Validation of an Inversion Scheme for Shear Wave Speed Using Scholte Wave Dispersion

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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 in the sediment by measuring the 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. The data collected was processed using an approach similar to the land based Spectral Analysis of Surface Waves (SASW) method to estimate the phase speed dispersion. Phase speed data was then inverted using an inversion scheme based on a genetic algorithm and the Godin-Chapman approach as the forward model. The results are compared to historic estimates of shear speed and recently acquired vibracore data collected at the experimental location to validate the inversion scheme. Results suggest that the inverted profile is consistent with the shear speed profiles related to sand and silt, which is in agreement with the types of sediment described in the boring logs and seen in the core. The values of the shear speed estimated from the inversion scheme are also close to the shear speeds estimated from the bore hole and core data. The overall validity and usefulness of the inversion scheme as a fast remote sensing tool providing a range averaged shear speed profile will be addressed.**

I. Introduction

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 wave velocity. 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 [1].

Measuring shear wave velocity with traditional testing methods, such as downhole 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 [2]. These methods provide a more time and cost efficient way of generating shear velocity profiles.

One such method that can be used to estimate 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 velocity of the sediment. 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 [3]. At the water-sediment bounday 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 provides information about the sediment shear speed gradient and the geoacoustic properties of the sea floor [4].

The objective of this research was to investigate the validity of the system in estimating the shear speed in the sediment by measuring the surface waves at the water-sediment interface. An inversion scheme was developed using the Godin-Chapman model to relate the phase speed of the interface waves and a simple shear speed profile in the sediment. A genetic algorithm was used to iteratively search for the parameter set which provided the best match to the data. The current system was tested in shallow waters at a site in Davisville, RI. Historic borehole and recent vibracore data were present at the testing site. The results obtained using the inversion scheme were compared to shear speed profiles estimated from sediment data from the site to determine the accuracy in the measurements taken by ASARS.

This paper will begin by introducing ASARS and discussing the data collection and processing procedure associated with the system. Then an overview of the inversion process, including a description of the Godin-Chapman model and the genetic algorithm, will be provided. The Davisville test will be described in more detail, along with the sediment data that was available at the site. The test results will be presented and conclusions drawn as to the validity of the inversion scheme.

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II. URI Shear Measurement System

ASARS 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 dispersion characteristics of interface (Scholte) waves. Similar techniques, specifically the Spectral Analysis of Surface Waves (SASW) method, are extensively applied on land using Rayleigh waves. The SASW approach is discussed in the next section, highlighting the difficulties encountered when transitioning this approach to offshore applications.

A. SASW

SASW is a popular non-invasive method used to characterize the shear wave velocity structure of sites on land. Non-invasive methods utilize active or passive sources, or both, and attempts to measure the fundamental mode dispersion curve of interface waves. The shear velocity structure is then obtained by inverting these dispersion curves, using either an iterative forward modeling approach or an inverse algorithm approach [5]. In the SASW 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 [6].

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 [3].

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 [3]. 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 [3] and [2]. 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 adequate resolution of shear wave velocities in the near-surface sediments [1].

Another problem involves deploying and coupling the receivers with the sediment in an underwater environment. Typically, vertically gimballed geophones are used to ensure vertical orientation of the sensors. The receivers are usually deployed with a linear array and a stationary source location [1]. Although there are difficulties in implementing this type of system underwater, several small scale laboratory experiments and full scale studies conducted by [3], [2], and [1] have shown that the SASW method works well at underwater sites.

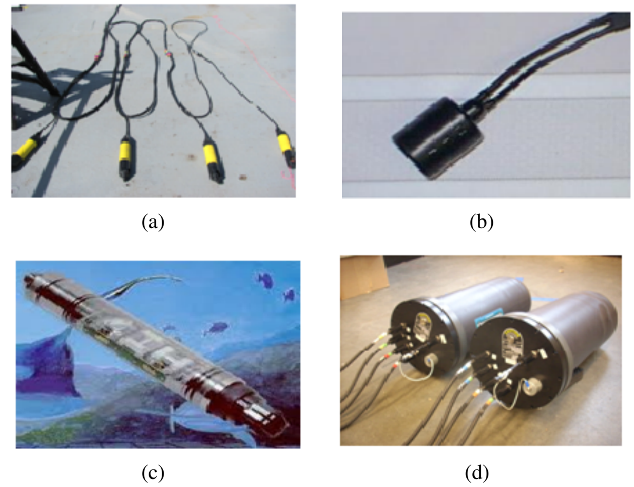


Fig. 1. ASARS system components. (a) GS-PV1-S vertically gimballed geophone and hydrophone (b) HTI-94-SSQ hydrophone (c) Sea Array 3-axis gimballed geophone and hydrophone (d) Several Hydrophone Receive Units (SHRUs).

B. ASARS System Design

The URI shear measurement system includes: eight vertically gimballed geophones and hydrophones (Fig.1 (a)), eight HTI-94-SSQ hydrophones (Fig.1 (b)), two Geospace Sea Array 3-axis gimballed geophones and hydrophones (Fig.1 (c)), and three Several Hydrophone Receive Units (SHRUs) (Fig.1 (d)).

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 and have not been incorporated into the system 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 Institution (WHOI). 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) [7]. 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 system was designed with the intention of being towable at slow speeds, with the SHRU end caps facing aft relative to the towed direction (Fig.2). This is due to the fact that once the system is deployed during a sea test it is vital that it be coupled to the bottom and that the sensors be in line with one another. To acheive this, the array must be extended and towed along the bottom to ensure that the geophone array is straight behind the SHRUs. In order to keep the SHRUs from sustaining any damage when they are towed on the bottom, the units were encased in an aluminum sled. Once the system is thought to be straight, it is left stationary on the seafloor for the duration of the data collection process.

III. Inversion

The inversion of interface wave speed measurements is a well-established technique used in the ocean acoustics and

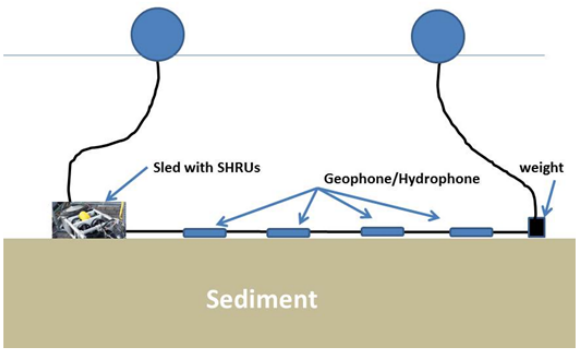


Fig. 2. ASARS system design for sea deployment.

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 [8]. There are a 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 this inversion scheme and will be discussed.

A. 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 (1) [9].

$$c_s = c_0 z^{\nu} \tag{1}$$

In the power-law profile relation described in (1), 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 [10].

The power-law speed profile is the case in which the shear speed increases with depth from zero at the interface (Fig.3). 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 [9]. These ideal conditions exist in nature to a sufficient degree of approximation such that the theoretically derived relations are observed in experimental data [10]. The dispersion of seismo-acoustic interface waves in marine sediments with constant density follows the shear speed profile according to (1).

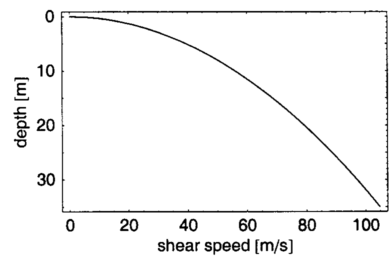


Fig. 3. Power-law shear speed profile for the case where $c_s = 10\sqrt{\pi}z^{1/2}$ [10].

A generic dispersion relation for interface waves in sediment where the shear speed variation obeys a power-law profile is:

$$V_n = \left(\frac{c_0^{1/\nu} n_{eff}(n,\nu,R)}{f B_\nu}\right)^{\nu/(1-\nu)} \tag{2}$$

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 [10]. The effective mode number for the fundamental mode is:

$$n_{eff}(n,\nu,R) = \frac{B_\nu}{2\pi}\left(\frac{2}{1+R}\right)^{1/2\nu}$$
$$exp\left[a(\nu-\frac{1}{2}) + b(\nu-\frac{1}{2})^2 + ...\right](n=0) \tag{3}$$

where

$$a = (1-\gamma-log2)/\nu$$
$$b = \frac{1}{\nu}\left\{\frac{2+R}{6}\pi^2 - 1 + (1+R)^2\left[\gamma + \Psi\left(\frac{R}{1+R}\right)\right]\right\}$$

The variable γ is equal to Euler's constant

$$\gamma = 0.57721$$

and Ψ is the Digamma function.

The analytical dispersion relations (2) and (3) 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 [11], [12], [13], and [14], and in all cases the power-law profiles agreed well with the staircase profiles. The only inconsistency observed was that the power-law fit was not able to completely resolve the upper few meters of the staircase profile due to the high variability and disturbance of the sediment in this region. Also it is not able to adjust if the staircase profile does not continually increase with depth [10].

Although there are some disadvantages to using this model, there are also advantages. 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 [10].

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 algorithim and is introduced in the following section.

B. Genetic Algorithm

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 [15].

Genetic algorithms are used for a number of different applications, including the optimization of non-linear systems with a large number of variables. 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 [16]. Global optimization refers to the process of attempting to find the solution which has the optimal value for a specified fitness function out of a set of possible solutions [15].

C. Implementation of Godin-Chapman Model

An inversion scheme was developed to estimate the shear speed profile using the interface wave dispersion data and 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 measured using the ASARS system. The theoretical dispersion was compared 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 (2) and (3), which make up the Godin-Chapman model, and iterates model parameters selected within the user specified 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 Fig.4.

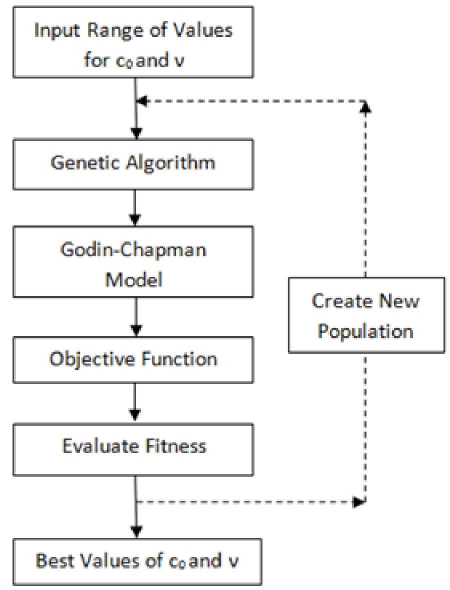


Fig. 4. Flowchart showing the inversion scheme process utilizing the Godin-Chapman model and a genetic algorithm to solve for the best parameters.

The purpose of the objective (fitness) 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.

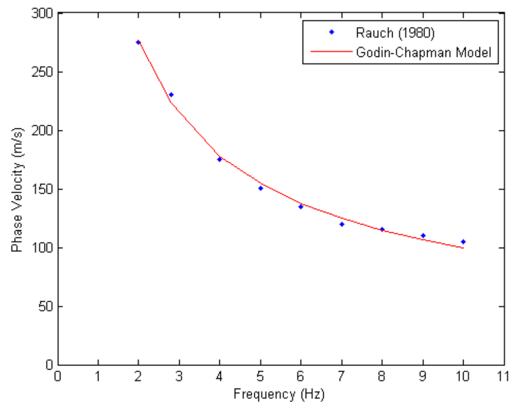
Once the ideal shear speed profile is determined, the depth limitation of the inversion is calculated. A maximum valid depth needs to be determined because the power law profile that is derived from the dispersion relations will in theory extend indefinitely in depth, but this is unlikely to hold true 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:

$$z_{max} = 2(V_{max}/c_o)^{\frac{1}{\nu}} \tag{4}$$

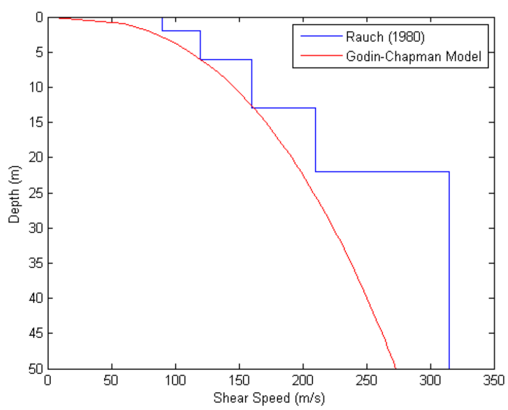
where $V_{max} = V(f_{min})$ is the maximum measured phase speed, which occurs at the lowest frequency of measurement, f_{min}, and the c_o and ν parameters are those given by the inversion model [10].

D. Validation of Inversion Scheme

The inversion scheme described above was validated against published dispersion data to ensure that it was imple-



(a)



(b)

Fig. 5. Comparison of the Godin-Chapman model results of (a) dispersion curves and (b) shear speed profiles with published results presented in [8].

mented correctly. The output of the model was compared with dispersion results from Rauch, which were also used to validate the model presented in [8]. Fig.5 (a) and (b) show the output of the inversion scheme with Rauch's results. Fig.5 (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 (1), a shear speed profile representative of the dispersion data was determined and shown in Fig.5 (b). The profile determined from the model was not able to fit the upper few meters of the actual staircase profile, which was expected after looking at the inconsistencies in the model fit previously discussed. The model fit also seems to underestimate the shear speed profile and follows 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 to invert experimental dispersion data for shear velocity profiles.

IV. Geotechnical Ground Truth Data

While the forward model had been validated against previously published dispersion data as shown in Fig.5, the validation of the entire inversion scheme was 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 was 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.

A. *Historic Borehole Data*

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 [17].

The boring logs taken in the Davisville Basin detail the soil layers by depth from the surface. The logs 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.

The N-value is the basis for many geotechnical engineering calculations and is a very important measure of the soil properties. The procedure to obtain the N-value is as follows: 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 [18].

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 100, the ground may be difficult to excavate and require blasting [19].

B. *Correlating N-Value to Shear Speed*

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.

Boring logs BH-15 and BH-8 were the representative logs used to estimate the shear speed profile of the Davisville site. The locations of these borings are described in more detail in [17]. 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 [20].

According to the recommendation of [20], 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 V_s. The proposed relationships 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

The resulting range of shear speed values estimated from boring BH-15 and BH-8 using the above three correlations are shown in Fig.9 (a) and (b).

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 profiles generated from the dispersion data taken at Davisville.

C. Vibracore Data

In April 2013 a 3 meter long vibracore was taken at Davisville near the location of boring BH-15. The sediment types contained in this core were determined to be layers of sand and silt, with the majority of the core being comprised of sandy sediment. This classification was determined by analyzing the grain size of the sediment through a sieve test.

V. Davisville Test

A test of URI's Shear Measurement System was completed on February 5, 2013 in the Davisville Basin in Rhode Island. For this test the R/V Shanna Rose was utilized as the testing vessel and the URI Shear Measurement System was used to record seismic interface waves generated by a 114 kg weight impacting the bottom. The shear measurement system consisted of the sled holding two SHRUs and eight geophones (Fig.6). 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.

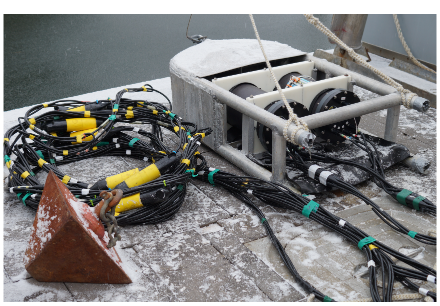


Fig. 6. Weight, geophones, and SHRUs in the sled as used during the Davisville Test.

During the duration of the test, the system was deployed twice. For both deployments the geophones were arranged in a linear array with a spacing of 2.5 meters between sensors for the first deployment and 5 meters between sensors for the second. The array was deployed over boring BH-15 and near boring BH-8 for both deployments. After the array was in place, the boat drifted away from the sled and dropped the weight at ranges of 10 to 100 meters away from the sled at intervals of 10 meters (Fig.7). The weight was dropped three times at each interval from a height of 1.5 meters for the first deployment and 2.4 meters for the second. The locations of the array and weight drops for both deployments relative to the borings are shown in Fig.7.

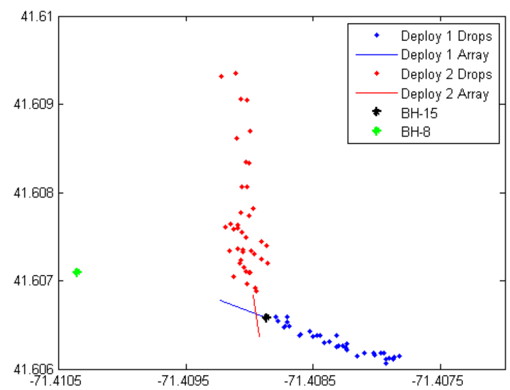


Fig. 7. Locations of the geophone array and weight drops for each deployment. The locations of BH-15 and BH-8 are approximate.

VI. Inversion of Davisville Data

The data collected during the Davisville test was processed to calculate the phase velocity of the interface waves. The phase difference as a function of frequency was calculated from the cross spectral density between signals from two geophones with known spacing. The composite dispersion curves calculated using multiple geophone pairs are shown in Fig.10 (a) and (b). The different colors in the curves represent the different pairs of geophones used in the calculation. The dispersion curve generated for the first deployment shows higher phase velocities than the curve generated for the second deployment. The differences in the dispersion curves will result in differences in the shear speed profiles determined from the inversion process.

The dispersion curves shown in Fig.10 were averaged over frequency. These averaged dispersion curves were then run through the inversion scheme to determine the best fit power-law shear speed profile.

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

Parameter	Deployment 1	Deployment 2
c_0	95.98	91.81
ν	0.3633	0.2677

The final parameter values that best define the shear speed profile inverted from the averaged dispersion curves are given in Table I. The standard deviations around the averaged dispersion curves were also determined. 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. Once the inversion was completed, (4) 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.

This difference in valid depth between the two deployments was expected given the fact that the energy imparted to the bottom during the two deployments was different due to the varied drop heights of the weight. The geophone spacing was also different between the two deployments, which will have an impact on the band of frequencies excited and therefore the depth sampled.

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 has higher phase velocities than the second deployment over the same frequency range. Therefore the higher phase speeds correlate to faster shear speeds when inverted.

VII. Validation of Inversion Scheme

A. Comparison with Published Shear Speed Relations

The inverted shear speed profiles were compared with published power-law representations (Table II) of the shear speed in various sediment types (Fig.8).

TABLE II. Geoacoustic properties of continental shelf and slope environments [21].

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

$c_s^{(1)} = 80\,\tilde{z}^{0.3}$ $c_w = 1500$ m/s, $\rho_w = 1000$ kg/m^3
$c_s^{(2)} = 110\,\tilde{z}^{0.3}$
$c_s^{(3)} = 180\,\tilde{z}^{0.3}$

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 [21].

Fig.8 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.

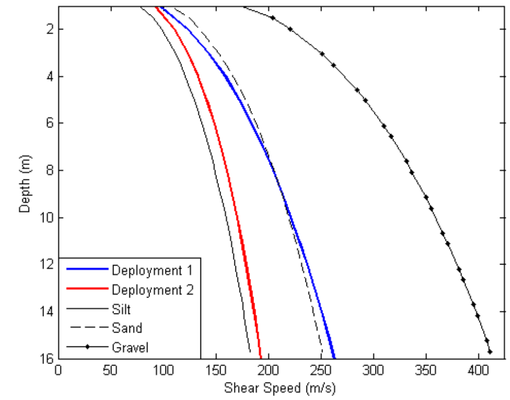


Fig. 8. Comparison of the shear speed profiles generated for Deployment 1 and Deployment 2 with published shear speed representations for various sediment types.

B. 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 (Fig.9 (a)) and BH-8 (Fig.9 (b)). 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.

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 locations 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. It should also be noted that the inversions provide a range averaged shear profile, whereas the borehole data provides a point measurement.

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 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. Fig.10 shows the comparison of the theoretical dispersion curves generated using the Godin-Chapman model to the composite dispersion curves from both deployments.

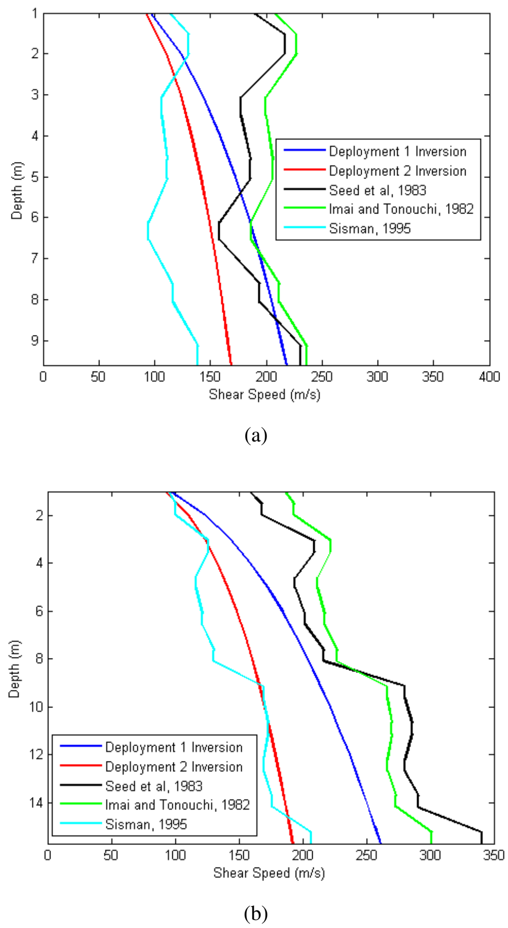


Fig. 9. Comparison of the shear speed profiles estimated for Deployment 1 and Deployment 2 at the Davisville site with the range of shear speed values estimated from the SPT blow counts contained in boring log (a) BH-15 and (b) BH-8 from Davisville.

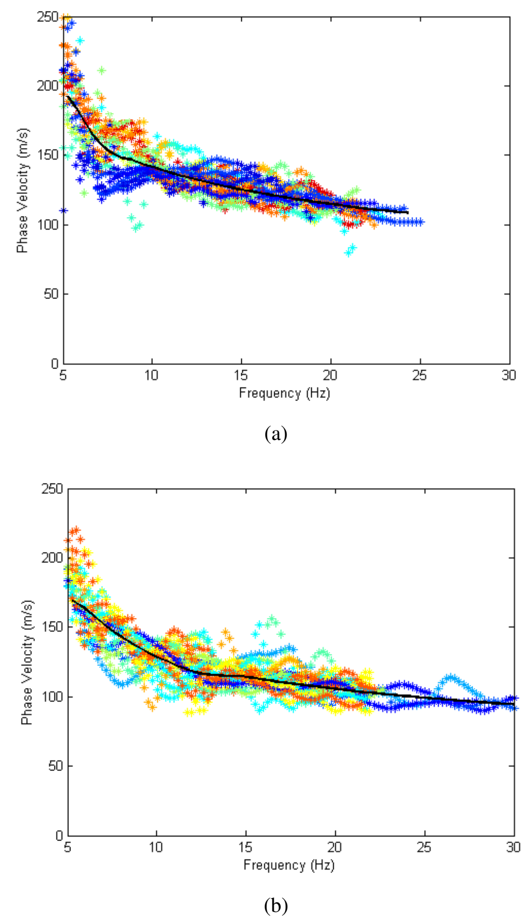


Fig. 10. Theoretical dispersion curves relating to the ideal values of c_o and ν (black line) determined from the inversion process overlaid on the composite dispersion curves from Davisville for (a) Deployment 1 and (b) Deployment 2. The different geophone pairs are represented by the different colors.

The theoretical phase velocity dispersion predicted by the inverted shear speed profiles at the two deployment locations compares well with the measured data. 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.

C. Comparison with Sediment Data from Vibracore

When the core taken near boring BH-15 was analyzed, the contents were determined to be mostly sand with some layers of silt present. This correlates well with the results of the inversion process in that the inverted profiles were similar to those of sand and silt (Fig.8). This further verifies the accuracy of the inversion scheme as a method to quickly and easily determine types of sediment in an area.

VIII. Conclusion

It can be concluded that the inversion scheme employed to invert the dispersion 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 and in the vibracore data. Therefore, these comparisons reveal that the inversion process was able to determine the types of sediment present in the test area with accuracy. These results confirm the value of this technology and inversion method as an alternative to, or in combination with, the classical, invasive, and expensive shear wave velocity measurement techniques for sediment characterization. The field test provided data to validate the inversion scheme, which can be considered a fast and non-invasive method to accurately determine shear speed profiles in shallow water.

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