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AN INVERSION SCHEME FOR SHEAR WAVE SPEED USING SCHOLTE
WAVE DISPERSION

BY
JENNIFER L. GIARD

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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ABSTRACT

Acoustic propagation in littoral waters is greatly affected by seafloor sediment properties. Shear properties of sediments are also directly related to the strength of sediments for geotechnical applications. These factors emphasize the importance of estimating shear wave speeds in semi-consolidated shallow water sediments. One of the most promising approaches to estimate shear speed is to invert the shear speed profile using the dispersion of seismo-acoustic interface (Scholte) waves that travel along the water-sediment boundary. The propagation speed and attenuation of Scholte waves are closely related to the shear wave speed and attenuation over a depth of 1-2 wavelengths into the seabed. Based on this concept, the University of Rhode Island Ocean Engineering Department has developed a geophone-hydrophone system for the measurement of these interface waves, along with an inversion scheme that would invert the dispersion data for sediment shear speed profiles. The objective of this research was to investigate the validity of the system in estimating the shear speed of surface waves at the water-sediment interface. This geophone-hydrophone system was tested at Davisville, RI and the results obtained from this test will be presented. These results will also be compared to correlated values of shear speed from existing boring log data at the site to validate the inversion scheme. The data collected was processed using the Spectral Analysis of Surface Waves (SASW) method and inverted using an inversion scheme based around the Godin-Chapman forward model. The inverted shear speed profile was consistent with the shear speed profiles related to sand and silt, which coincides with the types of sediment encountered in the boring logs. The validity of the inversion scheme will be addressed and future improvements and work will be discussed.

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CHAPTER 1

Introduction

1.1 Overview

The measurement of shear wave velocity profiles is an important component of geotechnical site investigations for many applications. The University of Rhode Island Ocean Engineering Department has developed a geophone-hydrophone system, referred to as the Amphibious Seismo-Acoustic Recording System (ASARS), for the measurement of sediment shear speed. The goal of research using this system is to characterize the seafloor based on shear wave velocity profiles in a non-invasive and time efficient manner. The estimation of shear wave velocities in shallow water marine sediments can provide valuable soil stiffness information for use in earthquake site response analysis, soil liquefaction evaluation, waste material characterization, and ground improvement evaluations [12].

1.2 Justification for and Significance of Study

Measuring shear wave velocity with traditional testing methods, such as down-hole and crosshole tests, is an invasive and very expensive approach. This is especially true if velocity profiles are required over a large area. In recent years, non-invasive profiling methods have been developed utilizing surface waves [13]. These methods provide a more time and cost efficient way of generating shear velocity profiles.

One such method that can be used to estimate the shear wave velocity profiles is to invert the relationship between the seismo-acoustic interface waves that travel along the water-sediment boundary and the shear wave speed of the sediment. These interface waves are known as Scholte waves and have a propagation speed and attenuation that are closely related to the shear wave speed and attenuation for

1-2 wavelengths into the seabed. The dispersion characteristics of the Scholte wave provide information about the sediment shear speed gradient and the geoacoustic properties of the sea floor. These waves exhibit properties that are directly related to the depth dependent shear rigidity [14].

Since there is interest in determining sediment shear properties, the University of Rhode Island developed ASARS to provide the acoustics community with the ability to acoustically map sediment variations over large regions of the ocean floor. This system was developed under a grant, awarded to Professors James Miller and Gopu Potty, from the Defense University Research Instrumentation Program (DURIP) through the Office of Naval Research. The objective of this grant was to develop an acoustic/seismic receive system for the estimation of sediment shear speed using Scholte wave data.

1.3 Objectives

The objective of this research was to investigate the validity of the system in estimating the shear speed of surface waves at the water/sediment interface. The work done by previous graduate student Jeannette Greene was extended by developing an inversion scheme to determine shear speed profiles from data collected using ASARS. The current system was validated against estimated shear speed profiles at an underwater site in Davisville, RI to determine the accuracy in the measurements taken by ASARS.

1.4 Organization of Thesis

This thesis is organized to introduce the project and provide a justification for the research being conducted, provide a summary of the theory needed to understand this research, present the measurement and inversion methods developed by URI, explain the testing conducted, and provide results and conclusions.

Chapter 2 introduces wave propagation theory related to body and interface waves, specifically Rayleigh and Scholte waves. It also introduces the dispersion properties of interface waves and discusses how dispersion can be used to determine shear velocity profiles. Typical shear measurement techniques, like Spectral Analysis of Surface Waves (SASW), are discussed in Chapter 3, along with the URI shear measurement system, ASARS.

Chapter 4 then discusses the method of inversion, including the Godin-Chapman forward inversion model, and how this was combined with a genetic algorithm to create an inversion scheme using the data collected by ASARS. This chapter also validates the implementation of the forward model by comparing the results with published shear speed data.

Chapter 5 discusses the published historic data taken at the Davisville site. Chapter 6 provides the details of the field test conducted at Davisville in order to collect interface wave data. Chapter 7 discusses the data processing methods to develop the dispersion curves and the implementation of the inversion scheme. The results and validation against published shear speed profiles are presented.

Chapter 8 discusses sources of error and areas of uncertainty associated with the inversion scheme. Overall conclusions and recommendations are then discussed in Chapter 9, along with future work that would help to further enhance URI's ability to determine shear speed profiles using this system.

CHAPTER 2

Wave Propagation Theory

Elastic waves may propagate and travel through a solid medium when the solid is deformed. In an unbounded, non-absorbing, homogeneous, and isotropic solid these body waves are the only types of waves that can propagate. When a free surface or a surface boundary between two solids is introduced, interface waves can also be propagated [15].

2.1 Body Waves

Body waves are stress waves that propagate in any elastic medium. There are two basic types of body waves that are supported in a solid: compression waves and shear waves. Compression waves, or primary (P) waves, have a faster arrival time than shear, or secondary (S) waves [12].

Compression, also known as dilatational, waves are longitudinal waves with a particle motion in the same direction of wave propagation (Figure 1). This type of particle motion is known as irrotational motion since these waves involve no rotation. When a medium is subjected to this type of wave, it is compressed or expanded in the direction the wave propagates. This movement causes volume changes at the wave front [12].

Shear, also known as distortional, waves are transverse waves with a particle motion perpendicular to the direction of wave propagation (Figure 1) [15]. This motion is equivolumetrical, meaning there is no volume change in the material due to wave propagation [12]. Fluids and gasses have no shear rigidity and cannot support shear waves. Therefore shear waves can only propagate through solids and have the same velocities in saturated and unsaturated media [16].

Compressional and shear waves propagate independently of each other with

Figure 1. Compression (P) and Shear (S) wave motion [4].

their characteristic phase velocities c_p and c_s . These velocities are related to each other by Equation 1, with $0 < n < 0.717$ [14].

$$c_s = nc_p \quad (1)$$

The velocities of these waves depend on the elastic properties and density of the material through which they propagate. Therefore their fundamental velocities (Equations 2 and 3) can be defined in terms of the material density ρ , elastic constants δ and μ (Lamè's Constants), or Poisson's Ratio σ and Young's Modulus E [14].

$$c_p = \sqrt{\frac{\delta + 2\mu}{\rho}} = \sqrt{\frac{(1 - \sigma)E}{\rho(1 + \sigma)(1 - 2\sigma)}} \quad (2)$$

$$c_s = \sqrt{\frac{\mu}{\rho}} = \sqrt{\frac{E}{2\rho(1 + \sigma)}} \quad (3)$$

with $0 < \sigma < 0.5$ for all materials.

Shear waves can also be horizontally, vertically, or a combination of horizontally and vertically polarized [16]. In a homogeneous elastic medium, the wave equations of motion reduce to separate wave equations for compression (P) waves, vertically polarized shear (SV) waves, and horizontally polarized shear (SH) waves [7].

2.2 Interface Waves

When a medium contains a bounding surface, interface waves can occur. An interface wave is a guided wave that propagates along the interface between two media that have different shear speeds. These waves are a result of interfering compression and shear waves that propagate along the surface of a solid. Only solid media can support shearing and therefore at least one of the media must be a solid in order for interface waves to exist.

The interface wave is given different names according to the media through which it travels and the scientists associated with their discovery. A Rayleigh wave is generated at a solid-air boundary, a Scholte wave propagates along a solid-fluid interface, and a Stoneley wave is associated with a solid-solid boundary [3].

Since these waves are localized at the interface, they spread cylindrically and therefore decay less rapidly with distance compared to the spherically spreading body waves. Surface waves are also more easily observed and detected than the compression and shear body waves [5].

When there are two adjacent, homogeneous media, or sufficient high frequencies, genuine interface waves and/or their generalized or pseudo versions may exist [14]. These waves may merge into another as the wavelengths or the significance of the media (such as the water column) changes [17]. Only genuine interface waves are focused on for the sake of this research, specifically the genuine Rayleigh and Scholte waves.

2.2.1 Rayleigh Waves

The simplest type of interface wave is the Rayleigh wave, which propagates along the solid-air interface. These waves were first investigated by Lord Rayleigh in 1885. He showed that their effect decreases rapidly with depth and that their velocity is smaller than that of body waves [15].

Rayleigh waves are the result of interfering P and SV waves and the motion causes both horizontal and vertical particle displacements [18]. The particle motion is confined to the vertical plane that includes the direction of wave propagation. This motion is counter-clockwise at the surface, changes to purely vertical motion at a depth of $1/5$ th the wavelength, and becomes clockwise at greater depths (Figure 2).

Figure 2. Particle motion and amplitude of Rayleigh waves with depth [1].

The amplitude of the wave decreases exponentially with depth (Figure 2). Most of the energy propagates to a depth equal to one wavelength. Therefore, the propagation of the wave is influenced by the geological and geotechnical properties of this depth range [1].

Rayleigh wave phase velocity is approximately 95% of the shear wave speed. It is a function of four parameters: S-wave velocity, P-wave velocity, density, and layer

thickness. Variations in shear wave velocities have a dramatic effect on Rayleigh wave phase velocities [18]. Therefore in a solid medium, a measurement of the Rayleigh velocity may give an accurate measure of the shear wave velocity [11].

2.2.2 Scholte Waves

A Scholte wave occurs along a solid-fluid boundary and propagates along the seafloor. The amplitude decay within the solid is comparable with that of the Rayleigh wave (Figure 3). The penetration depth in the fluid remains small when the adjacent solid is very soft, that is when the shear wave speed in the solid is smaller than the sound speed in the fluid. This is the case for most water/unconsolidated sediment situations. On the other hand, for most water/rock combinations, the penetration depth can be much larger in the fluid if the shear wave speed in the solid is larger than the sound speed in the fluid [11].

The propagation velocity of Scholte waves is lower than that of Rayleigh waves because of the interaction of the waves with the overlying water [19]. This propagation velocity and the attenuation of Scholte waves are closely related to the shear properties of the sediment [3].

Figure 3. Particle motion of Scholte waves [5].

Scholte waves assume the Rayleigh wave velocity of the sediment as its low-frequency limit and gradually approach the smaller Scholte wave velocity for high

frequencies. In the low frequency limit the water layer can be neglected and the Scholte wave can be regarded as a Rayleigh wave. Since Rayleigh waves have a strong sensitivity to the shear wave velocity structure of the medium and since Scholte waves are a pure or modified version of the Rayleigh wave, Scholte waves are also sensitive to the medium through which they travel.

For soft shallow water marine sediments Scholte waves have velocities as low as 10-50 m/s. For compact sediments such as till or sand, Scholte wave velocities higher than 200 m/s can be expected [19].

2.3 Dispersion

When interface waves propagate in a non-homogeneous media they exhibit dispersive behavior. When the medium is not vertically homogeneous, for example when it is layered, each layer has different elastic and geotechnical properties. When an interface wave propagates in this case, the different wavelengths will sample different depths (Figure 4). Each wavelength propagates at a phase velocity that is dependent of the elastic properties of the layer [1]. Therefore the interface wave has a phase velocity V that is a function of frequency based on Equation 4, where f is the input excitation frequency and λ is the wavelength. A plot of the phase velocity versus frequency or wavelength is known as a dispersion curve.

$$V = f\lambda \quad (4)$$

Due to the dispersive nature of interface waves, Rayleigh and Scholte waves are quite effective for seismic site investigations for the determination of shear velocity profiles. Longer wavelengths penetrate deeper than shorter wavelengths for a given mode, generally exhibit greater phase velocities, and are more sensitive to the elastic properties of the deeper layers. On the other hand, shorter wavelengths are sensitive to the physical properties of the surficial layers. For this reason, a

particular mode of surface wave will possess a unique phase velocity for each unique frequency, leading to the dispersion of the seismic signal [18].

Figure 4. Surface wave dispersion. In a homogeneous half space (left) all the wavelengths sample the same material and the phase velocity is constant. When the properties change with depth (right) the phase velocity depends on the wavelength [1].

At high frequencies, the phase velocity is close to the shear wave velocity in the uppermost layer. At low frequencies, the effect of the deeper layers becomes important and the phase velocity moves asymptotically to the shear wave velocity of the deepest material. Thus, for a profile where shear wave velocity increases with depth, a normal dispersion curve will be observed where the phase velocities decrease with frequency. For a profile where shear wave velocity decreases with depth, a reverse dispersion curve will be observed where the phase velocities increase with frequency. For an irregular shear wave velocity profile, the phase velocities show a complex relation to frequency (Figure 5) [1].

Figure 5. Normal, inverse, and irregular dispersion curves resulting from increasing, decreasing, and complex shear wave velocity profiles, respectively [1].

CHAPTER 3

Surface Wave Measurement Techniques

There are many different seismic methods used by seismologists to determine the shear wave velocity structure on land. While some of the conventional shear velocity profile testing methods are non-invasive, most require on-site drilling. These methods are similar in that they all propagate and receive compression and shear waves to measure the velocity of the material in its existing location [12]. Some examples of invasive and non-invasive seismic acquisition techniques used in shallow site investigations are summarized in Table 1.

Invasive		Noninvasive		
Surface source (Boore & Thompson, 2007)	Receiver in borehole	HVSr		
	Receiver in cone penetrometer	Multiple stations	Active sources	SASW
Downhole source	Suspension P-S logger (Nighbor and Imai, 1994)			DASW
			MASW	
	Crosshole (ASTM, 2003)		Passive sources	F-K
				SPAC
Combined active and passive sources			ReMi	
Acronyms	HVSr: Horizontal/vertical spectral ratio method (on single station microtremor data) (Bonnefoy-Claudet et al., 2006)			
	SASW: Spectral analysis of surface wave (Nazarian and Stokoe, 1984)			
	DASW: Distance analysis of surface wave (Phillips et al., 2004)			
	MASW: Multichannel analysis of surface wave (Park et al., 1999)			
	F-K: Frequency-wavenumber method of processing seismic array data (Horike, 1985)			
SPAC: Spatial autocorrelation method of processing seismic array data (Okada, 2003)				
ReMi: Refraction microtremor method (Louie, 2003)				

Table 1. Seismic acquisition techniques used in shallow site investigations [1].

Invasive methods require data from seismometers placed beneath the Earth's

surface and the use of surface or down-hole sources. This is a major disadvantage of invasive methods because of the cost associated with drilling. This reason lead to the development of non-invasive methods that seek to obtain the subsurface velocity structure without drilling.

The non-invasive methods shown in Table 1 utilize active or passive sources, or both, and attempt to measure the fundamental mode dispersion curves of Rayleigh waves. Rayleigh type interface waves are measured because they carry most of the input energy and attenuate more slowly than body waves, therefore dominating the ground motion at the interface [20]. The shear velocity structure is then obtained by inverting these dispersion curves, using either an iterative forward modeling approach or an inverse algorithm approach [1].

3.1 SASW

One popular non-invasive method to characterize the shear wave velocity structure on land is the Spectral Analysis of Surface Waves (SASW) method. In this method measurements are made at the surface and the dispersive characteristics of surface waves are used to determine the variation of the shear wave velocity of layered systems with depth. The shear and Young's moduli of the materials can also be calculated through the use of simple mathematical equations once the shear wave velocity profiles are determined [21]. SASW has been used to successfully characterize traditional soil sites, gravel deposits, debris slides and landfills [20].

3.1.1 SASW Procedure

The field procedure for the SASW method involves generating surface waves at one point and measuring the vertical motions on the surface at two or more locations. A typical SASW test arrangement includes two or more vertically oriented seismic receivers, an excitation source, and a data acquisition system. The

linear array of receivers are arranged on a level surface of a site centered around a common midpoint [12].

The measurement process begins with closely spaced receivers and a high frequency source to generate shorter wavelengths and sample material near the surface. The source is applied vertically at a point in line with the receivers at a distance from the first receiver equal to the distance between receivers. This allows the surface wave to be established and to minimize any near field effects. The receiver spacing is then increased and the measurement is repeated with a lower frequency source to generate longer wavelengths and sample deeper material [12].

The amplitude of the surface waves at a given distance from the source is affected by the kinetic energy of the dropped object while the frequency content is affected by the mass of the source. Typical sources include hammers, drop weights, explosives, construction machinery, and Vibroseis trucks [22]. A common 6.8 kg (15 lb) sledge hammer source on land provides sufficient energy and frequency content at most sites to generate wavelengths up to approximately 15 meters. The wavelengths in this range allow shear speed profiles to be determined to depths of around 7 meters [16].

3.1.2 SASW Data Processing

Spectral analysis is used to calculate the surface wave phase velocity at different frequencies to determine the experimental dispersion curve. An individual dispersion curve of surface wave velocity versus wavelength is generated for each receiver pair. The individual curves from all the receiver spacings are then combined to create a single composite dispersion curve, which represents the seismic signature of the site.

Once the composite dispersion curve is generated, an iterative forward mod-

eling approach is employed to create a theoretical dispersion curve to match to the experimental data. An example of this would be to assume a 1-D layered profile and calculate a theoretical dispersion curve for that profile. Then the thickness of the profile layers and their shear wave velocities would be iteratively changed until the theoretical dispersion curve matches the measured dispersion curve [23]. The theoretical curve that provides the best match to the experimental curve is presented as the shear wave velocity profile of the site [22].

3.1.3 SASW Calculations

SASW measurements from various receiver spacings and frequencies are used to generate the composite experimental dispersion curve. Since the receivers are in a linear array and the source is excited along the line of the array, the receivers closer to the source will record the signal at an earlier time than the receivers farther away. The time difference of arrivals for the signals is used to determine the dispersion curve and shear velocity profiles of the site.

For each spacing, the time series recorded by two receivers in the linear array are transformed to the frequency domain. The phase difference between the two receivers is used to calculate the time lag between them. This phase difference θ is related to the time lag Δt of a Rayleigh surface wave propagating between two receivers by Equation 5, where f is the frequency.

$$\Delta t = \frac{\theta}{360^\circ} \frac{1}{f} \quad (5)$$

The Rayleigh wave velocity, V_R , can then be calculated from Equation 6, where Δx is the known distance between the receivers.

$$V_R = \frac{\Delta x}{\Delta t} \quad (6)$$

Once the wave velocity is calculated for each frequency, the dispersion curve

can be determined [16].

3.2 MASW

MASW, which is known as Multi-Channel Analysis of Surface Waves, is a quicker method of evaluating the shear speed profile of a site than the SASW method. This is due to the fact that the standard SASW method usually uses two geophones that are moved multiple times to achieve the different spacings needed to cover the desired range of investigation depth. Since the tests need to be repeated in order to complete the whole procedure at one site, the standard method takes time to complete [16].

The MASW method on the other hand uses multiple geophones that cover the entire range of investigation depth. This decreases the amount of times the geophones need to be moved and the spacings need to be adjusted. Therefore, MASW is a more time efficient method than the standard SASW method to determine shear speed profiles at a site because it eliminates the necessity of repeated measurements by changing field configuration [24].

3.3 SASW Underwater

Although mainly used for land based site characterization, the SASW method is appealing for underwater applications as well. The challenges associated with characterizing geotechnical sites underwater, like difficulty accessing and observing a site, could be eased with SASW. This is due to the fact that SASW has the ability to gather information about a site remotely and in places with minimal site access [20].

The shear wave velocity is also an important indicator of lithology in marine sediment because it often varies by a factor of 10 within the first 50 meters of a sediment, as opposed to compression wave velocities which vary by less than

a factor of 2 [19]. Compression waves transmitted through soft, saturated sediments will travel at velocities close to the velocity of the fluid and obscure the properties of the sediment. On the other hand, shear waves at underwater sites cannot be transmitted through water and only reflect the mechanical properties of the sediments. Therefore the determination of shear wave velocities as part of site characterization is significant in underwater applications, like the siting of platforms and pipelines for offshore oil and gas production. [20].

In theory, the procedure for determining the shear speed profile of underwater sediments using Scholte waves is analogous to that followed for terrestrial sites using Rayleigh waves [20]. In reality, collecting surface wave measurements underwater in soft marine sediments is more complex than similar tests performed on land using the SASW method. When performing SASW underwater, the use of various sources generating a broad range of frequencies is problematic. Typically for underwater SASW testing, impulsive sources such as air guns or explosives have been used, as described in [20] and [13]. A disadvantage of using these sources is the large amount of energy that is radiated into the water column and the interference of this energy with the measurement of surface waves. For this reason, many studies using explosive sources have not provided good resolution of shear wave velocities in the near-surface sediments [12].

Another problem involves deploying and coupling the receivers with the sediment in an underwater environment. Typically, vertically gimbaled geophones are used to ensure vertical orientation of the sensors. Also, it is not practical to maintain a common midpoint array for SASW testing underwater as is done on land. The receivers are usually deployed with a linear array and a stationary source location [12].

Several small scale laboratory experiments and full scale studies conducted

by [20], [13], and [12] have shown that the SASW method works at underwater sites. The full scale field trial performed by [20] in the harbor of Venice, Italy utilized an array of vertically gimballed geophones in 5 meters of water. The shear velocity profile was developed from the experimental dispersion curve through a manual iterative forward modeling approach, which utilized a computer program called USWAVE. This program, which was developed by Dr. Lee at the University of Texas at Austin, models the site as a series of elastic, homogeneous horizontal layers on top of a homogeneous half space beneath a finite depth of water. This trial revealed that the SASW measurements and resulting shear speed profiles determined using USWAVE had the highest resolution near the surface and the resolution decreased with depth into the sediment [20].

3.4 URI Shear Measurement System

The shear measurement system, known as the Amphibious Seismo-Acoustic Recording System (ASARS), developed at the University of Rhode Island is an amphibious system that is deployable and functional on both land and in water. The main objective of research using this system is to accurately measure the shear wave velocity over large surface areas using the SASW method in order to classify the sediment. This section will describe the various components and design of the system.

3.4.1 System Components

At this time, URI has possession of: eight vertically gimballed geophones and hydrophones (Figure 6 (a)), eight HTI-94-SSQ hydrophones (Figure 6 (b)), two Geospace Sea Array 3-axis gimballed geophones and hydrophones (Figure 6 (c)), and three Several Hydrophone Receive Units (SHRUs) (Figure 6 (d)).

Figure 6. ASARS system components. (a)GS-PV1-S vertically gimballed geophone and hydrophone (b) HTI-94-SSQ hydrophone (c) Sea Array 3-axis gimballed geophone and hydrophone (d) Several Hydrophone Receive Units (SHRUs).

3.4.2 Hydrophone

A hydrophone is a passive listening device that records acoustic energy underwater and converts it into electrical energy. These devices are generally made from piezoelectric materials that generate small voltages when deformed by sound waves. A sound wave hitting the piezoelectric ceramic creates stresses in the material, which are then converted into a voltage [25]. Therefore, hydrophones detect and record pressure differences in the environment in which it is placed and convert these variations into electrical voltages.

It is desirable for hydrophones to have a flat frequency response, which means they will output the same amount of voltage per amount of acoustic excitation regardless of frequency [26]. The hydrophones utilized in the ASARS system,

HTI-94-SSQ, have a flat frequency response from 2 Hz through 30 kHz [27].

3.4.3 Geophone

A geophone is a passive seismic instrument that converts seismic energy inputs and vibrations into electrical voltages that can be measured. A classic mass-spring geophone is a simple electromechanical transducer and is used primarily as a velocity detector. The mechanical design of a geophone consists of a mass that is suspended by a system of springs enclosed within a housing. The electromagnetic system consists of permanent magnets that are attached to the housing and a coil of wire that is wound around the moving mass. The electrical signal at the output of the coil is proportional to the rate of the motion of the magnet and the coil in relation to the geophone housing [14].

The GS-PV1-S Dual Sensor (Figure 6 (a)) combines a hydrophone, which is the pressure sensor, and a geophone, which is the velocity sensor, in one unit. Combining the geophone and hydrophone into one unit is a technique used to reduce ghosting. The geophones are also vertically gimballed to ensure that the sensors are always measuring the vertical velocities through the medium [6]. The frequency response curve of these geophones is shown in Figure 7.

The Sea Array 3-axis (Figure 6 (c)) is a fully gimballed four component geophone/hydrophone unit. The gimballed unit maintains three mutually perpendicular geophones with one in the vertical and two in the horizontal, along with one hydrophone. This sensor can be used with all major ocean bottom cable systems for seismic data acquisition [28].

The three geophone units have an advantage over the use of the vertical axis geophones. The Sea Array 3-axis geophones will be able to record the multi-component wave field, whereas the vertical geophones will only be able to gather information along the vertical axis. This is usually enough when measuring the

Figure 7. Frequency response curve of GS-PV1-S geophones. [6]

vertical displacement of the sediment, but it would also be useful to know the motion of the vibrations along all three axes.

3.4.4 System Design

The vertically gimballed geophones have the ability to be deployed on cables ranging from 5 to 40 meters long, with a spacing of 5 meters. The hydrophones and 3-axis geophone and hydrophone units are part of the ASARS system upgrade. These sensors have been recently acquired by URI and have not been field tested as of yet.

The entire system design was primarily based around the SHRUs, which are the data acquisition components that were built at Woods Hole Oceanographic Institute. The SHRUs are rugged data recording units with data storage and battery power intended for long term deployments. They are designed to withstand a pressure of 5040 kPa (731 psi) [16].

Currently ASARS consists of three SHRUs. Each SHRU can receive up to four data channels at one time and are set to sample at a frequency of 1 kHz. The geophone and hydrophone data collected can be transferred from SHRU memory to a personal computer and analyzed. A MATLAB program reads the raw data recorded by the SHRUs and puts it into matrix form to make the processing of the data easier.

Each time the SHRU is turned on, the time and date must be set. This is done separately for each SHRU. This will allow all of the data channels to be synched by SHRU, but there will be a time difference between SHRUs since they cannot all be synched at the same time.

The system was designed with the intention of being towable at slow speeds, with the SHRU end caps facing aft relative to the towed direction (Figure 8). Once the system is deployed during a sea test, it is vital that the array be extended and towed along the bottom to ensure that the geophone array is straight behind the SHRUs. A type of cage was desired to keep the SHRUs from sustaining any damage, both internal and external, during the extension of the array.

Figure 8. ASARS system design for sea deployment.

For this purpose, a sled was designed that would house the SHRUs and also protect the cable junctions where the sensors connect to the SHRU (Figure 9). Once the system is deployed and extended along the seafloor, it is disconnected from the ship and left with surface buoys marking the beginning and end of the array. When the system is recording data, it is stationary on the seafloor.

Figure 9. SHRUs enclosed in sled design for deployment.

In order to isolate the system further from surface motions, a weight is placed at the end of the array to act as a damper. The weight absorbs the surface motions before they are felt by the geophones. Therefore the geophones will lie flat on the bottom and not be influenced by the surface waves.

The end buoy is first put in the water. As the boat moves in a straight line, the array is fed into the water by hand. Then the sled is lowered into the water using the A-frame. Once the sled is on the bottom, the array is stretched until it is thought that the geophones are in a straight line. The front buoy is then attached to the line and released. The system is then stationary and detached from the boat.

CHAPTER 4

Inversion of Interface Waves

The inversion of interface wave speed measurements is a well-established technique in the ocean acoustics and geotechnical communities to extract shear wave speed in the sediment. One of the key steps in the inversion approach is the modeling of the frequency dependent group or phase velocities of the Scholte interface waves for a given set of marine sediment parameters. A search is then performed for the shear speed profile which provides the best match between the modeled Scholte interface wave dispersion and the observed dispersion data [9]. There are few models available in literature which are based on simple half space sediment models or sediment dispersion with depth dependent shear speeds. A depth dependent sediment model was used in the inversion scheme and will be discussed.

4.1 Godin-Chapman Model

Godin and Chapman investigated the propagation of seismic interface waves in soft marine sediments. They determined that soft sediments can be treated mathematically as an incompressible or almost-incompressible solid based on the ratio of shear and compressional wave velocities being small. A set of analytical dispersion relations were developed that specify the phase and group speed of these interface waves as a function of frequency, mode number, and the geophysical properties of the medium. These relations can then be used in the direct inversion of experimental data to provide estimates of shear speed profiles having a power-law characteristic according to Equation 7 [29].

$$c_s = c_0 z^\nu \quad (7)$$

In the power law profile relation described in Equation 7, c_s is the shear speed,

z is the depth below the water-sediment boundary, and c_0 and ν are constants. The parameter c_0 is the shear speed at unit depth and the parameter ν , which must be in the range $0 < \nu < 1$, governs the rate of increase of the shear speed with depth [7].

Figure 10. Power-law shear speed profile for the case where $c_s = 10\sqrt{\pi}z^{1/2}$ [7].

The power-law speed profile is the case in which the shear speed increases with depth from zero at the interface (Figure 10). Two types of interface wave modes are supported by the power-law speed profile. The fundamental interface mode is the true interface wave since it is coupled to the water layer, has finite vertical particle displacement at the boundary, and is sensitive to the water-sediment density ratio. This mode is also strongly dispersive and has phase velocities on the order of the shear speed in a solid. The main sequence modes are decoupled from the water layer, meaning that the vertical displacement of these modes is zero at the boundary, and are insensitive to the density ratio [29].

Theoretical investigation of the fundamental and main sequence modes in the power-law profile reveals that the phase and group speeds scale with frequency as $f^{\nu/\nu-1}$. Also the relation between the group speed (U) and the phase speed (V) is $U = (1 - \nu)V$ for all modes and frequencies. These relations hold true when the density is constant, the shear modulus is small, and the profile of shear speed

versus depth exhibits power-law characteristics [29]. These ideal conditions exist in nature to a sufficient degree of approximation such that the theoretically derived relations are observed in experimental data [7].

The dispersion of seismo-acoustic interface waves in marine sediments with constant density follows the shear speed profile according to Equation 7

The generic dispersion relation for interface waves in a power-law profile is:

$$V_n = \left(\frac{c_0^{1/\nu} n_{eff}(n, \nu, R)}{f B_\nu} \right)^{\nu/(1-\nu)} \quad (8)$$

in which n is the mode number, $R = \rho_w/\rho$ is the ratio of water density to the sediment bulk density, $B_\nu = \sqrt{\pi} \Gamma(\frac{1-\nu}{2\nu})/\Gamma(\frac{1}{2\nu})$, and n_{eff} is the effective mode number.

The effective mode number is a dimensionless function of n , ν , and R that is determined by the solution of the wave equation with approximate boundary conditions [7]. The effective mode number for the fundamental mode is:

$$n_{eff}(n, \nu, R) = \frac{B_\nu}{2\pi} \left(\frac{2}{1+R} \right)^{1/2\nu} \exp \left[a \left(\nu - \frac{1}{2} \right) + b \left(\nu - \frac{1}{2} \right)^2 + \dots \right] \quad (n = 0) \quad (9)$$

where

$$a = (1 - \gamma - \log 2)/\nu$$

$$b = \frac{1}{\nu} \left\{ \frac{2+R}{6} \pi^2 - 1 + (1+R)^2 \left[\gamma + \Psi \left(\frac{R}{1+R} \right) \right] \right\}$$

and γ is equal to Euler's constant

$$\gamma = 0.57721$$

The analytical dispersion relations ((8),(9)) derived in this model serve as the basis for the geoacoustic inversion of experimental data for the shear profile parameters of c_0 and ν . These dispersion relations have been applied to previously

published data sets whose dispersion data exhibited the frequency scaling property indicative of a power-law profile to determine their validity in marine sediments. The continuous power-law profiles determined were compared to the staircase profiles previously published by [30], [31], [32], and [33] and in all cases the power-law profiles agreed well with the staircase profiles [7].

Two of these comparisons, taken from dispersion data gathered in sediments of coarse sand in the Straits of Sicily [32] and from sandy sediments in the Gulf of Mexico [33], are shown in Figure 11. Although the power-law profile agrees well with the staircase profiles in both cases, there are still some inconsistencies between the two profiles. In both cases it can be seen that the power-law fit, which is represented by the solid curve, is not able to resolve the upper few meters of the staircase profile. Also, in Figure 11 (b), the power-law fit is only able to fit the data down to a depth of about 2.5 meters before it diverges from the staircase profile. These examples prove that the Godin-Chapman model is not able to completely resolve the upper few meters of the profile and it is not able to adjust if the staircase profile does not continually increase with depth [7].

Figure 11. Staircase profiles from the Straits of Sicily and from the Gulf of Mexico compared with the power-law profiles (shown as the solid curve) inverted analytically from the dispersion data [7]

Although there are some disadvantages to using this model, there are also ad-

vantages. Advantages of using this model are that there are only a few parameters (c_0 and ν) that need to be inverted for and therefore the computational time it takes to invert the data is small. If the number of model parameters is large then there is a possibility of finding only a local fit, rather than a global. If the shear speed profile actually follows the power-law form, then the model presented by Godin and Chapman is a unique, robust, and quick inversion method. In reality, the sediments will most likely be layered in nature and this approach will fit a power law curve to the actual staircase profile [7].

The inversion scheme developed in this research employs a global optimization scheme to iteratively find the optimum value of c_o and ν in an efficient manner. A genetic algorithm was used as the optimization algorithm and is introduced in the following section.

4.2 Genetic Algorithms

In order to reduce the chance that the model only finds a local, rather than global fit, a genetic algorithm can be used. Genetic algorithms are a family of computational models inspired by Charles Darwin's theory of evolution. They are part of the field of evolutionary computing which encompasses a range of problem solving techniques based on the principles of biological evolution, such as natural selection and genetic inheritance [34].

Genetic algorithms are used for a number of different applications, including the optimization of non-linear systems with a large number of variables [35]. Non-linear implies that it is not possible to treat each parameter as an independent variable which can be solved in isolation from the other variables. The variables interact in such a way that the combined effects of the variables must be considered in order to maximize or minimize the output of a predefined function [36].

There are simpler solutions to the optimization problem that are based on the

use of local information to solve the problem. The limitation of these techniques is that they only find local optima, whereas genetic algorithms have the ability to escape from local minima and maxima points and find the global optimum [35]. Global optimization refers to the process of attempting to find the solution x out of a set of possible solutions S which has the optimal value for a specified fitness function f [34].

The evolutionary process of a genetic algorithm is executed by the creation of a population of individuals represented by chromosomes. The chromosomes are a set of character strings that are representative of the chromosomes that are seen in human DNA. The individuals in the population then go through a process of evolution [8].

The process of implementing a genetic algorithm is as follows:

1. Select the parameters to optimize.
2. Determine a chromosomal representation of these parameters.
3. Generate an initial population of the individuals represented by the chromosomes.
4. Evaluate the fitness of all of the individuals in the population.
5. Create a new population by comparing the fitness of randomly selected individuals, keeping the most fit members and discarding the least fit.
6. Iterate the new population.

One iteration of steps 3 through 6 is referred to as a generation, shown in Figure 12, where the parents are the most fit individuals in that generation. The first generation of this process operates on a population of randomly generated individuals [8].

Figure 12. Flowchart showing process of iterating a genetic algorithm [8].

Each random individual is tested to determine its fitness level, keeping only the most fit members. This process is reminiscent of Darwins Survival of the Fittest. In other words, the fitness of the population improves with every iteration and the most fit members remain. These iterations continue until the process converges on the optimum solution or until predetermined criteria are met. The genetic algorithm can reach a global optimum as long as enough iterations are performed [37].

4.3 Implementation of Godin-Chapman Model

An inversion scheme was developed to invert interface wave dispersion data using a genetic algorithm with the Godin-Chapman model as the forward model. The Godin-Chapman model was implemented in MATLAB and applied to dispersion data of marine sediments. The approximate dispersion relations were applied to the data to invert for the parameters c_0 and ν , which define the shear speed variation in the sediment, with an assumed value of R for the fundamental mode. The algorithm uses Equations 8 and 9, which make up the Godin-Chapman model, and iterates inputted ranges of c_0 and ν using a genetic algorithm to find the best fit between the experimental and theoretical dispersion data. The values of the parameters of the best fit describe the shear speed profile of the dispersion data.

The inversion scheme process is shown in Figure 13.

Figure 13. Flowchart showing the inversion scheme process utilizing the Godin-Chapman model and a genetic algorithm to solve for the best parameters.

The purpose of the objective function used in this process is to minimize the error between the experimental dispersion curve data and the theoretical data given by the Godin-Chapman model. The objective function used determines the root-mean-square error (RMSE) between the two data sets. RMSE is frequently used to measure the differences between values predicted by a model or an estimator and the values actually observed. The RMSE is determined according to Equation 10, where $\hat{Y}$ is the vector of predicted values and Y is the vector of observed values [38].

$$RMSE = \frac{1}{n} \sum_{i=1}^n (\hat{Y}_i - Y_i)^2 \quad (10)$$

Once the ideal shear speed profile is determined, the depth limitation of the inversion is calculated. A maximum valid depth needs to be determined because

the power law profile that is derived from the dispersion relations will in theory extend indefinitely in depth, but this is unlikely to hold true in nature. Dispersion experiments probe the shear speed profile up to a certain depth that is determined by the lowest frequency. Below this depth, the actual shear speed profile has little influence on the dispersion measurements. Therefore the inversion to a power-law profile is only trustworthy to a maximum depth z_{max} , given by:

$$z_{max} = 2(V_{max}/c_o)^{\frac{1}{\nu}} \quad (11)$$

where $V_{max} = V(f_{min})$ is the maximum measured phase speed, which occurs at the lowest frequency of measurement, f_{min} , and the c_o and ν parameters are those given by the inversion model [7].

4.4 Validation of Inversion Model

The inversion scheme described above, which utilizes the Godin-Chapman model and a genetic algorithm, was validated against published dispersion data to ensure that it was implemented correctly. The output of the model was compared with dispersion results from Rauch, which were also used to validate the model presented in [9]. Figures 14 (a) and (b) show the output of the inversion scheme with Rauch's results. Figure 14 (a) shows a good fit between the experimental dispersion data, shown as blue dots, and the theoretical dispersion curve determined from the Godin-Chapman model, shown in red. The values of c_o and ν that were used to generate this dispersion curve are then taken as the ideal values of these parameters.

When these values were used in Equation 7, a shear speed profile representative of the dispersion data was determined and shown in Figure 14 (b). The profile determined from the model is not able to fit the upper few meters of the actual staircase profile, which was expected after looking at the model compared to other

dispersion data shown in Figure 11. The model fit also seems to underestimate the shear speed profile and follow the minimum values of the shear speed. While these two discrepancies should be noted, overall the power-law profile determined from the model provides a good fit to the staircase shear speed profile presented by Rauch. Therefore, the present model was assumed to be implemented accurately and was used as part of the inversion scheme used to invert experimental dispersion data to shear velocity profiles.

Figure 14. Comparison of the Godin-Chapman model results with published results presented in [9]

CHAPTER 5

Geotechnical Ground Truth Data

While the forward model has been validated against previously published dispersion data as shown in Figures 11 and 14, the validation of the entire inversion scheme is still necessary. The inversion scheme consists of the process from data collection to the implementation of the forward model to the estimation of the best sediment shear speed profile. One way to perform this validation is to collect dispersion data in an area with previously published bottom data. One such site that exists in Rhode Island with this type of data is in the Davisville Basin.

5.1 Davisville Site

In 1981 the Maguire Group prepared a report for the possible expansion of the port in Davisville, RI. During this site investigation eighteen soil borings were obtained in the Davisville Basin. The borings, which were taken by Guild Drilling Company of East Providence, RI between March and April 1980, were patterned so as to yield geological and geotechnical information on the overburden and bedrock structural regimes throughout the site [39].

From a laboratory analysis of outwash sediments, it was found that from the depths of 0 to 12.19 meters, the sediment is characterized as medium-dense, fine to medium sand and silt. Any gravel observed within these depths is confined to minor sediment fractions occurring in thin, shallow lenses. The borings showed that the surficial sediment is a stratum of extremely loose and compressible organic silt from 0.304 to 3.04 meters thick. Underneath this is a deposit of medium dense, fine to medium sand which is locally varved with silt from 4.57 to 13.71 meters thick. This overlies a thin (1.52 to 4.57 meter thick), but ubiquitous layer of very dense glacial till. The final stratum was bedrock, consisting of shale, both graphitic

and nongraphitic in composition [39].

5.2 Information Contained in a Soil Boring Log

The extraction of soil borings at a site is a type of subsurface exploration that aims to retrieve information about the conditions below the ground surface. When borings are taken, a hole is advanced into the ground and samples of the material are taken at defined intervals. The information that is retrieved is recorded on a log as a way of documenting the findings and transferring the information to others [40].

The boring logs taken in the Davisville Basin detail the soil layers by depth from the surface. The log contained information such as the soil classification, sampling points, blow counts per foot, and drill refusal. One of the more important pieces of information reported in these logs was the Standard Penetration Test (SPT) blow count, or N-value.

When the driller reaches a certain sampling depth, the sample is retrieved by driving a standard sampler into the undisturbed soil. The driller advances the samples into the soil by using a 140-lb (63.5 kg) weight (hammer) falling 30 inches (0.76 meters). The number of hammer blows required to drive the sampler into the soil in 6 inch (0.15 meter) increments is recorded. The sum of the blows for the second and third driven interval (6 inches to 12 inches and 12 inches to 18 inches) provides the standard penetration resistance, or N-value [40].

The procedure used in the field to generate the N-value varies due to changes in the standard, variations in the test procedure, and poor workmanship. The test results are sensitive to these variations and will vary depending on the crew and equipment. Therefore the N-value is not a very repeatable measurement [41].

The N-value is the basis for many geotechnical engineering calculations and is a very important measure of the soil properties. The more blows needed to

advance the sampler, the denser the soil. Loose or soft soils will have blow counts of less than 10. Blow counts of 10 to 50 blows per foot usually mean the ground will be easily excavated. When the blow counts are over 50 but less than 100, ripping of the ground is likely. When the blow counts are over 100, the ground may be difficult to excavate and require blasting [42].

5.3 Correlating Blow Count to Shear Velocity

In order to compare the information contained in these boring logs to the output of the inversion model, the shear speed profile of the Davisville Site had to be estimated. Since the N-value is only an index of soil behavior and does not measure any of the conventional properties of soil, it had to be correlated to the shear speed.

There are many relations between the SPT blow count, N , and shear speed, V_s , that exist in literature; some are shown in Table 2. Some of the early correlations often involve blow counts that were not corrected for energy, rod length, or sample inside diameter. Therefore it is not known whether bias was introduced by the hammer efficiency or other sample issues. Also, there are various methods of measuring shear speed in-situ, including cross-hole, seismic CPT, SASW, and suspension logging. These different methods provide different resolutions for the shear speed measurements at different depths [2].

Author(s)	All soils	Sand	Silt	Clay
Shibata (1970)	-	$V_s = 31.7 N^{0.54}$	-	-
Ohba and Toriuma (1970)	$V_s = 84 N^{0.31}$	-	-	-
Imai and Yoshimura (1975)	$V_s = 76 N^{0.33}$	-	-	-
Ohta et al (1972)	-	$V_s = 87.2 N^{0.36}$	-	-
Fujivara (1972)	$V_s = 92.1 N^{0.337}$	-	-	-
Ohsaki and Iwasaki (1973)	$V_s = 81.4 N^{0.39}$	-	-	-
Imai et al (1975)	$V_s = 89.9 N^{0.341}$	-	-	-
Imai (1977)	$V_s = 91 N^{0.337}$	$V_s = 80.6 N^{0.331}$	-	$V_s = 80.2 N^{0.292}$
Ohta and Goto (1978)	$V_s = 85.35 N^{0.348}$	-	-	-
Seed and Idriss (1981)	$V_s = 61.4 N^{0.5}$	-	-	-
Imai and Tonouchi (1982)	$V_s = 96.9 N^{0.314}$	-	-	-
Sykora and Stokoe (1983)	-	$V_s = 100.5 N^{0.29}$	-	-
Jiran (1987)	$V_s = 116.1 (N+0.3185)^{0.202}$	-	-	-
Okamoto et al (1989)	-	$V_s = 125 N^{0.3}$	-	-
Lee (1990)	-	$V_s = 57.4 N^{0.49}$	$V_s = 105.64 N^{0.32}$	$V_s = 114.43 N^{0.31}$
Athanasopoulos (1995)	$V_s = 107.6 N^{0.36}$	-	-	$V_s = 76.55 N^{0.445}$
Sisman (1995)	$V_s = 32.8 N^{0.51}$	-	-	-
Iyisan (1996)	$V_s = 51.5 N^{0.516}$	-	-	-
Kanai (1966)	$V_s = 19 N^{0.6}$	-	-	-
Jafari et al (1997)	$V_s = 22 N^{0.85}$	-	-	-
Kiku et al (2001)	$V_s = 68.3 N^{0.292}$	-	-	-
Jafari et al (2002)	-	-	$V_s = 22 N^{0.77}$	$V_s = 27 N^{0.73}$
Hasancebi and Ulusay (2006)	$V_s = 90 N^{0.309}$	$V_s = 90.82 N^{0.319}$	-	$V_s = 97.89 N^{0.269}$
Ungererli and Uyank (2007)	${}^a V_{su} = 23.291 \ln(N) + 405.61$	-	-	-
Ungererli and Uyank (2007)	${}^b V_{su} = 52.9 e^{-0.011N}$	-	-	-
Dikmen (2009)	$V_s = 58 N^{0.39}$	$V_s = 73 N^{0.33}$	$V_s = 60 N^{0.36}$	$V_s = 44 N^{0.48}$
Pitlikis et al (1999)	-	$V_s = 145(N_{60})^{0.178}$	-	$V_s = 132(N_{60})^{0.271}$
Hasancebi and Ulusay (2006)	$V_s = 104.79(N_{60})^{0.26}$	$V_s = 131(N_{60})^{0.205}$	-	$V_s = 107.63(N_{60})^{0.237}$

Table 2. Some existing correlations presenting V_s as a function of SPT blow count, N [2].

Although there are many areas of bias or uncertainty that can be introduced in the blow count to shear speed correlations, most of the relations utilize the form of $V_s = A * N^B$, where A and B are constants determined by the statistical regression of a data set. The N -values are typically not corrected for overburden stress, but are sometimes corrected for hammer energy, rod length, and sampler

inside diameter. If the values are corrected for these three areas, then N is known as N_{60} . If the N value is also corrected for overburden stress, then it is known as $(N_1)_{60}$ [2].

While the ideal correlation to use for the Davisville site borings would be one that uses constants that were determined by the statistical regression of a data set taken from Davisville, this was not possible for this test. Therefore, the next best thing was to determine which correlation would yield the best estimate of the shear speed profile for Davisville.

Some of the correlations shown in Table 2 are broken up by soil type. Sykora and Stokoe (1983) suggest that geological age and type of soil are not important parameters in determining V_s , while the uncorrected SPT N -value is most important. Hasancebi and Ulusay (2006) also determined that the correlations for different soil categories yield similar values of V_s , indicating that the soil type has little effect on the correlations. Due to these observations, the general soil relations were used where applicable.

Different variations of N are also presented in Table 2. Hasancebi and Ulusay (2006) suggest that the equations based on the uncorrected N -value provide a better fit to the actual data than the equations based on the energy-corrected N_{60} value of the blow counts. Due to these significant differences in SPT equipment and practices around the world, it is not unreasonable for uncorrected N -values to vary by $\pm 50\%$ of the median value [10]. Therefore the equations based on the uncorrected values are preferable for indirect estimations of V_s and an equation developed for all soils based on this uncorrected N -value should be used for practical purposes [43].

5.4 Shear Speed Profile of Davisville Site

The boring logs BH-15 and BH-8 were the boring logs used to estimate the shear speed profile of the Davisville site. The full boring logs are provided in Appendix A. The profiles of the SPT N-values contained in these boring logs versus depth into the sediment are shown in Figure 16.

Figure 16. Profiles of the SPT N-values contained in the boring logs of BH-15 and BH-8.

The shear speed profile for each boring was estimated according to various correlation equations. Correlations are not meant to replace measurements of shear wave velocity, but rather to estimate a potential range of values when direct measurements are not available. It is recommended that a few different correlations be used to develop an idea of the potential range of values [10].

According to the recommendation of [10], three correlation equations were considered to provide a range of possible shear speed values. The recommended correlations generally had higher correlation coefficients between the dispersion data during the regression analysis. Together they represent a range of estimated shear wave velocities. The relationships proposed for all soils were used and are indicated below.

1. $V_s = 56N^{0.5}$ from Seed et al, 1983

2. $V_s = 97N^{0.314}$ from Imai and Tonouchi, 1982

3. $V_s = 32.8N^{0.51}$ from Sisman, 1995

A comparison of the estimated shear wave velocity values for various correlations for all soils is shown in Figure 17. The recommended equations are shown in bold.

Figure 17. Comparison of estimated shear wave velocity from various SPT correlations for all soils [10]

The resulting range of shear speed values estimated from boring BH-15 using the above three correlations is shown in Figure 18.

Figure 18. Range of shear speed values for boring BH-15 estimated from correlations presented by Seed et al, 1983, Imai and Tonouchi, 1982 and Sisman, 1995 for all soils.

The resulting range of shear speed values estimated from boring BH-8 using the above three correlations is shown in Figure 19.

Figure 19. Range of shear speed values for boring BH-8 estimated from correlations presented by Seed et al, 1983, Imai and Tonouchi, 1982 and Sisman, 1995 for all soils.

These three correlations provide a range of shear speed values for the Davisville site. This range of values was used to validate the inversion scheme by comparing the inverted shear speed profile generated from the dispersion data taken at Davisville.

Figure 15. Davisville Basin showing borings taken by Guild Drilling Company in 1980. [39]

CHAPTER 6

Davisville Test

A test of URI's Shear Measurement System was completed on February 5, 2013 in Fry's Cove in Davisville, RI. The purpose of this test was to collect Scholte interface wave data in an area with previously published bottom sediment data. Previous tests have proved that the measurement system is capable of sensing and recording both Rayleigh and Scholte seismic interface waves. A technique has been developed to invert the dispersion of these seismic interface waves for shear speed profiles. This inversion scheme had to be validated against published shear wave speed data to ensure its accuracy. This validation was achieved by using the interface wave data collected in Davisville, RI and inverting this data to obtain a shear speed profile to compare to the previously published sediment data contained in the boring logs.

6.1 Test Description

The location of this test was in the Fry's Cove area of the Davisville Basin in Davisville, RI (Figure 20). Dredging was taking place in the Davisville Channel, but the testing was planned in areas that were not impacted by these operations.

Figure 20. Narragansett Bay showing location of Davisville, RI.

[39]

6.2 Test Setup

For this test the R/V Shanna Rose was utilized as the testing vessel (Figure 21 (a)). The URI Shear Measurement System was used to record seismic interface waves generated by a 114 kg weight impacting the bottom (Figure 21 (b)). The shear measurement system consisted of the sled holding two SHRUs and eight geophones, referred to as geophones A,B,C,D,E,F,G,and H. Geophones A,B,C,and D were connected to one SHRU and geophones E,F,G,and H were connected to the other SHRU. The weight drop setup was such that the weight was able to free fall underwater from a height of 1.5 meters and 2.4 meters off the bottom. The winch on the boat was used to pick the weight up after each drop.

(a) R/V Shanna Rose

(b) Weight, Geophones, and SHRUs in the Sled

Figure 21. Equipment used during Davisville Test.

6.3 Test Summary

The testing took place on February 5, 2013 between the hours of 10:00 AM and 2:00 PM. Due to the shallow waters in the area of testing, the test was planned around the high tide in Fry's Cove, which occurred around 3:30 PM. This timing ensured that the boat would have enough water depth to access the shallow areas of the cove where the borings were taken.

During the duration of the test, the system was deployed twice. For the first deployment, the geophones were arranged in a linear array which had an effective spacing of 1.25 meters between sensors. The order of the sensors was A-E-B-F-C-G-D-H and the total length of the array was 8.75 meters (Figure 22).

Figure 22. Setup of the geophones for the first deployment. Spacing between geophones was 1.25 meters. The total length of the array was 8.75 meters.

The array was deployed so that it lay parallel to the pier over boring BH-15 (Figure 23). The deployment went very smoothly and the system was in position and detached from the boat within 10 minutes of when it first entered the water.

Figure 23. First deployment of array over BH-15. Buoys indicate ends of array.

After the array was in place, the boat moved away from the sled in a direction parallel to the pier and dropped the weight. The weight, as shown in Figure 24, was dropped at ranges of 10 to 100 meters away from the sled at intervals of 10 meters (Figure 26) . It was dropped three times at each interval from a height of 1.5 meters off the bottom. At the 100 meter distance the weight was dropped three extra times from a free fall height of 2.4 meters.

Figure 24. Weight used as the source to generate seismic waves on the bottom.

Then the system was recovered and the SHRU program was stopped to ensure that data was collected. There was a problem with the data storage on one of the SHRUs and none of the drops were recorded on geophones E,F,G,and H. The other SHRU recorded the entire deployment. This problem was fixed and the array was deployed for a second time.

For the second deployment the linear array had an effective spacing of 5 meters between sensors and a total length of 40 meters. The order of the geophones was A-B-C-D-E-F-G-H (Figure 25). It was placed perpendicular to the pier over boring BH-15.

Figure 25. Setup of the geophones for the second deployment. Spacing between geophones was 5 meters. The total length of the array was 40 meters.

Once the array was in the water the boat backed away from the sled in a northerly direction. The weight was dropped for a range of 10 meters to 100 meters from the sled at intervals of 10 meters (Figure 26). Three drops were done at each interval from a drop height of 2.4 meters. Then the weight was dropped twice at a range of 130 meters, 170 meters, 210 meters, 250 meters, and 290 meters from the array.

Figure 26. Locations of the geophone array and weight drops for each deployment. The locations of BH-15 and BH-8 are approximate.

The array was then recovered and the SHRU program stopped to ensure that data was collected. Both SHRUs recorded the entire second deployment. The locations of the array and weight drops for both deployments relative to the borings are shown in Figure 26.

6.4 Geophone Data

The first deployment of the system consisted of a total of 33 weight drops (Figure 27 (a)). These weight drops were recorded on geophones A,B,C,and D which were spaced 2.5 meters apart. All of the drops are visible in the raw time series of all four geophones.

Figure 27. Raw data from geophone A for both deployments.

The second deployment of the system consisted of a total of 40 weight drops (Figure 27 (b)). These drops were recorded on all of the geophones, which were spaced 5 meters apart. Although all of the channels recorded the drops, the time series of geophones A,B,C,and D were less noisy than the time series of geophones E,F,G,and H. Therefore,the data sets from geophones E,F,G,and H were not used in the following analysis.

Figure 28 shows one of the weight drops from the first deployment recorded on geophones A, B, C, and D. This drop was at a 100 meter range from the array and the weight was dropped from a height of 1.5 meters off the bottom. The time delay is evident between the geophones, with geophone A receiving the signal before geophone D.

Figure 28. Weight drop shown on geophones A, B, C, and D to demonstrate the time delay between sensors. This weight drop was at a range of 100 meters from the array and from a free fall height of 1.5 meters. The time shown on the x-axis is arbitrary.

During the second deployment, the weights were all dropped from a height of 2.4 meters off the bottom. The difference in height resulted in a different amount of energy being transferred to the bottom sediment. Therefore the amplitudes of the signals recorded by the geophones differed based on the free fall height of the weight. Figure 29 demonstrates this difference in amplitudes between drop heights.

Figure 29. Time series of weight drop recorded on geophone A at a range of 100 meters. The free fall height for deployment 1 was 1.5 meters and the free fall height for deployment 2 was 2.4 meters. Amplitudes are normalized to that of the signal from deployment 2. The time shown on the x-axis is arbitrary.

The weight drop shown was the drop at a range of 100 meters from the array in both deployments as recorded on geophone A. The amplitude was normalized to that of the drop from the second deployment. The difference in drop height of the weight resulted in roughly a 35% reduction in the amplitude of the signal.

6.4.1 Time-Frequency Analysis

A time-frequency analysis was performed on the signals shown in Figure 29, which were both recorded at a larger distance from the source, in order to observe the dispersive effects of the signal. The analysis was performed using a wavelet transform, which is a useful tool used to discover the time-frequency structure of wideband acoustic signals that travel in dispersive waveguides. It can be used to model the modal dispersion characteristics of wideband acoustic arrivals, where the lower frequency components of a particular mode have a slower arrival time and the higher frequency components arrive earlier [44].

The wavelet transform is a localized transform in both time and frequency, which allows information to be extracted from the signal that would not be possible using a Fourier transform [45]. The scalogram of the signal, which is the square of

the absolute value of the output from the wavelet transform, was produced for each weight drop (Figure 30). Compared with Fourier Analysis, wavelet analysis is able to dilate or compress according to each spectral component. Thus, the resolution of the scalogram is dependent on frequency. The drawback of the scalogram is that its spectral resolution becomes poorer as the frequency increases. Therefore it is difficult to extract the time-frequency structure of the higher modes [44].

Figure 30. Time-frequency scalograms of the time series recorded on geophone A for a weight drop at a range of 100 meters from the array. The time in seconds is arbitrary. The color scale is also arbitrary and corresponds to energy in the signal.

The scalograms presented in Figure 30 illustrate the dispersive nature of the interface waves as they travel through the sediment and allow the modal arrival times to be accurately observed. The distribution of frequencies present in the signal are displayed as a function of time, with the higher frequencies showing an earlier arrival time as compared to the lower frequencies. From these figures it can be determined that the majority of the energy is contained in the frequency band between 5 and 30 Hz.

The wavelet components of the signals also result in a wave group representation of the dispersed signal. This representation of the transient signal generated from the weight drops can be used to illustrate the group velocity of the wave packet, which determines how fast the energy in the wave packet propagates. The

dispersive nature of these waves causes the shape of the overall wave form to change with time and spread out. This is because the group velocity also depends on frequency, and since there is a range of frequencies contributing to the wave packet, there is a range of group velocities which cause the spreading effect [46].

The time-frequency analysis shown in Figure 30 (b) shows the presence of two modes as compared to the one mode present in the signal shown in Figure 30 (a). There were more modes present in the signal from the second deployment because the weight was dropped from a larger height and therefore more energy was transferred into the sediment. This in turn was able to generate higher order modes that were recorded at a range of 100 meters. The first deployment only reveals one mode that was recorded at the same range.

6.4.2 Geometrical Damping

In addition to the presence of a time delay between sensors, an amplitude decay is also seen. As the interface waves generated by the weight drop propagate away from the source, they experience losses due to sediment interaction. This causes their energy density, and in turn their amplitude of motion to decrease. This decrease in motion amplitude with distance is known as geometrical damping. Body waves attenuate in proportion to r^{-2} while interface waves decay in proportion to $r^{-1/2}$, where r is the distance from the source [47].

Geometrical damping was observed in the raw geophone data of the weight drops in both deployments. It was compared to the published relations that describe the amplitude decay over distance of body and interface waves. These comparisons are shown in Figure 31.

Figure 31. Amplitude decay versus distance determined from the signal of one weight drop as seen on all four sensors. The rate of decay of interface and body waves are compared to the amplitude decay seen in the raw geophone data for both deployments.

The amplitude has been normalized to that of geophone A from each of the respective deployments to show the decay in amplitude between sensors. The weight drop recorded on geophone A has the highest amplitude since it is the closest sensor to the source. The amplitude of the weight drop on geophones B, C, and D decays as the sensor gets farther away from the location of the source. The x-axis indicates the distance of each geophone from geophone A, which is located at 0 meters. The proceeding geophones are spaced 2.5 meters apart for the first deployment and 5 meters apart for the second deployment. Therefore the locations of the sensors, indicated by dots in Figure 31, increment by 2.5 and 5 meters respectively.

The decay of the weight drop amplitude in both deployments is most similar to the rate of decay of an interface wave amplitude. Therefore it can be concluded that the waves recorded by the geophones were indeed interface waves and not body waves.

CHAPTER 7

Davisville Test Data Processing

The data sets collected during both deployments were processed using the SASW method in order to form the composite dispersion curves for the Davisville site. To determine the Scholte wave speeds for the dispersion curves, the time delay between each geophone pair for every weight drop had to be determined. The analysis of both deployments used an array of four geophones, which created a total of six geophone pairs for each weight drop (Figure 32).

Figure 32. Geophone pairs used during the data processing. The time delay of each weight drop for each pair was determined.

The actual time delay between geophone signals could not be determined visually. This was due to the fact that the spacing between geophones in this test was small, which caused the time of arrival of the impulses to be close together in the time record. Therefore, in order to determine the time delay between geophone signals, the phase shift between signals in the frequency domain was used.

7.1 Coherence

The first step to developing the dispersion curve was to determine which weight drops had the highest signal to noise ratio (SNR) and were therefore recorded best by the geophones. This was done by looking at the frequency coherence between pairs of geophones. The magnitude squared coherence is a function of the power spectral densities ($P_{xx}(f)$ and $P_{yy}(f)$) and the cross power spectral density ($P_{xy}(f)$) of the signal recorded on two geophones, as described in Equation 12.

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)} \quad (12)$$

It is used to provide a measure of the mutual information between two signals [48]. The weight drops that produced high coherence in the frequency range of 5 Hz to 30 Hz were used to develop the dispersion curve for the site. An example of a shot with high coherence in the desired frequency range is shown in Figure 33.

Figure 33. An example of a weight drop that produced high coherence between geophones A and B, which were spaced 5 meters apart. This specific weight drop was the first drop from the second deployment at a range of 10 meters from the array.

It can be seen that the coherence is high (close to 1) in the frequency range of 5 Hz to 30 Hz. This indicates that the data in this frequency range will be ideal for further analysis and inversion.

7.2 Spectral Analysis

Once the best drops for further processing were identified, the next step was to determine the frequency content of the time records in order to compare the signals more easily and accurately. First, the frequency content of each individual signal

was investigated. This was accomplished by taking the power spectral density of the signal to determine the frequency ranges with the highest amounts of energy.

Taking the power spectral density (PSD) of a signal will provide an understanding of how the strength of the signal is distributed in the frequency domain. The computation of the PSD is done directly by taking the Fast Fourier Transform (FFT) of the signal. Figure 34 shows the PSD of the first weight drop from the second deployment recorded on geophone A, which reveals that the signal is strongest below 30 Hz.

Figure 34. Power spectral density of the first weight drop from the second deployment at a range of 10 meters from the array.

Next, the relationship between the time series from two different geophones was determined. To accomplish this, the cross power spectral density (CPSD) of the two signals was calculated. The CPSD is defined as the distribution of power per unit frequency according to Equation 13, where P_{xy} is the cross power spectral density of the discrete time signals x and y [49].

$$P_{xy}(\omega) = \sum_{m=-\infty}^{\infty} R_{xy}(m)e^{-j\omega m} \quad (13)$$

The CPSD yields valuable information about the relationship between the two signals. It was used to identify the predominant frequency range present in both geophone signals. The corresponding phase shift between signals was determined by taking the phase of the CPSD, unwrapping the phase, and using the predominant frequency range to identify the range of phase delay values.

Unwrapping is a method that corrects the phase angles to produce smoother phase plots. It is based on the assumption that phase jumps by more than π radians must have been "wrapped". Therefore, multiples of 2π are added or subtracted so that the phase changes by no more than $\pm\pi$ from one spectral bin to the next [50]. Once the spectrum had been unwrapped (Figure 35 (b)), the range of phase shifts relating to the predominant frequency range was determined.

Figure 35. Wrapped and unwrapped phase spectrums for the first weight drop during the second deployment, which was at a range of 10 meters from the array.

7.3 Dispersion Curves

Using the range of phase shifts determined from the unwrapped spectrum and Equations 5 and 6, the Scholte wave speeds were calculated for the predominant frequency range. Scholte wave speeds were calculated for all six geophone pairs

for all of the weight drops that generated high coherence in the signals. All of the wave speeds were plotted versus frequency to produce the composite dispersion curve of the test area for each deployment (Figure 36 (a) and (b)).

Figure 36. Composite phase velocity dispersion curves generated using the weight drops with the highest coherence from each deployment. The colors are arbitrary and represent the different weight drops and the different geophone pairs.

7.4 Inversion

7.4.1 Simplified Inversion (Elastic Half-Space Inversion)

Before the URI inversion scheme was performed on the dispersion data from the two field deployments, a simple inversion presented in [11] was done. This inversion assumed the shear speeds in the elastic half-space sediment model and iteratively fit the resultant dispersion curve to the data. This simplified inversion gives a relationship between phase speed and shear speed versus frequency. A relationship between the phase speed and shear speed was determined by iterating the shear speed in the half-space.

In order to determine the relationship, a Scholte wave propagating along the interface between two homogeneous, isotropic, and non-dissipative half-spaces was considered. The situation, as shown in Figure 37, assumes the water has a sound speed c_0 , a density ρ_0 , and is at a depth z which is less than zero. The sea bottom is assumed to be an elastic medium at a depth greater than zero, a P-wave speed

c_{p1} , a S-wave speed c_{s1} , and a density ρ_1 .

Figure 37. Wave propagation in a half-space water column over a homogeneous half-space solid bottom. R_b is the reflection coefficient of the bottom [11].

The water depth is assumed infinite and therefore there is no reflection from the sea surface. The expression for the phase speed of the Scholte wave is given by Equation 14.

$$4\sqrt{1 - \left(\frac{v_p}{c_{p1}}\right)^2} \sqrt{1 - \left(\frac{v_p}{c_{s1}}\right)^2} - \left(2 - \frac{v_p^2}{c_{s1}^2}\right)^2 = \frac{\rho_0}{\rho_1} \left(\frac{v_p}{c_{s1}}\right)^4 \frac{\sqrt{1 - \left(\frac{v_p}{c_{p1}}\right)^2}}{\sqrt{1 - \left(\frac{v_p}{c_{p0}}\right)^2}} \quad (14)$$

The solution to Equation 14 always has one positive real root, which is the Scholte wave speed $v_p = v_{Sch}$.

In finite water depth, the sound propagates as in a waveguide by reflections from both the sea surface and the bottom. In this case, the dispersion relation is given by Equation 15. When the water depth D goes to infinity, this expression becomes identical to Equation 14 for infinite water depth. This dispersion equation gives the phase speed as a function of frequency for given media parameters and layer thickness.

$$\begin{aligned}
& 4\sqrt{1 - \left(\frac{v_p}{c_{p1}}\right)^2} \sqrt{1 - \left(\frac{v_p}{c_{s1}}\right)^2} - \left(2 - \frac{v_p^2}{c_{s1}^2}\right)^2 \\
& = \frac{\rho_0}{\rho_1} \left(\frac{v_p}{c_{s1}}\right)^4 \frac{\sqrt{1 - \left(\frac{v_p}{c_{p1}}\right)^2}}{\sqrt{1 - \left(\frac{v_p}{c_{p0}}\right)^2}} \tanh \left(\frac{\omega D}{v_p} \sqrt{1 - \left(\frac{v_p}{c_{p0}}\right)^2} \right)
\end{aligned} \tag{15}$$

The dispersion equation (Equation 15) can be solved numerically for the phase speed v_p . The average phase speed determined from the dispersion curves from the deployments was used to determine a quick and robust relationship between phase speed and shear speed. This numerical solution, shown in Figure 38, used the geoacoustic parameter values $\rho_0 = 1000kg/m^3$, $\rho_1 = 2000kg/m^3$, $c_{p0} = 1500m/s$, $c_{p1} = 2500m/s$, and $c_{s1} = 110m/s$. The water depth D was taken to be 2.4 meters.

Figure 38. Phase speed of an interface wave, relative to the S-wave speed, expressed as a function of the frequency-thickness product $f * D$ for the numerical values provided. Average phase speed from the dispersion curves of the Davisville site was used.

Since the frequency appears only in a product with the water depth, the speed must be a function of the product of f and D . Figure 38 shows that the phase

speed of the interface wave is slightly lower than the S-wave speed and that the phase speed decreases slightly with increasing frequency. This implies that the interface wave is dispersive in the general case with finite water depth D . When the water depth is infinite, the phase speed of the interface wave is approximately 90% of the S-wave speed in the bottom. When the water depth is zero, the speed is about 95% of the bottom S-wave speed [11].

This simple inversion provides a quick and robust method of comparing the relationship between phase speed and shear speed.

7.4.2 URI Inversion Scheme

A more accurate and realistic, but computationally efficient, scheme of inverting the dispersion curves was developed. Once the dispersion curves were determined for each the deployment, the inversion scheme was applied to the curves to determine the shear velocity profile related to the curve. To do this, the outliers were eliminated from the composite dispersion curve and the phase velocities were averaged over frequency to produce a mean dispersion curve representative of the composite. The representative curves for both deployments are shown in Figure 39 .

Figure 39. Comparison of the averaged dispersion curves for both deployments that were used in the inversion scheme.

The dispersion curve generated for the first deployment shows higher phase velocities than the curve generated for the second deployment. The slope of the curve between 5 Hz and 10 Hz is different between the two deployments, but seems to be more similar at higher frequencies. These differences in the dispersion curves will result in differences in the shear speed profiles determined from the inversion process.

These averaged curves were then run through the inversion scheme to determine the best fit power law shear speed profile. The parameters were given bounds as shown in Table 3. These values were run through the genetic algorithm for 500 generations, with a population size of 100 for each generation.

Parameter	Lower Bound	Upper Bound
c_0	20	200
ν	0	1

Table 3. Bounds of power-law profile parameters run through inversion scheme to find ideal fit.

The dispersion curves were also separated into sections before they were run through the inversion scheme. The lower frequency portion of the curve was run through the program and an ideal c_0 and ν were determined. The higher frequency portion of the curve was then run through the program and a separate ideal c_0 and ν were determined. The bounds of the low and high frequency portions for each deployment are shown in Table 4. The parameters chosen to represent the shear speed profile from each deployment were a combination of the two inversion scheme runs.

	Low Frequency Bounds		High Frequency Bounds	
	Lower	Upper	Lower	Upper
Deployment 1	5.2 Hz	7.3 Hz	7.3 Hz	24.3 Hz
Deployment 2	5.2 Hz	13.3 Hz	13.3 Hz	30 Hz

Table 4. Low and high frequency portions of the dispersion curve used in the inversion process for each deployment.

The c_0 parameter was determined from the higher frequency portion of the curve because this is where it has the most impact. On the other hand, the ν impacts the lower frequency portion most but impacts the higher frequency part as well. Therefore the representative ν parameter was an average of the values given from both runs of the inversion scheme. The final parameter values to define the shear speed profile inverted from the averaged dispersion curves are given in Table 5.

Parameter	Deployment 1	Deployment 2
c_0	95.98	91.81
ν	0.3633	0.2677

Table 5. Best fit parameters defining the power-law shear speed profile given by the inversion scheme for both deployments.

The standard deviations around the averaged dispersion curves were also de-

terminated. The upper and lower standard deviation limits were run through the model as well. This gives a range of shear speed profiles that were applicable to each deployment. The resulting shear speed profiles for both deployments are shown in Figure 40.

Figure 40. Comparison of the shear speed profiles generated through the inversion of the dispersion curves with standard deviation upper and lower limits.

Once the inversion was completed, Equation 11 was used to estimate the depth to which the inversion was valid. The maximum depth that the first deployment inversion was valid to was 22.39 meters, while the maximum depth for the second deployment was 30.75 meters. The inversions for both deployments were compared to each other down to the minimum valid depth of 22.39 meters.

When comparing the profiles determined from both deployments, it is seen that the inversion of the dispersion curve from the first deployment results in a profile with higher shear speeds than that from the second deployment. This is due to the fact that the dispersion curve for this deployment, shown in Figure 39, has higher phase velocities than the second deployment over the same frequency range. Therefore the higher phase speeds correlate to higher shear speeds when

inverted.

Also, the rate of decay of the inverted shear speed profiles for both deployments differ slightly as well. The rate of decay, which is controlled by the ν parameter, could differ due to the different slopes in the lower frequency portion of the dispersion curves. The slopes of the higher frequency portions of the dispersion curves were more similar and therefore the c_o parameter of the inverted profiles is similar. This parameter controls the shear speed at 1 meter into the sediment, which is similar between the profiles.

To gain a better understanding of the shear speed profiles generated through the model, a sensitivity analysis on the model parameters was completed. Figure 41 presents this sensitivity analysis, with the fitness plotted as a function of each parameter and the final ideal parameters represented by the vertical red line.

Figure 41. Sensitivity analysis. The dots represent the fitness as a function of parameter values during the inversion. Parameters are c_0 and ν . The vertical line gives the final estimate value for each parameter for both deployments.

Figures 41 (b) and (d) show the sensitivity of the ν parameter for each deployment. This final parameter is an average of the two values generated from the inversion scheme runs for the low and high frequency portions of the curve. It is more sensitive than c_0 as it is harder to fit the lower frequency portion of the curve than it is to fit the higher frequency portion.

The c_0 from both deployments (Figure 41 (a) and (c)) converged nicely on an ideal value. The ideal values were similar between the two deployments. This is due to the fact that the higher frequency portion of the curve controlled the fit of the c_0 value and the slope in this portion of the curve was similar between deployments.

The reason that the ν value does not converge to one value as concisely as the c_o parameter does is the fact that the final ν value was an average. The fitness of the ν values for both the low and high frequency portions of the curve were averaged together. Therefore, while there is a convergence onto a single best fit value for ν , the value is not as clear as it is for c_o .

7.5 Validation of Inversion Scheme

7.5.1 Comparison with Published Shear Speed Relations

The inverted shear speed profiles were compared with published power law representations (Table 6) of the shear speed in various sediment types (Figure 42).

Bottom type	p (%)	ρ_b/ρ_w —	c_p/c_w —	c_p (m/s)	c_s (m/s)	α_p (dB/ λ_p)	α_s (dB/ λ_s)
Clay	70	1.5	1.00	1500	<100	0.2	1.0
Silt	55	1.7	1.05	1575	$c_s^{(1)}$	1.0	1.5
Sand	45	1.9	1.1	1650	$c_s^{(2)}$	0.8	2.5
Gravel	35	2.0	1.2	1800	$c_s^{(3)}$	0.6	1.5
Moraine	25	2.1	1.3	1950	600	0.4	1.0
Chalk	—	2.2	1.6	2400	1000	0.2	0.5
Limestone	—	2.4	2.0	3000	1500	0.1	0.2
Basalt	—	2.7	3.5	5250	2500	0.1	0.2
$c_s^{(1)} = 80 \bar{z}^{0.3}$ $c_s^{(2)} = 110 \bar{z}^{0.3}$ $c_s^{(3)} = 180 \bar{z}^{0.3}$							
$c_w = 1500 \text{ m/s}, \rho_w = 1000 \text{ kg/m}^3$							

Table 6. Geoacoustic properties of continental shelf and slope environments [3].

These representations of shear speed in unconsolidated sediments (clay, silt, sand, gravel and moraine) show that the shear speeds in these sediments are quite low but increase rapidly with depth below the water-sediment interface. Therefore the shear speeds in marine sediments are most appropriately given in terms of their depth dependence [3].

Figure 42. Comparison of the shear speed profiles generated through the inversion of the dispersion curves with published shear speed representations for various sediment types.

Figure 42 shows that the shear speed profiles determined from the inversion are most similar to the profiles relating to sand and silt. This is consistent with the information given in the Davisville borings, which state that the bottom is mostly layers of sand and silt.

7.5.2 Comparison with Profiles Estimated from Davisville Boring Logs

The ideal shear speed profiles given by the inversion scheme were then compared to the range of shear speed values estimated from the blow counts contained in borings BH-15 (Figure 43) and BH-8 (Figure 44). The shear speed profiles from both deployments fall into the range of shear speed values estimated for the test site. Therefore it can be concluded that the inversion scheme was able to produce shear speed profiles that correlate to the range of shear speed values present at the site.

Figure 43. Comparison of the shear speed profiles generated through the inversion of the dispersion curves with the range of shear speed values estimated from the SPT blow counts contained in boring log BH-15 from Davisville.

Figure 44. Comparison of the shear speed profiles generated through the inversion of the dispersion curves with the range of shear speed values estimated from the SPT blow counts contained in boring log BH-8 from Davisville.

The profiles from the deployments seem to align with the profiles estimated for both borings, rather than just where the array was deployed over BH-15. This

could indicate that the ASARS system was deployed closer to BH-8 than originally planned. This could have occurred because precise latitude/longitude coordinates of the borings were not available. Instead their positions were estimated by triangulating their position relative to the shoreline and the piers at Davisville. Therefore, the locations of the borings might not have been accurate and the deployment of the array might not have been directly over BH-15 as planned.

Also, the fact that the inversions correlate well with the range of values estimated from both of the borings indicates that the sediment in both areas is similar. This is consistent with what was presented in the borings logs at BH-15 and BH-8, which indicated layers of sand and silt. Since the sediment is similar in both locations, the inversions match well with both.

Overall, the inversions of the average dispersion curves for both deployments show a shear speed profile that falls in the range of shear speed values estimated from the borings. To further validate the inversion scheme and the resulting shear speed profiles, the fit of the theoretical dispersion curves relating to the ideal values of c_o and ν were compared to the experimental dispersion curves. Figure 45 shows the theoretical dispersion curves generated using the Godin-Chapman model to the composite dispersion curves from both deployments.

Figure 45. Theoretical dispersion curves relating to the ideal values of c_o and ν (black line) overlaid on the composite dispersion curves from Davisville.

The theoretical dispersion curve matches well with the trend of the composite dispersion curve. The fact that the modeled dispersion curves provide a good match to the experimental curve is further validation that the inversion scheme was able to accurately fit the data. This supports the accuracy of the inverted shear speed profiles.

It can be concluded that the inversion scheme was able to accurately predict the types of sediment in Davisville Basin as sand and silt. The scheme was successfully validated by both the published shear speed relations for sand and silt presented in Figure 42 and the estimated ranges of shear speed values from the borings.

CHAPTER 8

Sources of Error and Uncertainty

The inversion scheme, from the gathering of the dispersion data to the determination of the shear speed profile, contains steps that induce error into the final result. Some of these errors relate to areas that can be addressed and changed, but others should just be noted.

8.1 Data Collection Process

During the field tests performed to gather Scholte wave dispersion data, the array is assumed to be in a straight line. This implies that the geophones are evenly spaced and are coupled with the bottom sediment. In reality, the position of the geophones relative to each other is unknown when testing underwater.

To address this issue, an ROV could be used to visually look at the array once it is placed on the bottom. This would allow the scientist to know how the array is oriented and if the geophones are coupled to the sediment. In some shallow water environments divers could also be used to place the geophones in the desired locations.

Another way to address this issue would be to use the hydrophones that are contained in the sensor units. Using these hydrophones, in conjunction with other hydrophones of known position and a simple source like a lightbulb breaking, the location of the geophones could be triangulated. This would give the scientist a position for the geophones relative to the reference hydrophones.

Another area that should be addressed is the fact that the time needs to be set on the SHRUs before each use. Currently there is no method of setting the time on multiple SHRUs simultaneously. This means that the time is not synched between SHRUs and this makes it difficult to match up the time series between

SHRUs when using more than four channels of data. If this issue was fixed and the SHRUs could be time set and started simultaneously then the ability to record over a longer array would exist. This would provide more geophone pairs to analyze and therefore more data to run through the inversion scheme.

8.2 Data Processing

An area that induces errors during the processing of the Scholte interface wave data is in the determination of the phase differences between signals. The method of unwrapping the phase angle spectrum can sometimes lead to unrepresentative dispersion curves of the tested site. Under some conditions spurious cycles may exist in the phase spectrum which are mistakenly counted as true, which in turn cause errors in the unwrapping of the phase angles. Currently there are no methods of detecting these invalid phase angles and consequently inconsistent dispersion points may result. This in turn will lead to errors in the calculation of the site properties and shear speed profile [51].

These errors in the phase differences lead to inaccurate points in the dispersion curves. The equation used to calculate the phase velocities illustrated in the dispersion curves is shown in Equation 16, where Δx is the known distance between the receivers and Δt is the time lag of a Scholte surface wave propagating between two receivers.

$$V = \frac{\Delta x}{\Delta t} \quad (16)$$

Therefore, if there is an error in the time calculation, then the phase velocity will be directly affected. It was also stated that there is an error associated with the locations of the geophones. The uncertainty in their positions relates to an error in the distance between geophones and directly affects the calculation of the phase velocity.

One way to address the issue in the calculation of the phase velocities would be to use the group velocity instead. Using the group velocity dispersion curve in the inversion process would eliminate errors associated with the phase calculations. This is because the group velocity inversion only uses one geophone instead of two and therefore no time or phase delay would have to be calculated. Group velocity inversions would be a more robust method to determine the shear velocity profile at the site.

8.3 Forward Model Assumptions

The Godin-Chapman model was used as the forward model for this research, and while it provided a good estimate of the shear speed profile from the dispersion data, it makes assumptions that should be noted. The biggest assumption made by using this model is that the sediment is a single layer that has a shear speed profile that exhibits power-law characteristics . In reality the sediment includes layers and follows more of a staircase profile. Additional areas that should be noted about the Godin-Chapman model are that the model is not able to resolve the top one meter of sediment and that it is not able to fit profiles that include sharp changes in the shear speed.

To address these assumptions, which might not always be correct, a layered model could be used that would resolve the actual layers in the sediment. The output of this model would be a staircase profile instead of a power-law curve. Since this type of model would resolve the individual layers, there would be more variables that would need to be inverted for. This would increase the computational time needed to invert the profile, but would be able to resolve the profile in more detail. One such model is currently being developed by Dr. Gopu Potty at the University of Rhode Island. This model is described in more detail in [9].

Another source of error is in the genetic algorithm used to implement the

Godin-Chapman model. The goal of using a genetic algorithm was to ensure that a global, rather than a local, fit was determined. If the model is not able to converge on a value, then the best fit will not be found. One way to address this issue would be to make sure that the population and generation size is large enough to allow the algorithm to converge on a value.

8.4 Ground Truth

Another area where error is introduced is in the determination of the shear speed profile from the boring logs. The reliability of the blow counts determined from the Standard Penetration Test depend on the competence of the personnel performing the test and on the suitability of the equipment and facilities used [52]. Therefore the accuracy of the correlations between blow count and shear speed relies on the accuracy of the blow count measurements.

The fact that the SPT blow counts are not a repeatable measurement means that the experimental shear speed profile determined from the blow counts can vary each time blow counts are taken at a site. This will in turn change the fit of the inverted shear speed profile to the actual shear speed profile at the site. Also, the correlations between blow counts and shear velocity are site specific and it is difficult to accurately use them at sites for which they were not determined.

One way to address this issue is to use more than one correlation to develop a range of shear speed values representative of the site. This was the method employed in this research to try and match the inverted profiles to the estimated profiles from the boring blow counts.

Another way to try and improve the accuracy of the blow count correlations would be to determine a correlation specific to Davisville or Rhode Island waters in general. The correlations are determined from a regression analysis performed on dispersion data from a specific site. Therefore these correlations are very site

specific and are not easily related to other sites. If such a site specific correlation was developed for Davisville then the estimated shear speed profile would be more accurate.

CHAPTER 9

Conclusions and Recommendations

The University of Rhode Island Ocean Engineering Department has developed a geophone-hydrophone system (ASARS) for the measurement of sediment shear speed and an inversion scheme to invert the interface wave dispersion data for shear speed profiles. The estimation of shear wave velocities in shallow water marine sediments can provide valuable soil stiffness information for use in earthquake site response analysis, soil liquefaction evaluation, waste material characterization, and ground improvement evaluations [12]. Therefore the goal of research using this system was to characterize the seafloor based on the shear speed profiles in a non-invasive and time efficient manner.

The objective of this thesis research was to investigate the validity of the system in estimating the shear speed of surface waves at the water-sediment interface. An inversion scheme was developed to determine shear speed profiles from data collected using ASARS. The current system was validated against historic boring log data taken at an underwater site in Davisville, RI to determine the accuracy in the measurements taken by ASARS.

A test was performed at the site in Davisville, RI that included two separate deployments of the system. The dispersion data from both deployments was successfully inverted for shear speed profiles using the inversion scheme. The scheme utilized the Godin-Chapman model presented in [29] and [7] and a genetic algorithm to ensure that a global, rather than a local, minima was found. The inverted profiles were then compared to boring log data taken from the site and other published shear speed relations presented in [3].

It can be concluded that the inversion scheme employed to invert the disper-

sion curve data into shear speed profiles provided results consistent with the range of shear speed values estimated from the boring logs at the Davisville site. From the comparison with published shear speed relations for different sediment types, it was concluded that the sediment at Davisville is comprised mostly of sand and silt. This sediment classification correlates with what was presented in the boring logs. Therefore, these comparisons reveal that the inversion process was able to determine the types of sediment present in the test area with accuracy. It was concluded that the inversion scheme was validated and is a method to quickly and accurately determining shear speed profiles in a non-invasive and time efficient manner.

9.1 Future Work

In order to resolve the upper few meters of the shear velocity profile, it would be helpful to compare the inverted profiles to cores taken from the Davisville site. These cores would cover the upper few meters of sediment and would help to better match the top layers of the sediment.

Another way to improve the accuracy of the inversion scheme would be in the conversion of the boring log blow counts to the shear speed. If a correlation between blow counts and shear speed that was unique to Narragansett Bay, RI was determined, then the shear speed profile determined from the boring logs could be more accurate. This would further ensure that the inversion scheme produces reliable results and would further validate the scheme.

In the near future, this system will be utilized in an extensive sea trial. This inversion scheme can now be used to complete the system, in that URI now has a process in place to collect interface wave data and quickly invert this data for shear speed profiles. The next step to prepare this system for the sea trial would be to integrate the remaining sensors, including the hydrophones, 3-axis geophones, and

third SHRU. These sensors should all be tested with the current system configuration to ensure their applicability. This will enhance URI's ability to collect a broad range of acoustic data.

LIST OF REFERENCES

- [1] D. Pei, “Modeling and inversion of dispersion curves of surface waves in shallow site investigations,” Ph.D. dissertation, University of Nevada, Reno, August 2007.
- [2] S. J. Brandenburg, N. Ballana, and T. Shantz, “Shear wave velocity as a statistical function of standard penetration test resistance and vertical effective stress at caltrans bridge sites,” June 2010.
- [3] F. B. Jensen, W. A. Kuperman, M. B. Porter, and H. Schmidt, *Computational Ocean Acoustics*, 2nd ed. Springer, 2011.
- [4] P. Stoffer, 2012, accessed on December 5, 2012. [Online]. Available: <http://www.geologycafe.com/class/chapter4.html>
- [5] G. Meegan, M. Hamilton, Y. A. Il’inskii, and E. Zabolotskaya, “Nonlinear stoneley and scholte waves,” *Journal of the Acoustical Society of America*, vol. 106, no. 4, October 1999.
- [6] “Multi-component gs-pv1-s,” accessed on December 5, 2012. [Online]. Available: <http://www.geospace.com/multi-component-gs-pv1-s/>
- [7] D. M. F. Chapman and O. A. Godin, “Dispersion of interface waves in sediments with power-law shear speed profiles. ii. experimental observations and seismo-acoustic inversions,” *Journal of Acoustical Society of America*, October 2001.
- [8] “What’s a genetic algorithm (ga)?” accessed on January 15, 2013. [Online]. Available: <http://www.cs.cmu.edu/afs/cs/project/ai-repository/ai/html/faqs/ai/genetic/part2/faq-doc-2.html>
- [9] G. R. Potty and J. H. Miller, “Measurement and modeling of scholte wave dispersion in coastal waters,” in *AIP Proceedings of the OA2012 Conference, Beijing, 2012*, 2012.
- [10] J. T. DeJong, “Site characterization - guidelines for estimating shear wave velocity based on in-situ tests stage 1 - interm report,” Soil Interactions Laboratory University of California, Davis, Tech. Rep., December 2007.
- [11] H. Dong and J. M. Hovem, “Interface waves,” InTech, Tech. Rep., 2011. [Online]. Available: <http://www.intechopen.com/books/waves-in-fluidsand-solids/interface-waves>

- [12] M. M. Holrah, "Development and implementation of an underwater system for interface wave measurements," Master's thesis, University of Missouri - Columbia, 2005.
- [13] B. L. Rosenblad, "Experimental and theoretical studies in support of implementing the spectral-analysis-of-surface-waves (sasw) method offshore," Ph.D. dissertation, University of Texas at Austin, August 2000.
- [14] D. Rauch, "Seismic interface waves in coastal waters: A review," SACLANT ASW Research Centre, Tech. Rep., 1980.
- [15] H. Kolsky, *Stress Waves in Solids*. Dover Publications, 1963.
- [16] J. Greene, "Development of an amphibious seismo-acoustic recording system," Master's thesis, University of Rhode Island, 2011.
- [17] J. A. TenCate, T. G. Muir, and et al, "Beamforming on seismic interface waves with an array of geophones on the shallow sea floor," *IEEE Journal of Oceanic Engineering*, vol. 20, no. 4, October 1995.
- [18] J. Xia, R. D. Miller, and C. B. Park, "Estimation of near-surface shear-wave velocity by inversion of rayleigh waves," *Geophysics*, vol. 64, no. 3, May-June 1999.
- [19] T. Bohlen, S. Kugler, G. Klein, and F. Theilen, "Inversion of lateral variation of scholte-wave dispersion," *Geophysics*, vol. 69, no. 2, March-April 2004.
- [20] B. A. Luke and K. H. S. II, "Application of sasw method underwater," *JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING*, vol. 124, no. 6, June 1998.
- [21] "Spectral analysis of surface waves," accessed on December 5, 2012. [Online]. Available: http://www.olsoninstruments.com/pdf_downloads/catOI_sasw-s.pdf
- [22] K. H. Stokoe, B. L. Rosenblad, I. G. Wong, J. A. Bay, P. A. Thomas, and W. J. Silva, "Deep v_s profiling along the top of yucca mountain using a vibroseis source and surface waves," in *13th World Conference on Earthquake Engineering*, no. 538, Vancouver, B.C., Canada, August 2004.
- [23] B. L. Rosenblad, K. H. Stokoe, M. Kalinski, and E. Kavazanjian, "Shear wave velocity profiles of sediments determined from surface wave measurements," in *The Thirteenth (2003) International Offshore and Polar Engineering Conference*, May 2003.
- [24] C. B. Park, R. D. Miller, and J. Xia, "Multi-channel analysis of surface waves (masw)," Kansas Geological Survey, Tech. Rep., January 1997.

- [25] “Underwater microphones - hydrophones,” accessed on December 5, 2012. [Online]. Available: <http://www.dolphinear.com/data/underwater-microphones.htm>
- [26] O. Corporation, “Theory of operation of hydrophones,” accessed on December 5, 2012. [Online]. Available: http://www.ondacorp.com/tecref_tutorialhydrophone_theory.shtml
- [27] H. T. Inc, “Hti-94-ssq,” accessed on December 5, 2012. [Online]. Available: http://www.hightechincusa.com/94_SSQ.html
- [28] “Multi-component sea array 3,” accessed on December 5, 2012. [Online]. Available: <http://www.geospace.com/multi-component-sea-array-3/>
- [29] O. A. Godin and D. M. Chapman, “Dispersion of interface waves in sediments with power-law shear speed profiles. i. exact and approximate analytical results,” *Journal of Acoustical Society of America*, October 2001.
- [30] J. C. Osler and D. M. Chapman, “Seismo-acoustic determination of the shear-wave speed of surficial clay and silt sediments on the scotian shelf,” *Can. Acoustics*, vol. 24, pp. 11–22, 1996.
- [31] S. Frivik, R. Allnor, and J. Hovem, “Estimation of shear wave properties in the upper sea-bed using seismo-acoustical interface waves,” in *High Frequency Acoustics in Shallow Water*, N. Pace, E. Pouliquen, O. Bergem, and A. Lyons, Eds. NATO SACLANT Undersea Research Centre, Italy, 1997, pp. 155–162.
- [32] A. Caiti, R. Stoll, and T. Akal, “Estimation of shear wave velocity in shallow marine sediments,” *IEEE J. Ocean Engineering*, vol. 19, pp. 58–72, 1994.
- [33] R. Stoll and T. Akal, “Experimental techniques for bottom parameter inversion in shallow water,” in *Full Field Inversion Methods in Ocean and Seismo-Acoustics*, O. Diachok, A. Caiti, P. Gerstoft, and H. Schmidt, Eds. Kluwer Academic, The Netherlands, 1995, pp. 311–316.
- [34] A. Eiben and J.E.Smith, *Introduction to Evolutionary Computing*, 2nd ed. Springer, 2007.
- [35] B. J. Lynch, “Optimizing with genetic algorithms,” 2006, accessed on January 15, 2013. [Online]. Available: <https://www.msi.umn.edu/sites/default/files/OptimizingWithGA.pdf>
- [36] D. Whitley, “A genetic algorithm tutorial,” accessed on January 15, 2013. [Online]. Available: http://webcache.googleusercontent.com/search?q=cache:PVuKK3P_rokJ:samizdat.mines.edu/ga_tutorial/ga_tutorial.ps+&cd=1&hl=en&ct=clnk&gl=us

- [37] A. Persichetti and C. Smart, “Simulation of the lateral line using a genetic algorithm and least squares model,” Spring 2012, oCE 516 Biomimetics Paper.
- [38] “Root mean square deviation,” accessed on March 16, 2013. [Online]. Available: http://en.wikipedia.org/wiki/Root_mean_squared_error
- [39] I. CE Maguire, “Final report: Preliminary engineering davisville port expansion,” January 1981.
- [40] R. P. Weber, “Interpretation of boring logs for structural engineers,” *STRUCTURE Magazine*, December 2006.
- [41] D. P. Coduto, *Foundation Design Principles and Practices*. Prentice-Hall, Inc, 1994.
- [42] E. Washington, “Understanding the geotechnical report as an engineering and construction reference,” accessed on February 10, 2013. [Online]. Available: <http://www.pdhonline.org/courses/g106/g106.htm>
- [43] N. Hasancebi and R. Ulusay, “Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments,” Tech. Rep.
- [44] C.-S. Chen, J. H. Miller, G. F. Bourdreaux-Bartels, G. R. Potty, and C. J. Lazauski.
- [45] G. R. Potty, J. H. Miller, J. F. Lynch, and K. B. Smith, “Tomographic inversion for sediment parameters in shallow water,” *Journal of the Acoustical Society of America*, vol. 108, 2000.
- [46] M. V. Raamsdonk, “Group velocity and phase velocity,” accessed March 28, 2013. [Online]. Available: <http://www.phas.ubc.ca/~mav/p200/groupandphase.pdf>
- [47] M. Al-Hunaidi, “Insights on the sasw nondestructive testing method,” *Can. J. Civil Engineering*, vol. 20, pp. 940–950, 1993.
- [48] MathWorks, “mscohere,” accessed on February 10, 2013. [Online]. Available: <http://www.mathworks.it/it/help/signal/ref/mscohere.html>
- [49] MathWorks, “cpsd,” accessed on February 10, 2013. [Online]. Available: <http://www.mathworks.it/it/help/signal/ref/cpsd.html>
- [50] J. O. Smith, *Spectral Audio Signal Processing*, accessed March 7, 2013, online book.
- [51] M. Al-Hunaidi, “Insights on the sasw nondestructive testing method,” *Can. J. Civ. Eng.*, vol. 20, pp. 940–950, 1993.

- [52] “Astm d1586 - 11 standard test method for standard penetration test (spt) and split-barrel sampling of soils,” accessed March 28, 2013. [Online]. Available: <http://www.astm.org/Standards/D1586.htm>

APPENDIX

A. Davisville Boring Logs

GUILD DRILLING CO., INC.

100 WATER STREET EAST PROVIDENCE, R. I.

TO C. E. Maguire, Inc.

ADDRESS Providence, R. I.

PROJECT NAME Davisville Bulkhead

LOCATION Quonset Point, R. I.

REPORT SENT TO above

PROJ. NO. 3603

SAMPLES SENT TO "

OUR JOB NO. 80-256

SHEET 1 OF 2

DATE _____

HOLE NO. BH-8

LINE & STA. _____

OFFSET _____

SURF. ELEV. _____

GROUND WATER OBSERVATIONS				Rods-"AW"	CASING	SAMPLER	CORE BAR.	Date	Time
At _____	after _____	Hours		Type	BW	S/S		START	3/20/80
	7'8"	Low Tide		Size I.D.	2 1/2"	1 3/8"		COMPLETE	3/21/80
At _____	after _____	Hours		Hammer Wt.	300#	140#	BIT	TOTAL HRS.	
				Hammer Fall	24"	30"		BORING FOREMAN	E. Peterson
								INSPECTOR	D. Calvi
								SOILS ENGR.	

LOCATION OF BORING:

DEPTH	Casing Blows per foot	Sample Depths From - To	Type of Sample	Blows per 6" on Sampler			Moisture Density or Consist.	Strata Change Elev.	SOIL IDENTIFICATION Remarks include color, gradation, Type of soil etc. Rock-color, type, condition, hardness, Drilling time, seams and etc.	SAMPLE		
				From 0-6"	6-12"	12-18"				No.	Pen	Rec.
3		0'-1'6"	D	5	4	3	Wet/m stiff		Black oily & fine sandy Organic SILT	1	18"	18"
5								2'				
8												
11												
10												
5		5'-6'6"	D	6	5	4	Wet loose		Gray Brown fine to coarse SAND, little silt, trace of fine gravel	2	18"	12"
11												
15												
19												
19								10'				
17		10'-11'6"	D	5	6	8	Wet medium dense		Brown fine to medium SAND, little silt	3	18"	12"
19												
18												
21												
20									(Running Sand 2' to 3' up casing from 10' to 25')			
17		15'-16'6"	D	7	5	7	"			4	18"	12"
22												
27												
48												
62												
29		20'-21'6"	D	5	6	7	"			5	18"	12"
28												
33												
36												
20		25'-26'6"	D	6	7	8	"			6	18"	12"
36												
38												
41												
44												
30		30'-31'6"	D	6	10	15	"			7	18"	12"
38												
48												
50												
50												
31		35'-36'6"	D	6	10	16	"			8	18"	12"
44												
56												
61												
66												

GROUND SURFACE TO 50' USED BW "CASING: THEN S/S to 51'6"

Sample Type

D=Dry C=Cored W=Washed

UP=Undisturbed Piston

TP=Test Pit A=Auger V=Vane Test

UT=Undisturbed Thinwall

Proportions Used

trace 0 to 10%

little 10 to 20%

some 20 to 35%

and 35 to 50%

140 lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density

0-10 Loose

10-30 Med. Dense

30-50 Dense

50+ Very Dense

Cohesive Consistency

0-4 Soft

4-8 M/Stiff

8-15 Stiff

15-30 V-Stiff

SUMMARY:

Earth Boring 51'6"

Rock Coring

Samples 5 (11)

HOLE NO. BH-8

TOWN PRESS - EAST PROV.

100 WATER STREET EAST PROVIDENCE, R. I.

DATE _____

HOI F NO	BH-8
----------	------

LINE & STA. _____

OFFSET _____

SURF. ELEV. _____

TO _____ ADDRESS _____
PROJECT NAME _____ LOCATION _____
REPORT SENT TO _____ PROJ. NO. _____
SAMPLES SENT TO _____ OUR JOB NO. 80-256

SAMPLES SENT TO _____ OUR JOB NO. 80-256

GROUND WATER OBSERVATIONS			CASING	SAMPLER	CORE BAR.	Date	Time
At _____	after _____ Hours	Type _____	_____	_____	_____	START _____	a.m.
		Size I.D. _____	_____	_____	_____	COMPLETE _____	p.m.
At _____	after _____ Hours	Hammer Wt. _____	_____	_____	_____	TOTAL HRS. _____	a.m.
		Hammer Fall _____	_____	_____	BIT _____	BORING FOREMAN _____	p.m.
						INSPECTOR _____	
						SOILS ENGR. _____	

LOCATION OF BORING:

[illegible]

GROUND SURFACE TO

USED

"CASING: THEN

Sample Type

D=Dry C=Cored W=Washed

UP = Undisturbed Piston

TP=Test Pit A=Auger V=Vane Test

UT=Undisturbed Thinwall

Proportions Used

trace 0 to 10%

little 10 to 20%

some 20 to 35%

and 35 to 50%

140lb Wt. x 30" fall on 2" O.D. Sampler

Cohesionless Density

0-10 Loose

10-30 Med. Dense
30-50 Dense

30-50 Dense
50+ Very Dense

Cohesive Consistency

0-4 Soft 30 + Hard

4-8 M/Stiff

8-15 Stiff
15-30 V-Stiff

SUMMARY:

Earth Boring

Rock Coring

Samples _____

HOLE NO. BH-8

TOWN PRESS - EAST PROV.

100 WATER STREET EAST PROVIDENCE, R. I.
TO C. E. Maguire, Inc. ADDRESS Providence, R.I.
PROJECT NAME Davisville Bulkhead LOCATION Quonset Point, R.I.
REPORT SENT TO above PROJ. NO. 3603
SAMPLES SENT TO " OUR JOB NO. 80-256

SHEET 1 OF 1
DATE _____
HOLE NO. BH-15
LINE & STA. _____
OFFSET _____
SURF. ELEV. _____

SOUNDING WATER OBSERVATIONS				CASING		SAMPLER		CORE BAR		Date	Time
At 13'3"	at 9:30 AM	Rods-"AW"	Type	BW	S/S	START	4/1/80		a.m.		
	after _____ Hours			2 1/2"	1 3/8"	COMPLETE	4/1/80		p.m.		
At 11'8"	@ 0.0	Size I.D.		300#	140#	TOTAL HRS.					
	after _____ Hours	Hammer Wt.		24"	30"	BORING FOREMAN	Peterson				
	Gauge	Hammer Fall				INSPECTOR	D. Calvi				
						SOILS ENGR.					

[illegible]

GROUND SURFACE TO 30'		USED BW	"CASING: THEN	S/S to 31'6"	
Sample Type	Proportions Used	140lb Wt. x 30' fall on 2" O.D. Sampler	Cohesive	Consistency	SUMMARY:
D=Dry C=Cored W=Washed	trace 0 to 10%				Earth Boring 31'6'
UP=Undisturbed Piston	little 10 to 20%	0-10 Loose	0-4 Soft	30 + Hard	Rock Coring
TP=Test Pit A=Auger V=Vane Test	some 20 to 35%	10-30 Med. Dense	4-8 M/Stiff		Samples 5
UT=Undisturbed Thinwall	and 35 to 50%	30-50 Dense	8-15 Stiff		HOLE NO BH-15
		50 + Very Dense	15-30 V-Stiff		

BIBLIOGRAPHY

- “Astm d1586 - 11 standard test method for standard penetration test (spt) and split-barrel sampling of soils,” accessed March 28, 2013. [Online]. Available: <http://www.astm.org/Standards/D1586.htm>
- “Multi-component gs-pv1-s,” accessed on December 5, 2012. [Online]. Available: <http://www.geospace.com/multi-component-gs-pv1-s/>
- “Multi-componentsea array 3,” accessed on December 5, 2012. [Online]. Available: <http://www.geospace.com/multi-component-sea-array-3/>
- “Spectral analysis of surface waves,” accessed on December 5, 2012. [Online]. Available: http://www.olsoninstruments.com/pdf_downloads/catOI_sasw-s.pdf
- “Underwater microphones - hydrophones,” accessed on December 5, 2012. [Online]. Available: http://www.dolphinear.com/data/underwater_microphones.htm
- “What’s a genetic algorithm (ga)?” accessed on January 15, 2013. [Online]. Available: <http://www.cs.cmu.edu/afs/cs/project/ai-repository/ai/html/faqs/ai/genetic/part2/faq-doc-2.html>
- “Root mean square deviation,” accessed on March 16, 2013. [Online]. Available: http://en.wikipedia.org/wiki/Root_mean_squared_error
- Al-Hunaidi, M., “Insights on the sasw nondestructive testing method,” *Can. J. Civil Engineering*, vol. 20, pp. 940–950, 1993.
- Al-Hunaidi, M., “Insights on the sasw nondestructive testing method,” *Can. J. Civ. Eng.*, vol. 20, pp. 940–950, 1993.
- Bohlen, T., Kugler, S., Klein, G., and Theilen, F., “Inversion of lateral variation of scholte-wave dispersion,” *Geophysics*, vol. 69, no. 2, March-April 2004.
- Brandenberg, S. J., Ballana, N., and Shantz, T., “Shear wave velocity as a statistical function of standard penetration test resistance and vertical effective stress at caltrans bridge sites,” June 2010.
- Caiti, A., Stoll, R., and Akal, T., “Estimation of shear wave velocity in shallow marine sediments,” *IEEE J. Ocean Engineering*, vol. 19, pp. 58–72, 1994.
- CE Maguire, I., “Final report: Preliminary engineering davisville port expansion,” January 1981.

- Chapman, D. M. F. and Godin, O. A., "Dispersion of interface waves in sediments with power-law shear speed profiles. ii. experimental observations and seismo-acoustic inversions," *Journal of Acoustical Society of America*, October 2001.
- Chen, C.-S., Miller, J. H., Bourdreaux-Bartels, G. F., Potty, G. R., and Lazauski, C. J.
- Coduto, D. P., *Foundation Design Principles and Practices*. Prentice-Hall, Inc, 1994.
- Corporation, O., "Theory of operation of hydrophones," accessed on December 5, 2012. [Online]. Available: http://www.ondacorp.com/tecref_tutorialhydrophone_theory.shtml
- DeJong, J. T., "Site characterization - guidelines for estimating shear wave velocity based on in-situ tests stage 1 - interm report," Soil Interactions Laboratory University of California, Davis, Tech. Rep., December 2007.
- Dong, H. and Hovem, J. M., "Interface waves," InTech, Tech. Rep., 2011. [Online]. Available: <http://www.intechopen.com/books/waves-in-fluidsand-solids/interface-waves>
- Eiben, A. and J.E.Smith, *Introduction to Evolutionary Computing*, 2nd ed. Springer, 2007.
- Frivik, S., Allnor, R., and Hovem, J., "Estimation of shear wave properties in the upper sea-bed using seismo-acoustical interface waves," in *High Frequency Acoustics in Shallow Water*, Pace, N., Pouliquen, E., Bergem, O., and Lyons, A., Eds. NATO SACLANT Undersea Research Centre, Italy, 1997, pp. 155–162.
- Godin, O. A. and Chapman, D. M., "Dispersion of interface waves in sediments with power-law shear speed profiles. i. exact and approximate analytical results," *Journal of Acoustical Society of America*, October 2001.
- Greene, J., "Development of an amphibious seismo-acoustic recording system," Master's thesis, University of Rhode Island, 2011.
- Hasancebi, N. and Ulusay, R., "Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments," Tech. Rep.
- Hollrah, M. M., "Development and implementation of an underwater system for interface wave measurements," Master's thesis, University of Missouri - Columbia, 2005.
- Inc, H. T., "Hti-94-ssq," accessed on December 5, 2012. [Online]. Available: http://www.hightechincusa.com/94_SSQ.html

- Jensen, F. B., Kuperman, W. A., Porter, M. B., and Schmidt, H., *Computational Ocean Acoustics*, 2nd ed. Springer, 2011.
- Kolsky, H., *Stress Waves in Solids*. Dover Publications, 1963.
- Luke, B. A. and II, K. H. S., “Application of sasw method underwater,” *JOURNAL OF GEOTECHNICAL AND GEOENVIRONMENTAL ENGINEERING*, vol. 124, no. 6, June 1998.
- Lynch, B. J., “Optimizing with genetic algorithms,” 2006, accessed on January 15, 2013. [Online]. Available: <https://www.msi.umn.edu/sites/default/files/OptimizingWithGA.pdf>
- MathWorks, “cpsd,” accessed on February 10, 2013. [Online]. Available: <http://www.mathworks.it/it/help/signal/ref/cpsd.html>
- MathWorks, “mscohere,” accessed on February 10, 2013. [Online]. Available: <http://www.mathworks.it/it/help/signal/ref/mscohere.html>
- Meegan, G., Hamilton, M., Il’inskii, Y. A., and Zabolotskaya, E., “Nonlinear stoneley and scholte waves,” *Journal of the Acoustical Society of America*, vol. 106, no. 4, October 1999.
- Osler, J. C. and Chapman, D. M., “Seismo-acoustic determination of the shear-wave speed of surficial clay and silt sediments on the scotian shelf,” *Can. Acoustics*, vol. 24, pp. 11–22, 1996.
- Park, C. B., Miller, R. D., and Xia, J., “Multi-channel analysis of surface waves (masw),” Kansas Geological Survey, Tech. Rep., January 1997.
- Pei, D., “Modeling and inversion of dispersion curves of surface waves in shallow site investigations,” Ph.D. dissertation, University of Nevada, Reno, August 2007.
- Persichetti, A. and Smart, C., “Simulation of the lateral line using a genetic algorithm and least squares model,” Spring 2012, oCE 516 Biomimetics Paper.
- Potty, G. R. and Miller, J. H., “Measurement and modeling of scholte wave dispersion in coastal waters,” in *AIP Proceedings of the OA2012 Conference, Beijing, 2012*, 2012.
- Potty, G. R., Miller, J. H., Lynch, J. F., and Smith, K. B., “Tomographic inversion for sediment parameters in shallow water,” *Journal of the Acoustical Society of America*, vol. 108, 2000.
- Raamsdonk, M. V., “Group velocity and phase velocity,” accessed March 28, 2013. [Online]. Available: <http://www.phas.ubc.ca/~mav/p200/groupandphase.pdf>

- Rauch, D., "Seismic interface waves in coastal waters: A review," SACLANT ASW Research Centre, Tech. Rep., 1980.
- Rosenblad, B. L., "Experimental and theoretical studies in support of implementing the spectral-analysis-of-surface-waves (sasw) method offshore," Ph.D. dissertation, University of Texas at Austin, August 2000.
- Rosenblad, B. L., Stokoe, K. H., Kalinski, M., and Kavazanjian, E., "Shear wave velocity profiles of sediments determined from surface wave measurements," in *The Thirteenth (2003) International Offshore and Polar Engineering Conference*, May 2003.
- Smith, J. O., *Spectral Audio Signal Processing*, accessed March 7, 2013, online book.
- Stoffer, P., 2012, accessed on December 5, 2012. [Online]. Available: <http://www.geologycafe.com/class/chapter4.html>
- Stokoe, K. H., Rosenblad, B. L., Wong, I. G., Bay, J. A., Thomas, P. A., and Silva, W. J., "Deep v_s profiling along the top of yucca mountain using a vibroseis source and surface waves," in *13th World Conference on Earthquake Engineering*, no. 538, Vancouver, B.C., Canada, August 2004.
- Stoll, R. and Akal, T., "Experimental techniques for bottom parameter inversion in shallow water," in *Full Field Inversion Methods in Ocean and Seismo-Acoustics*, Diachok, O., Caiti, A., Gerstoft, P., and Schmidt, H., Eds. Kluwer Academic, The Netherlands, 1995, pp. 311–316.
- TenCate, J. A., Muir, T. G., and et al, "Beamforming on seismic interface waves with an array of geophones on the shallow sea floor," *IEEE Journal of Oceanic Engineering*, vol. 20, no. 4, October 1995.
- Washington, E., "Understanding the geotechnical report as an engineering and construction reference," accessed on February 10, 2013. [Online]. Available: <http://www.pdhonline.org/courses/g106/g106.htm>
- Weber, R. P., "Interpretation of boring logs for structural engineers," *STRUCTURE Magazine*, December 2006.
- Whitley, D., "A genetic algorithm tutorial," accessed on January 15, 2013. [Online]. Available: http://webcache.googleusercontent.com/search?q=cache:PVuKK3P_rokJ:samizdat.mines.edu/ga_tutorial/ga_tutorial.ps+&cd=1&hl=en&ct=clnk&gl=us
- Xia, J., Miller, R. D., and Park, C. B., "Estimation of near-surface shear-wave velocity by inversion of rayleigh waves," *Geophysics*, vol. 64, no. 3, May-June 1999.