Sonic Properties of Multiphase Media

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LONG-TERM GOALS

Shallow water (SW) with sandy-silty bottoms has a nonlinear-frequency-dependent attenuation from the lower to mid frequencies. The simplified theory predicts sandy sediment attenuation with quadratic frequency dependence. The estimated dependence was reported by multiple investigators to be slightly less than quadratic. The conversion to shear waves in the sedimentary layer was identified as the cause. However, the shear speed profiles in sandy sediments are not well known. The long-range goal is to provide a method to determine these geoacoustic profiles using inversion techniques in areas of tactical naval significance.

The simplified theory is not applicable to muddy sediments over the large range of porosities, fine platelet sizes and does not include electro-physical-chemical effects. Thus the long-range goal is to develop a simplified theory of muddy sediments that can be applied in areas of naval interest. A second goal is to development a simplified treatment of compressional wave scattering from complex shaped gaseous inclusions and compliant objects in muddy sediments.

OBJECTIVES

The first objective is to provide a constrained method to determine these geoacoustic profiles including the effects of attenuation and shear using currently developed inversion techniques in areas of tactical naval significance.

The second objective is to identify the basic physical principles (the importance of electro-physical-chemical characteristics) that govern the formation, size, shape and distribution of gas bubbles in sediments. It is known, for example, that in some examples of muddy sediments, the bubbles are not spherical, but more closely resemble oblate spheroids. Analytical reasoning based on physical principles and existing experimental results [11,13] may help to determine whether this is universally true, especially for sediments lying at the bottom of coastal waters.

A third objective is to determine a physics-based model for the processes involved in the scattering of sound by bubbles in sediments. It is anticipated that the model will yield boundary conditions that apply at the interface of the water sedimentary layer that contains micro-bubbles. This boundary condition is required to calculate the reflection, scattering, attenuation and reverberation of higher frequency sound (>1 kHz).
**APPROACH**

The first objective can be met by performing experiments in tactically significant conjunction with designated laboratory investigators to obtain complex pressure at two depths, one mid water and one 1m off the bottom. The results of a measurement and calculation of the horizontal wavenumber spectra are shown in Fig. 1. This result was obtained by calculation of the pressure field and a spatial transform comparable to that of the measurement. The interface wave, Sholte, has a wavenumber proportional to 0.875 times the shear wave speed. Also shown wavenumbers that describe the water column compressional wave propagation, these wave numbers when coupled with geophysical parameters are the parameters required to demonstrate inversion accuracy.

![Image of horizontal wavenumber spectra](image)

**Figure 1: Horizontal wavenumber spectra, left measured and right calculated. [7]**

Muddy sediments found in rivers, deltas and harbors are classified as slow bottoms and pose a problem for the detection of buried ordnance [9,10,11]. The research questions for mud are: first, the frequency dependence dispersion characteristic and second the qualitative description of the boundary conditions on a microbubble. Millions of suspended and dissolved matter (clay, silt, and sand, organic matter) is transported from the rivers to the sea. The Mississippi River alone transports approximately 136 million tons of dissolved matter and 340 million tons of suspended matter each year. The resulting "mud" composed of small particle sizes and porosities less than 20% in very shallow water and porosities ranging between 60-90% in deeper waters. Electro-physical-chemical effects strongly influenced by organic materials, water salinity and PH complicate the problem. Many of the geophysical properties and their influence on high frequency scattering and reflection of sound may be found in the recent work of Jackson and Richardson [13]. It is the intent of this proposal to extend their work to lower frequencies and high porosity muddy sediments were the nature of the dispersion is not well known. The approach is to examine current theoretical formulations for their applicability frequencies between 1KHz and 10 KHz. Second using measured properties of muddy sediments such as particle size, composition, porosity and PH, define regions wherein simplified models can be used to describe the scattering of sound from compressible objects. In this regard classical scattering theory previously developed by us and others [14] will be examined for its analytical tractability. The technical approach can be summarized as a balance between theory, numerical calculations, and measured sound transmission. Fig. 2 [11], an example of measured transmission, illustrates the combined effect of a mud, water and microbubbles. The short duration 10 kHz pulse received on a hydrophone 3 m below the water mud interface is seen in the left panel has appreciable time spread.
due to scattering from bubbles in the sediment. The mean square pressure, which is proportional to
energy versus time, is shown in the right panel. In this experiment the sound speed was observed to be
slower than expected due to the presence of bubbles. The approach here is to explain these
observations by determining the scattering response of a single and multiple bubbles in three phase
media.

\[ p_s(r, \theta) = \frac{ikp_0 e^{ikr}}{r} \sum_{m=0}^{\infty} (-1)^m (2m+1)P_m(\cos \theta) / (1 + iC_m); \]

Where the constant \( C_m \) is

\[ C_m = \left[ \frac{\alpha_m(k' a)}{\alpha_m(ka)} \right] \frac{n_m(ka)}{j_m(k' a)} - \frac{\beta_m(ka)}{\alpha_m(ka)} (\rho' c' / \rho c) \left[ \frac{\alpha_m(k' a)}{\alpha_m(ka)} \right] \frac{j_m(ka)}{j_m(k' a)} - (\rho' c' / \rho c). \]

![Fig. 2: Dodge pond measurement results showing the importance of methane micro bubbles.](image)

Examples of this scattering phenomena and be found in [15] and the reference thereof and the
following measurements of sound scattering from a bubbly viscoelastic gel mixture shown in Fig.3.

![Fig. 3: (A) Shows the Zanthan Gum and Bubbly Target and (B) shows the Scattering geometry.](image)
Here the spherical Bessel function, $j$, and Neumann function, $n$, have arguments referenced to the liquid, unprimed, and the mixture, primed as shown in Fig. 3 B. The experimental results are shown in Fig. 4 for a volume fraction $\beta = 0.12$.

**Fig. 4:** Target strength versus frequency is shown with the solid curve for the calculation and the symbol curve for the measurements. The volume fraction of the gas in bubble form is 12%.

The qualitative agreement between theory using mixture properties and measurement is excellent. Differences with theory as see in the level and width of the spectral peak are attributed to the of the compressional wave theory and viscoelastic nature of the gel. The approach adopted here is to use a computation that includes a realistic treatment of these effects such as found in [14] and to estimate the appropriate acoustical parameters to be used in the treatment of compressional scatters in muddy sediments. The recent Dodge Pond experiment will provide a basis for comparison of the properties of mud with microbubbles.

**WORK COMPLETED**

The analysis of the data collected by a vertical array in the mud of Dodge Pond has been the focus of the work this year. Multichannel analysis is currently underway to characterize multipath and time spread effects. The results to date have produced lower sonic speeds than expected from a mud sediment saturated with water, that is 3% lower than the water alone. The semi-empirical expression we derived for saturated Dodge Pond mud, with $s$ and $w$ subscripts designating sediment and water, was

$$1 - \frac{c_m}{c_w} \approx \left( \frac{f_s}{2} \right) \left( \frac{\rho_s}{\rho_w} + \frac{B_w}{B_s} - 2 \right)$$

$$\approx \left( \frac{f_s}{2} \right) (2.6 + 0.267 - 2) \approx 0.434 f_s$$

**Dodge Pond Mud:**

$$\frac{c_m}{c_w} = 0.94 \; ; \; \chi_w \approx 0.84$$

This expression treated the mud sediment and water as liquids, no shear, and used conventional mixture theory developed initially by Mallock and Wood. A three component theory was developed and it was shown that the properties of the sediment water mixture, $sw$, could be treated as one component and then the gas in microbubble form, $bg$, as a second component. There result was a simplified expression for the three component mixture.
This equation treats the mud-water sediment as a single fluid and the effect of the ensemble of microbubbles volume fraction, $\chi$. When the volume fraction is between $10^{-4}$ and $10^{-5}$ the resulting sonic speeds are consistent with the measured results.

Table I: Volume fraction versus mixture speed for muddy-bubbly mixtures.

<table>
<thead>
<tr>
<th>$\chi_{gb}$</th>
<th>$c_m$</th>
<th>$c_m/c_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-3}</td>
<td>243</td>
<td>0.17</td>
</tr>
<tr>
<td>10^{-4}</td>
<td>771</td>
<td>0.54</td>
</tr>
<tr>
<td>10^{-5}</td>
<td>1236</td>
<td>0.86</td>
</tr>
<tr>
<td>10^{-6}</td>
<td>1347</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Range of sonic speeds and ratio of mixture speed (water, sediment and bubbles) to the water sound speed as measured:

$$C_m \approx 1200 \text{ m/s}; C_w \approx 1436; \frac{C_m}{C_w} \approx 0.8357$$

$$C_m \approx 857 \text{ m/s}; C_w \approx 1436; \frac{C_m}{C_w} \approx 0.599$$

$$0.599 \leq \frac{C_m}{C_w} \leq 0.8357.$$

The work is continuing to improve the analysis of selected runs from Dodge pond to serve as a basis for the evaluation of bubble scattering and reverberation algorithms to enable the calculation of time spread and reverberation.

RESULTS

Measurements of the sound speed characteristic of the high porosity Dodge Pond mud were found to have a sonic speed less than that observed by Wood and Weston [9], a compressional speed 3% less than that of water. Other experiments performed on muddy sediments at frequencies greater than a kilohertz are consistent with the Dodge Pond observations when microbubbles are present. The presence of bubbles is known to be an important factor in decreasing the sound speed. A theoretical treatment of "muddy sediments", the Card House Theory, Pierce and Carey [11], estimated the slow sound speed and frequency dispersion proportional to mud porosity, $C_{mud} \approx (0.91-0.97)C_w$. The presence of a micro-bubbles can lower the sound speed consistent with the Mallock-Wood equation when the bubble size distribution and mean bubble separation are less than the wavelength of the propagating wave. Since measurement of the bubble size distribution within the mud is difficult; theoretical limits on the size distribution in the complex card house structure can be useful in interpreting measurements on muddy sediments and provide a basis for acoustic distribution measurement. The bubble size distribution in mud to determine the applicability of the Mallock-Wood approach to estimate the additional reduction in sound speed due to the bubbles. The limits this
unusual structure places on bubble size, shape and dampening characteristics are estimated along with sound speed reductions based on mixture theory. [16]

IMPACT/APPLICATIONS

The potential impact of this work is twofold. First remote surveillance of ocean areas such as the Indian ocean basins using inexpensive autonomous vehicles using sources of opportunity would have a significant impact on the geoacoustic parameters required to perform accurate performance predictions. While the gross characteristics of the bottom in areas such as the Bay of Bengal and the Arabian Sea. The second impact is on the design and use of unexploded ordnance submerged in muddy sediments in areas of ordnance disposal. The determination of frequency of operation, band width and signal processing classification algorithms could be enhanced and optimized with the information and characterizations from this investigation.

RELATED PROJECTS

This effort is a partial continuation of the current Boston University "Sound Speed and Attenuation Multiphase Media" grant (W. Carey), Award Number: N00014-04-1-0164 and is related to the Strategic Environmental Research and Development Program (SERDP) office, NSWCPCD - Unexploded Ordnance (UXO) program. This proposed effort is related to collaborative research of Dr. Lynch, WHOI. Collaboration results in shared experimental resources and facilities as well as the opportunity to contribute to major ONR programs such as the SPAWAR Ocean Bottom Classification Initiative, OBCI and exploratory development programs at NCSS. A companion project is being performed at the RPI-Dept. Applied Mathematics on the modeling of the electro-physical effects on mud, bubble shapes and oscillations.

REFERENCES


[8] W.M. Carey, "Official Correspondence; W. Carey, Boston University, to F. Herr, Office of Naval Research, dated April 8, 2009"


PUBLICATIONS

Invited Papers

2011 161st Mtg ASA "Mid-basin deep-water low-frequency ambient noise estimation"
2010 160th Mtg ASA "Low-frequency sound scattering from microbubble distributions."
2010 159th Mtg ASA "An overview of unmanned underwater vehicle noise ........... "
2010 159th Mtg ASA "Oceanic Noise: mechanisms, radiation characteristics, and array results."
2009 158th Mtg ASA "Measurement of sound transmission through mud at Dodge Pond, Connecticut
2009 158th Mtg ASA "The applicability of a small towed array system to the ocean bottom ...........
2009 158th Mtg ASA "Sediment shear as a perturbation in geoacoustic inversions and an ............"