Attenuation of Shear Waves in Near-Surface Sediments

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Abstract

In situ measurement of compressional and shear speed and compressional attenuation in near-surface marine sediments is a well-developed technology but techniques required to measure shear attenuation have lagged behind. In this paper, a pulse technique based on transposition is used to measure wave attenuation. Compressional attenuation determined by transposition compared favorably with standard techniques, confirming use of this approach for shear waves. Shear attenuation was much higher than compressional attenuation but within the range of previously reported measurements.

1. Introduction

Knowledge of sediment geoacoustic properties is of fundamental importance to marine environmental, military, and engineering applications. For instance, geoacoustic properties are used to predict the stability of marine slopes, sediment consolidation behavior, strength of marine foundations, liquefaction potential, mine burial, and high-frequency bottom acoustic scattering. In situ measurement of compressional wave speed and attenuation in marine sediments is a well-developed technology [1,2]. Recent developments in instrumentation allow in situ measurement of shear wave speeds but techniques required for measurement of shear wave attenuation have lagged behind [3]. In most unconsolidated sediments, near surface values of shear wave attenuation are estimated to be 1-2 orders of magnitude greater than for compressional waves [4,5,6,7]. Most of the few higher frequency (>100 Hz) shear attenuation measurements were made under laboratory conditions; whereas, most in situ measurements were made at lower (<10 Hz) frequency. This lack of comparable data has hampered the development of frequency-dependent and depth-dependent predictive relationships [7]. No attempt has been made to develop a predictive relationship between shear wave attenuation and easily measured sediment physical properties such as mean grain size, porosity, or bulk density. Simultaneous measurement of in situ compressional and shear wave speed and attenuation in unconsolidated sediment is rare. In this paper, a pulse technique is developed to measure in situ shear wave attenuation in surficial sediments. The validity of this new approach is demonstrated for compressional waves of known attenuation. Simultaneous measurements of compressional and shear wave speed and attenuation are presented for muddy and sandy sediments on the northern California continental shelf.

2. Attenuation Measurement Techniques

Measurement of compressional wave attenuation in sediments is facilitated by the presence of a convenient standard (seawater). Attenuation can be calculated as 20 $\log_{10}$ of the ratio of received voltage amplitude between probes in seawater and in sediment. No such convenient standard exist to measure shear wave attenuation. The transposition technique described below allows both compressional and shear wave attenuation to be measured without standards. The need to know transducer sensitivity or variable insertion loss when measuring shear wave attenuation is therefore eliminated.

The technique requires two transmitters (T_a and T_b) and two receivers (R_1 and R_2). Transducers are inserted into sediment at fixed distances with the two receivers located between transmitters (Fig. 1). As will be shown, only the three distances between transducers (d_1, d_2 and d_3) and the four received voltages (e_{1a}, e_{1b}, e_{2a}, and e_{2b}) are needed to calculate shear or compressional wave attenuation.

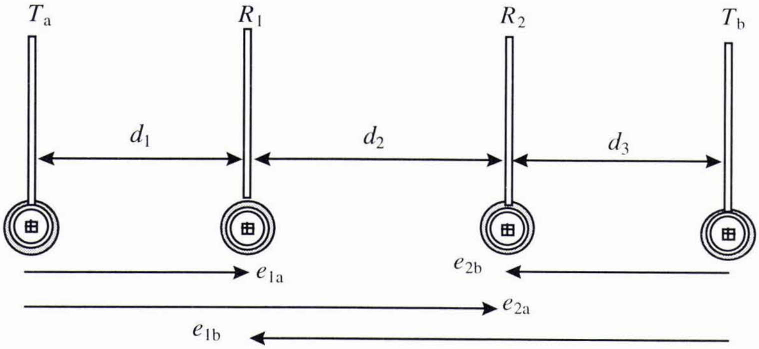

Figure 1. A schematic depiction of the transducer configuration for measuring shear and compressional wave attenuation by transposition of transmit direction. See text for definition of symbols.

The voltage received at R_1 and R_2 when transmitter T_a is driven can be expressed as

$$e_{1a} = M_1 p_{1a} \quad (1a)$$

$$e_{2a} = M_2 p_{2a}\,, \quad (1b)$$

where p_{1a} and p_{2a} are the acoustic pressures or wave amplitudes at receivers R_1 and R_2 and M_1 and M_2 include receiver sensitivity and insertion loss for R_1 and R_2. Sensitivity includes mechanical to electronic conversions and insertion loss accounts for the variable coupling of receivers to the sediment. The transfer function of the transmitters is included in the pressures (p) and are later canceled out. If we assume symmetry in the sensitivities of R_1 and R_2, it follows that the receive voltage at R_1 and R_2 when transmitter T_b is driven is

$$e_{1b} = M_1 p_{1b} \quad (2a)$$

$$e_{2b} = M_2 p_{2b}\,. \quad (2b)$$

Solving (2a) and (2b) for M_1 and M_2, substituting M_1 and M_2 into (1a) and (1b), and dividing the results yields

$$\frac{p_{1a}}{p_{2a}} = \frac{p_{1b}}{p_{2b}}\left(\frac{e_{1a}}{e_{2a}}\right)\left(\frac{e_{2b}}{e_{1b}}\right) \quad (3)$$

Assuming measurements are made in a homogeneous free-field and receivers are in the far-field, the ratio of the pressures in (3) is only dependent on spreading loss and sediment attenuation. If spherical spreading is assumed (far-field), the ratio of pressures can be expressed as

$$\frac{p_{1a}}{p_{2a}} = \frac{d_1 + d_2}{d_1}\exp(\alpha_e d_2) \quad (4a)$$

$$\frac{p_{1b}}{p_{2b}} = \frac{d_3}{d_2 + d_3}\exp(-\alpha_e d_2) \quad (4b)$$

Inserting (4a) and (4b) into (3) and solving for the attenuation (α) yields

$$\alpha_e = \frac{1}{2d_2}\ln\left[\left(\frac{d_1}{d_1 + d_2}\right)\left(\frac{d_3}{d_2 + d_3}\right)\left(\frac{e_{1a}}{e_{2a}}\frac{e_{2b}}{e_{1b}}\right)\right], \quad (5)$$

where attenuation α_e is measured in nepers per meter. Attenuation (α in $\mathrm{dBm^{-1}}$) can be calculated from the following expression

$$\alpha = \frac{4.343}{d_2}\ln\left[\left(\frac{d_1}{d_1 + d_2}\right)\left(\frac{d_3}{d_2 + d_3}\right)\left(\frac{e_{1a}}{e_{2a}}\frac{e_{2b}}{e_{1b}}\right)\right]. \quad (6)$$

3. Measurements with ISSAMS

Compressional and shear wave transducers were deployed with the latest version of the In Situ Sediment geoAcoustic Measurement System (ISSAMS) [2]. ISSAMS is a remotely-operated, hydraulic platform that allows fixed mounted geoacoustic probes to be driven into the sediment at precise depths (Fig. 2). Live video is used to monitor probe deployment and to provide visual information on seafloor type. Water conductivity, pressure, and temperature are used to calculate bottom water sound speed. Compressional and shear wave speed and attenuation are measured over pathlengths ranging from 30 to 100 cm and at depths up to 50 cm below the sediment-water interface. For compressional wave measurements, transmit pulses were driven utilizing 38-kHz pulsed sine waves and time delays and voltages were used to determine values of speed and attenuation between identical radial-poled ceramic cylinders. Speed (V_p) is calculated by comparison of received signals transmitted through the sediment with those transmitted through seawater overlying the sediments, where C_w is the bottom water speed, d is the distance between transmitter and receiver, and Δt the water travel time minus the sediment travel time.

$$V_p = \frac{C_w}{1-(\Delta t C_w / d)}. \quad (7)$$

Compressional wave attenuation (α_p in $\mathrm{dBm^{-1}}$) is calculated as

$$\alpha_p = \frac{20}{d}\log_{10}\left(\frac{e_w}{e_s}\right) \quad (8)$$

where e_w / e_s is the ratio of received voltage between probes in seawater and sediment. For these measurements, the maximum amplitude of the first sine wave (e.g., the second peak) was used as the received voltage. Distances between transmitters and receivers are calculated from the known water speed (C_w) and measured time delays. Shear wave speed is calculated from time-of-flight between bimorph bender elements mounted in flexible silicone rubber mounts and driven at 0.25 to 2.0 kHz. Distances between shear wave transducers are measured from center-to-center of the bender elements before and after deployment [8].

For measurement of attenuation, as described in section 2, distances d_1 and d_3 are calculated from known water speed (C_w) and measured time delays between compressional transducers and measured directly between shear wave transducers. The distance between receivers (d_2) is calculated as one-half the sum of the distance difference between transmitters (T_a, T_b) and their respective near and far receivers (R_1, R_2). Received voltages (e_{1a}, e_{1b}, e_{2a}, and e_{2b}) were measured as described in the preceding paragraph for both compressional and shear waves.

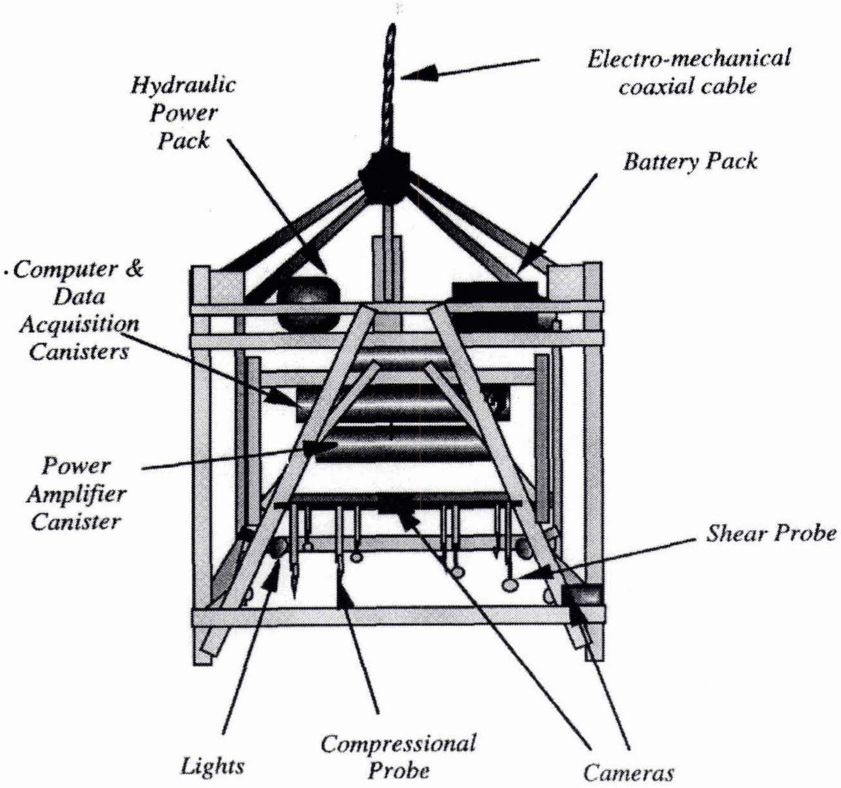

Figure 2. In Situ Sediment geoAcoustic Measurement System (ISSAMS): the aluminum and stainless steel platform weighs approximately 1 metric ton in air, is just under 3 meters in height and has a 2.5-meter square footprint.

4. Results

Sediment geoacoustic measurements were made along the northern California continental shelf as part of the Office of Naval Research STRATAFORM program [9]. The overall objective of our study is to quantify the effects of biological (bioturbation) and hydrodynamic (storms and floods) processes on sediment physical and geoacoustic properties. In order to achieve this goal, techniques needed to be developed to measure shear wave attenuation which complements existing techniques used to measure other sediment geoacoustic properties. Measurements reported here were made at two sites (S-40 and S-80, where number gives approximate water depth) chosen to represent contrasting sediment types. Three deployments of the ISSAMS system were made at both the shallower sandy (S-40) and the deeper muddy (S-80) sites. Compressional and shear wave speed and attenuation were measured at sediment depths of 10, 20 and 30 cm. The results of 36 measurements of compressional and shear wave speed and compressional wave attenuation (V_p, V_s, α_p) and the 9 measurements of compressional and shear wave attenuation (α_p , α_s) using the new transposition technique are presented in Table 1. Attenuation is expressed as dBm^{-1}, $dB\lambda^{-1}$ and dBm^{-1} kHz^{-1} in order to facilitate comparision with shear wave attenuation reported from other studies. Compressional velocity ratio (V_p-ratio = ratio of in situ sediment compressional speed to the sound speed of the overlying pore water) is used for inter-site comparisions to eliminate the effect of temperature, salinity and pressure on compressional speeds. Compressional and shear wave speed and compressional wave attenuation were significantly higher at the shallower sandy site. Wave speeds and attenuation are in agreement with past studies for the given sediment types (Fig 3).

Table 1. A comparison of sediment physical and geoacoustic properties for two sites on the northern California continental shelf. Most values of sediment geoacoustic properties are complement with standard deviations in parentheses.

Site	S-40	S-80
Depth (m)	43	80
Sediment type	Sand	Clayey-silt
Mean Grain Size (ϕ)	2.97	7.82
V_p (ms^{-1})	1623 (10.3)	1479 (4.3)
V_p -ratio	1.097	0.999
V_s (ms^{-1})	80 (5.1)	42 (3.8)
α_p (dBm^{-1}@38kHz)	20.8 (4.4)	5.6 (1.6)
k_p (dB m^{-1} kHz^{-1})	0.55	0.15
Transposition		
α_p (dBm^{-1}@38 kHz)	26.7 (5.5)	4.9 (2.5)
α_s (dBm^{-1}@1.0 kHz)	59.7 (11.3)	
α_s (dBm^{-1}@0.3 kHz)		25.6 (5.7)
Shear log decrement (dBλ^{-1})	4.7 (1.0)	3.8 (0.9)
Compressional log decrement (dBλ^{-1})	1.14	0.19
k_p (dBm^{-1} kHz^{-1})	0.70 (0.14)	0.13 (0.06)

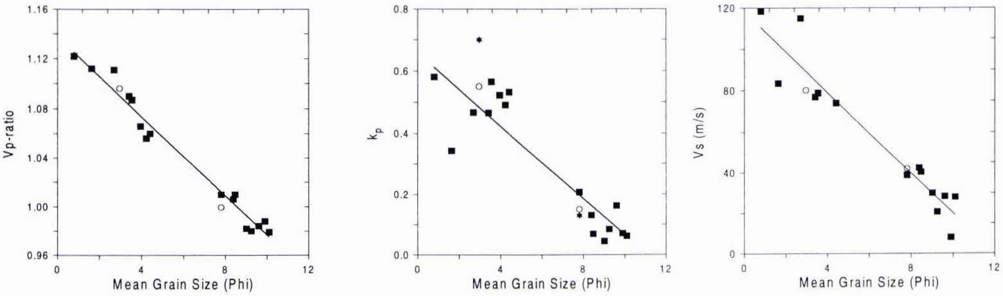

Figure 3. Predictive relationships between sediment mean grain size and compressional wave velocity ratio (V_p-ratio), compressional wave attenuation (k in dBm^{-1} kHz^{-1}) and shear wave speed (V_s in ms^{-1}) for near surface silicilastic sediments. Data were compiled from geoacoustic studies, using ISSAMS, in a variety of sediment types near the Bay of La Spezia, Italy, hard-packed sand near Panama City, Florida, and soft mud in Eckernförde Bay, Baltic Sea [8,10]. Sediment geoacoustic measurements from the northern California continental shelf include standard methods (o) and by measurement of attenuation using transposition (*).

Compressional wave attenuation determined by transposition (6) was not significantly different (t-test) than attenuation measured using standard techniques (8) which are based on the ratio of received amplitudes in water and in sediment. These data confirm the use of transposition to measure wave attenuation and techniques of (6) were therefore used to calculate shear wave attenuation. Shear wave attenuation was very high; 2-3 orders of magnitude higher than compressional wave attenuation when compared as dBm^{-1} per kHz (Hamilton's k) and 5-20 times higher when expressed as dBλ^{-1} (log decrement in decibels per wavelength).

5. Discussion and Conclusions

Based on reviews of both laboratory geotechnical testing and in situ geophysical studies, Hamilton [4,5,11] concluded that in near-surface sediments most values of shear attenuation or log decrement range between 0.86 to 5.21 $dB\lambda^{-1}$ (0.1 to 0.6 nepers per wavelength) with slightly higher log decrements in sandy (mean = 2.6 $dB\lambda^{-1}$) compared to muddy (mean = 1.7 $dB\lambda^{-1}$) sediment. High-frequency laboratory shear wave measurements summarized by Kibblewhite [6] show shear attenuation in sand, measured at 1.0-kHz, range between 20-70 dBm^{-1}. Bowles [7] summarized values of shear wave attenuation based recent direct borehole measurements and from inversion of Scholte waves. He found near surface (upper 5 meters) attenuation ranged from 0.1 to 6.7 $dB\lambda^{-1}$. All values of log decrement, in his summary, greater than 1.8 $dB\lambda^{-1}$ were measured at higher frequency (80-100 Hz). In summary, shear wave attenuation reported here (Table 1) is higher than the average of previously reported measurements, but well within the range of those measurements.

Comparison of values of near-surface shear wave attenuation is complicated by differences in the variety of laboratory and field measurement techniques used to measure shear wave attenuation, very steep shear wave attenuation gradients, poorly understood frequency dependence, and because measured shear attenuation often includes not only intrinsic attenuation but losses due to scattering and conversion of shear energy to compressional energy (i.e., the effect of sediment heterogeneity and layering). Based on theory and confirmed by laboratory measurements, Stoll [12,13,14] has shown that the power law relationship between shear wave attenuation and frequency is not constant over the entire frequency range and that steep gradients of shear wave attenuation are to be expected in the upper few meters of sediment. Steep gradients reflect the effects of increased overburden pressure (effective stress) on frame moduli. These steep gradients in shear wave attenuation are supported by laboratory and field measurements [7] and may account for part of the wide variation in reported surficial shear wave attenuation. The nonlinear dependence of shear wave attenuation with frequency results when different forms of energy dissipation (intergranular friction, relative motion between fluid and solid, and local fluid motion) dominate at different frequencies. Recent field [15] and laboratory [16] measurements support the nonlinearity of this frequency-attenuation relationship. Based on an admitted scarcity of comparable data, Hamilton (5) presents a case for a power law (with frequency scaled to the first power) relationship between shear wave attenuation and frequency. Buckingham (17) provides a theory of wave propagation in which shear wave attenuation is scaled to the first power of frequency. ISSAMS is ideally suited to contrast these competing theories by providing shear attenuation measurements in the frequency band (0.1 to 2.5 kHz) where changes in dissipation mechanisms are predicted to occur. These data may help reconcile differences in shear attenuation measured by low frequency geophysical techniques and higher frequency laboratory methods and bring order to predictive relationships between shear wave attenuation and sediment physical properties.

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