investigation on the influence of clay minerology on shear wave velocity.

2) Account for volume changes during testing: Modifying the triaxial testing chamber to account for changes in volume when applying the confining stresses will help provide a better understanding of the effect of density on shear wave velocity.

3) Testing more natural soils in the lab: A lot of the tested soils in this study were manufactured soils, which provides a more controlled and uniform specimens, but it does not represent the wide range of soil types found in the field.

4) Examine the proposed model against a wider variety of soils: Having a larger set of soils and data will help provide a more accurate model that works for a larger group of soils in the field.

5) Investigate the influence of clay minerology on the behavior of shear wave velocity: Looking into various types of clay mineralogy (kaolinite, montmorillonite, and illite) will provide an understanding of the influence of clay minerology on shear wave velocity.

References

- Asslan, M., & Wuttke, F. (2012). Wave velocity change and small-strain stiffness in unsaturated soils: experimental investigation. In Unsaturated soils: Research and applications (pp. 355-362). Springer, Berlin, Heidelberg.
- ASTM International. (2000). Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.
- ASTM International. (2012). Standard Test Method for Electronic Friction Cone and Piezocone Penetration Testing of Soils. ASTM D5778-12.
- ASTM International. (2014). Standard Guide for Direct Push Soil Sampling for Environmental Site Characterizations. ASTM D6282-14.
- ASTM International. (2015). Standard Practice for Thin-Walled Tube Sampling of Fine-Grained Soils for Geotechnical Purposes. ASTM D1587-15.
- ASTM International. (2016). Standard Practice for Soil Exploration and Sampling by Auger Borings. ASTM D1452-16.

  ASTM International. (2017). Standard Test Method for Cetane Number of Diesel Fuel Oil. ASTM D613-17.
- ASTM International. (2019). Standard Test Methods for Downhole Seismic Testing. ASTM D7400-19.
- ASTM International. (2019). Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass. ASTM D2216-19.
- Bishop, A. W. (1959). “The principle of effective stress.” Teknisk Ukeblad I Samarbeide Med Teknikk, 106(39), 859–863.

- Cho, G. C., and Santamarina, J. C. (2001). “Unsaturated particulate mate- rials: particle-level studies.” J. Geotech. Geoenviron. Eng., 10.1061/ (ASCE)1090-0241(2001)127:1(84), 84–96.
- Claria, J.Jr., Rinaldi, V.A. 2004. Shear wave velocity of a compacted silt, Geotechnical Testing Journal, 3, 5: 1-9
- Dong, Yi, and Ning Lu. "Dependencies of shear wave velocity and shear modulus of soil on saturation." Journal of Engineering Mechanics 142.11 (2016): 04016083.
- Fredlund, D. G., & Rahardjo, H. (1993). Soil mechanics for unsaturated soils. John Wiley & Sons.
- Fredlund, D. G., & Xing, A. (1994). Equations for the soil-water characteristic curve. Canadian geotechnical journal, 31(4), 521-532.
- Hardin, B. O., and Drnevich, V. P. (1972). “Shear modulus and damping in soils: Design equations and curves.” J. Soil Mech. Found. Div.,98 (SM7), 6–7.
- Hardin, B. O., and Richart, F. E. (1963). “Elastic wave velocities in granular soils.” J. Soil Mech. Found. Div., 89(SM1), 33–65.
- Hardin, Bobby & Black, Wl. (1968). Vibration Modulus of Normally Consolidated Clay. J. Soil Mech. Found. Div., Am. Soc. Civ. Eng.. 94. 10.1061/JSFEAQ.0001100.
- Hayashi, K., and Inoue, A. (2007). "Effect of clay mineralogy on shear wave velocity of soils." Soil Dynamics and Earthquake Engineering, 27(5), 459-469.
- Indraratna, Buddhima; Heitor, Ana; and Rujikiatkamjorn, Cholachat: Effect of compaction energy on shear wave velocity of dynamically compacted silty sand soil 2012, 635-640.
- James A. Blatz, Yu-Jun Cui, Luciano Oldecop 2008.Vapour Equilibrium and Osmotic Technique for Suction Control. Geotech Geol Eng (2008) 26:661–673

- Khalili, N., and M. H. Khabbaz (1998), A unique relationship for c for the determination of shear strength of unsaturated soils, Geotechnique, 48, 681–688, doi:10.1680/geot.1998.48.5.681.
- Khosravi, A., & McCartney, J. S. (2012). Impact of hydraulic hysteresis on the small-strain shear modulus of low plasticity soils. Journal of Geotechnical and Geoenvironmental Engineering, 138(11), 1326-1333.
- Khosravi, A., and McCartney, J. S. (2012). "Impact of hydraulic hysteresis on the small-strain shear modulus of unsaturated soils." J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)GT.1943-5606 .0000713, 1326–1333.
- Khoury, N. N., and Zaman, M. M.2004. "Correlation between resilient modulus, moisture variation, soil suction for subgrade soils."Trans-portation Research Record. 1874, Transportation Research Board,Washington, D.C.
- Lee, J. S., and Santamarina, J. C. (2005). "Bender element: Performance and signal interpretation." J. Geotech. Geoenviron. Eng., 10.1061/ (ASCE)1090-0241(2005)131:9(1063), 1063–1070.
- Leong, E. C., Cahyadi, J., and Rahardjo, H. (2009). "Measuring shear and compression wave velocities of soil using bender-extender elements." Can. Geotech. J., 46(7), 792–812.
- Likos, W.J., and N. Lu. 2004. Hysteresis of capillary stress in unsaturated granular soil. J. Eng. Mech. 130:646–655. doi:10.1061/(ASCE)0733- 9399(2004)130:6(646)
- Lu, N., and Likos, W. J. (2004). Unsaturated soil mechanics, Wiley, Hoboken, NJ.
- Lu, N., J. Godt, and D.T. Wu. 2010. A closed-form equation for ef- fective stress in unsaturated soil. Water Resour. Res. 46:1–14. doi:10.1029/2009WR008646

- Lu, N., and Likos, W. J. (2006). “Suction stress characteristic curve for unsaturated soils.” J. Geotech. Geoenviron. Eng., 10.1061/(ASCE) 1090-0241(2006)132:2(131), 131–142.
- Lu, Z., & Sabatier, J. M. (2009). Effects of soil water potential and moisture content on sound speed. Soil Science Society of America Journal, 73(5), 1614-1625.
- Mancuso, C., Vassallo, R., and d’Onofrio, A. (2002). “Small strain behav- ior of a silty sand in controlled-suction resonant column torsional shear tests.” Can. Geotech. J., 39(1), 22–31.
- Ng, C. W. W., Xu, J., and Yung, S. Y. (2009). “Effects of imbibition- drainage and stress ratio on an-isotropic stiffness of an unsaturated soil at very small strains.” Can. Geotech. J., 46(9), 1062–1076.
- Oh, S., N. Lu, Y.K. Kim, S.J. Lee, and S.R. Lee. 2012. Relation between the soil water characteristic curve and the suction stress characteristic curve: Experimental evidence from tests on residual soils. J. Geotech. Geoenviron. Eng. 138:47–57. doi:10.1061/(ASCE)GT.1943-5606.0000564
- Oh, W. T., and Vanapalli, S. K. (2014). “Semi-empirical model for estimat- ing the small-strain shear modulus of unsaturated non-plastic sandy soils.” Geotech. Geol. Eng., 32(2), 259–271.
- Salager, S., M. Nuth, A. Ferrari, and L. Laloui. 2013. Investigation into water retention behaviour of deformable soils. Can. Geotech. J. 50:200–208. doi:10.1139/cgj-2011-0409
- Sawangsuriya, A., Edil, T. B., & Bosscher, P. J. (2008). Modulus− suction− moisture relationship for compacted soils. Canadian Geotechnical Journal, 45(7), 973-983.
- Sawangsuriya, A., Edil, T. B., & Bosscher, P. J. (2009). Modulus-suction-moisture relationship for compacted soils in postcompaction state. Journal of Geotechnical and geoenvironmental engineering, 135(10), 1390.

- Sawangsuriya, A., Edil, T. B., and Bosscher, P. J. (2009). “Modulus-suction moisture relationship for compacted soils in post compaction state.” J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)GT.1943-5606 .0000108, 1390–1403.
- Sawangsuriya, A., Edil, T. B., Bosscher, P. J., & Wang, X. (2006). Small-strain stiffness behavior of unsaturated compacted subgrade. In Unsaturated Soils 2006 (pp. 1121-1132).
- Vanapalli, S. K., D. E. Fredlund, D. E. Pufahl, and A. W. Clifton (1996), Model for the prediction of shear strength with respect to soil suction, Can. Geotech. J., 33, 379–392, doi:10.1139/t96-060.
- Wei, C.-F., & Muraleetharan, K.K. (2002). A continuum theory of porous media saturated by multiphase fluids: I. Linear poroelasticity. International Journal of Engineering Science, 40, 1807-1833.
- Wei, Y., & Miller, G. A. (2018). Determining Osmotic Suction Using a Chilled Mirror Device. Geotechnical Testing Journal, 42(6), 1457-1474.
- Whalley, W. R., Jenkins, M., & Attenborough, K. (2012). The velocity of shear waves in unsaturated soil. Soil and Tillage research, 125, 30-37.
- Wood, D. M., and Wightman, S. H. (1972). "Clay mineralogy and the seismic properties of soils." Geotechnique, 22(3), 401-416.
- Yang, S. R., Lin, H. D., Kung, J. H. S., & Liao, J. Y. (2008). Shear wave velocity and suction of unsaturated soil using bender element and filter paper method. Journal of GeoEngineering, 3(2), 67-74.
- Zapata, C. E., Houston, W. N., Houston, S. L., & Walsh, K. D. (2000). Soil–water characteristic curve variability. In Advances in unsaturated geotechnics (pp. 84-124).