Integrated Model for the Acoustics of Sediments

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LONG-TERM GOALS

Physically sound models of acoustic interaction with the ocean floor including penetration, reflection and scattering in support of MCM and ASW needs.

OBJECTIVES

The objectives are: (1) Integration of phenomenological components of the Biot plus grain contact physics models, to reconcile the physical constants and processes, with a view to reducing the number of input variables, (2) a comprehensive model for all sediment types and improved modeling of grain contact physics, and (3) the development and testing of sediment acoustic models through a series of at-sea experiments.

APPROACH

(1) The approach is guided by experimental results. Extensive measurements since the 1980s, particularly the ONR sponsored experiments SAX99, ASIAEX, SAX04, and SW06, indicate that fluid and elastic models of the seabed cannot account for the observed frequency dependence of wave speeds, attenuations, and reflection loss. From direct measurements and inversions, it was found that attenuation increases approximately as the second power of the frequency, at frequencies below a few kiloHertz. At higher frequencies, the rate of increase is lower but variable. This is illustrated in Fig. 1. The Biot-Stoll poro-elastic model goes part of the way toward explaining the measurements but it cannot match the magnitude of the wave speed dispersion and high frequency attenuation trends. Guided by the experimental results, the approach is to extend the Biot-Stoll model to include the physics of the sand grains, particularly random variations in the grain-grain contact stiffness, squirt flow in the contact region, and the change of pore fluid viscosity as a function of contact width.

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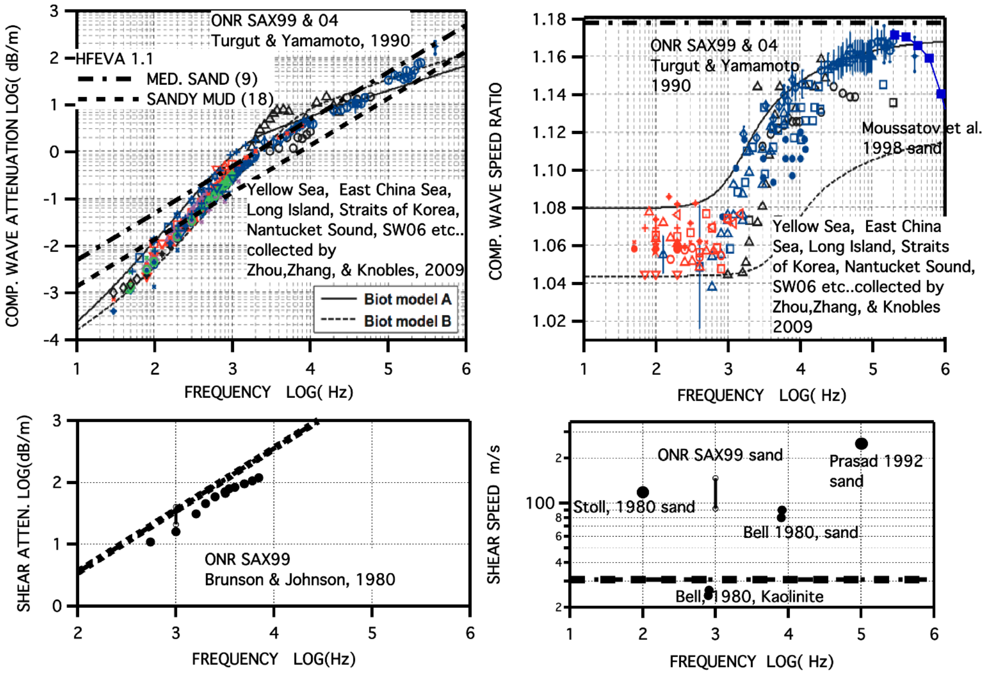

Fig. 1. Recent measurements and inversions of wave speeds and attenuations in sandy sediments from numerous sources compared to visco-elastic models with constant parameters (straight dashed lines under HFEVA) and with the Biot-Stoll model curves (Biot models A and B).
[The top left panel shows compressional wave attenuation as a function of frequency. The top right panel shows the compressional wave speed as a function of frequency. The bottom left panel shows the shear wave attenuation as a function of frequency. The bottom right panel shows shear wave speed as a function of frequency.]

(2) It has been observed that ocean sediments are often inhomogeneous, paticularly in the context of high frequency acoustics. The patchy seabed concept needs to be properly developed and explored in order to assess its impact on acoustic propagation and reverberation models. Practically, all underwater sediments are porous and water-permeable, therefore compatible with poro-elastic models. Although much effort has been devoted to the modeling of the sandy sediments, there are other sediments, particularly softer sediments, in which the attenuation is proportional to the first power of frequency. The goal of this task is a model that is able to represent a broad range of sediments, and smoothly transition from one type of sediment into another.

(3) Model based inversions directly from array data have had some success, but the assumption of a model can bias the result and obscure inconsistencies. The preferred approach is to isolate the bottom reflected signals and measure bottom loss, and then to use the measured bottom loss as a function of frequency and angle to invert for sediment properties. This approach allows more than one bottom model to be tested, and is less likely to be biased.

WORK COMPLETED

Following the three broad tasks above, the work completed may be divided into three corresponding sections. This work builds upon the work done in the previous grant (N00014-06-1-0125) and includes some work done towards the end of that grant.

(1) Some extensions of the Biot-Stoll model have been integrated into one model. The extensions include random variations in the grain-grain contact stiffness, squirt flow in the contact region, and the change of pore fluid viscosity as a function of contact width. In addition, there are effects due to the pore size distribution, and multiple scattering at high frequencies. These extensions have been brought together and integrated where possible to eliminate redundant parameters. The model has been compared to the extant database of measurements of wave speeds and attenuations. The result is a model that can better match the measured wave speeds and attenuations with a set of input parameters that are more closely related to the physical processes within a granular medium. This formulation is expected to lead to a reduction in the number of input parameters. This study was done in collaboration with Dr. Marcia Isakson, and resulted in ann invited review paper that will be published in the proceedings of the Ocean Acoustics Conference 2012, and a recently submitted paper for the special issue of the Journal of the Acoustical Society of America on Sediment Acoustics.

(2) The Biot model is extended to cover sediments other than sand. By adjusting the standard deviation of the pore sizes, according to Yamamoto and Turgut (1988), the frequency dependence of attenuation and sound speed can be adjusted to match a wide range of sediments types. It provides the theoreical foundations for modeling an inhomogeneous, or patchy, seabed. This is a science issue that is of particular interest to the NAVO. In collaboration with Dr. Marcia Isakson, a new project titled "Seafloor Spatial Variability Mitigation", funded by SPAWAR, will explore the issue of patchiness. The extended model will provide the theoretical frame work for the bulk property variations, while Dr. Isakson will model the changes due to roughness and layering.

(3) The testing of the models with at-sea measurements, is being realized through a number of collaborative experiments. Acoustic data from a thin line array, towed by an AUV and developed by the Applied Acoustics Laboratory of the National Unversity of Singapore, were successfully analyzed for seabed characterization. The AUV did not have a sound source dedicated to seabed characterization. Under the noise inversion component of this task, the initial plan was to use its self-noise, such as motor and gear noises. As it turned out, the motor and gear noises were not detectable, but the acoustic communication signals were adequate for seabed characterization. A paper has been accepted for publication in the IEEE Journal of Ocean Engineering. Participation in the Noble Mariner 2012 Experiment, in cooperation with the NATO Centre for Maritime Research and Experimentation (CMRE), was successfully completed, in which the roughness of the seabed was measured with a laser profiler and the acoustic reflection loss was measured with an echo sounder, both deployed on a ROV. Participation in future experiments are planned, including the Transmission and Reverberation Experiment 2013, and the Sediment Characterization Experiment 2015.

RESULTS

Following the three broad tasks above, the results may be divided into three corresponding sections:

(1) The extant database of sediment sound speed and attenuation measurements [1-15] and a best-fit extended Biot model are shown in Fig. 2(a). The legend explaining the data sources is shown in Fig. 2(b). An intermediate step in the model development was the Biot + contact physics model of 2008 (BIC08). It includes the basic Biot equations, with modifications that account for the squirt flow at the grain contacts by Chotiros and Isakson [16] and Kimura [17], low frequency wave speed anomaly due to grain rotation, and high frequency attenuation and dispersion due to shear flow at the grain contacts.

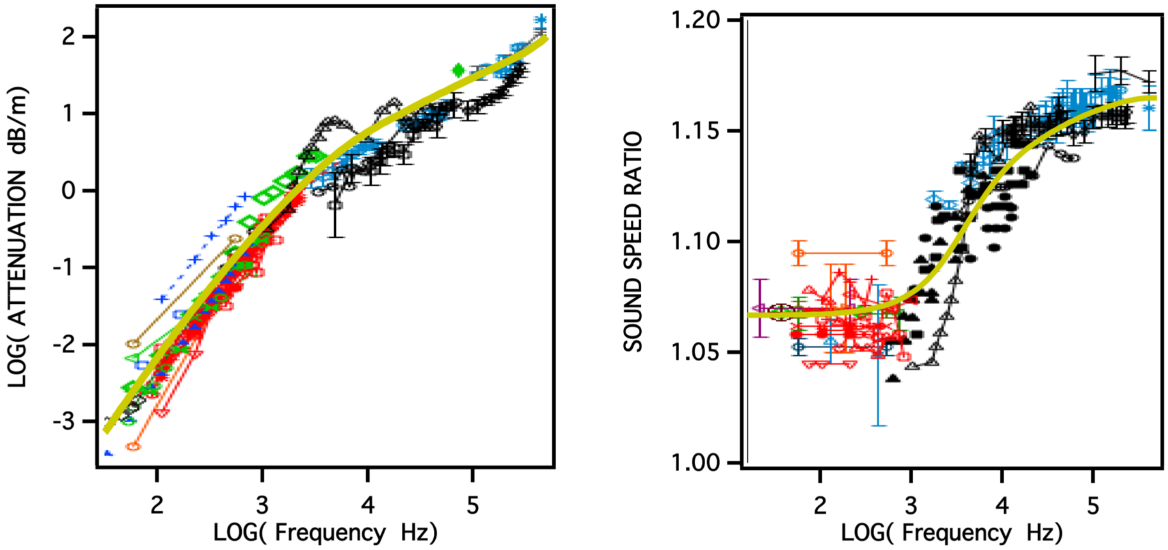

Fig. 2(a). Extant measurements of sound speed and attenuation in sandy sediments from numerous sources, compared to latest extended Biot model fitted to the average trend in yellow. [The left panel shows compressional wave attenuation as a function of frequency. The right panel shows the compressional wave speed a function of frequency.]

○ Williams et al. 2002, 11-50 kHz buried array
○ Williams et al. 2002, 100-260 kHz attenuation array
△ Stoll 2002, 200 Hz Geophone
△ Buckingham and Richardson 2002, 25-100 kHz ISSAMS
◇ Williams et al. 2002, Chirp sonar
✳ Williams et al. 2002, 400 Hz geophones
✳ Buckingham and Richardson 2002, 38 kHz ISSAMS
✳ Williams et al. 2002, 150 kHz tomography
✳ Williams et al. 2002, 400 kHz diver cores
—+— Zimmer et al. 2010
● Hines et al. 2005, buried source, receiver, TX-V2
■ Hines et al. 2005, buried source, receiver, V2-V4
▲ Hines et al. 2005, in-water source, buried receiver
—□— Hefner et al. 2009, 5-50 kHz buried array
—◇— Hefner et al. 2009, 30-300 kHz attenuation array
♦ Goff et al. 2004, Table I (-73.03603, 39.02733)
—◇— Knobles et al. 2008
—◁— Huang et al. 2008
—○— Jiang and Chapman 2008, WP21 station
—○— Jiang and Chapman 2008, WP22 station
—○— Jiang and Chapman 2008, WP23 station

—◁— Potty et al. 2008
—▷— Ballard and Becker 2008
○ Zhou et al. 2009, site 1
○ Zhou et al. 2009, site 2
○ Zhou et al. 2009, site 3
□ Zhou et al. 2009, site 4
○ Zhou et al. 2009, site 5
—○— Zhou et al. 2009, site 6
—△— Zhou et al. 2009, site 7
—◁— Zhou et al. 2009, site 8a
—+— Zhou et al. 2009, site 8b
—✳— Zhou et al. 2009, site 9
—▽— Zhou et al. 2009, site 10
—●— Zhou et al. 2009, site 11a
—■— Zhou et al. 2009, site 11b
—□— Zhou et al. 2009, site 11c
—×— Zhou et al. 2009, site 11d
—△— Turgut and Yamamoto 1990
—○— Simpson et al. 2003

Fig. 2(b). Legend for the extant measurements of sound speeds and attenuations in sandy shown in Fig. 2(a).

In the squirt flow concept, there is a thin film of pore fluid at each grain-grain contact. As a wave propagates through the medium, the contact gap width oscillates causing the fluid to be expelled from or drawn into the contact gap, hence the term “squirt” flow. With reference to Fig. 3, the contact between any two grains may be considered as a rough surface contact. There are many micro-asperities on the surface of each grain. The solid contacts are made on the peaks of the asperities. Surrounding the solid contact, is a film of fluid. The contact may be idealized as cylindrical solid contact of height h and radius a_s, surrounded by a concentric circular fluid film radius a_f.

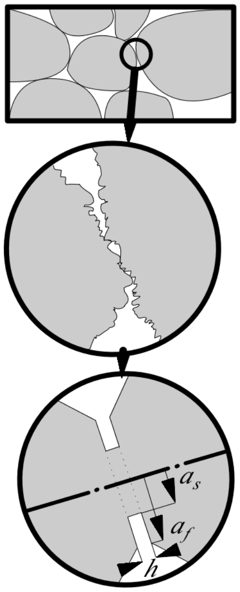

Fig. 3. Idealization of the grain-grain contact: Each of the grain-grain contacts (top panel) is a rough interface contact consisting of a few solid contacts surrounded by a fluid film (middle panel). It may be idealized as a gap that is filled with circular fluid film of thickness h and outer radius af, punctured by a concentric solid contact of radius a_s at the center (bottom panel).
[The top left panel shows a random packing of grains. The middle panel shows an expanded view of a grain-grain contact. The bottom panel shows the idealization of the contact as a single solid contact surrounded by a fluid film.]

Using the BIC08 equations, numerical estimates of the fluid film width h, and radius a_f, as well as the radius of the solid contact a_s were made by fitting the model to measured data. The assumption that the solid contact radius is much smaller than the outer fluid film radius was numerically confirmed, but the width of the fluid film, calculated at around one picometer, was implausible, because it was two orders of magnitude smaller than a water molecule. The difficulty was resolved by recent measurements of the enhanced viscosity of water when confined in a thin film [18,19]. In a couple of independent experimental measurements using atomic force microscopes, it was found that the viscosity of water increases by several orders of magnitude when the film width decreases below a few nanometers, when confined between hydrophilic surfaces, such as silica. After including the effects of viscosity variations as a function of film thickness, a more reasonable estimate of the fluid film thickness was found - approximately an order of magnitude thicker than a water molecule – and the role of micro-fluidics in the physics of sound propagation in water-saturated sand is established. A consequence of this result is that forces due to shear flow at the grain contacts are too small to explain the high frequency attenuation and dispersion. The multiple scattering hypothesis of Schwartz and Plona [20] and confirmed by Kimura [21] is now is the most plausible explanation for the high frequency attenuation and dispersion. The current model, tentatively called BIC12, contains the random contact stiffness variation extension that explains the low frequency sound speed anomaly, the squirt flow mechanism with gap-dependent viscosity, and the high-frequency dispersion due to multiple-scattering. In addition, it also includes the pore size distribution model of Yamamoto and Turgut [22] to produce a model that is applicable to a wide range of sediments. By connecting the intermediate model parameters with the dimensions of the grain-grain contact, the various extensions may be consolidated, resulting in a reduction in the number of input parameter values.

(2) The Biot model was extended to cover sediments other than sand. By adjusting the standard deviation of the pore sizes, according to Yamamoto and Turgut [22], the frequency dependence of attenuation and sound speed can be adjusted to match a wide range of sediments types. As an illustration, the figure below shows the SAX99 and SAX04 experimental data compared to a two models with different pore size distribution widths. This approach provides the theoretical foundation for smoothly transitioning the poro-elastic model between different sediment types, such as sand, silt and mud. It also will be useful in the modeling of sediment inhomogeneity, which may be an important source of acoustic variability in the shallow water environment.

(3) The testing of the models with at-sea measurements, is being realized through a number of collaborative at-sea experiments. A joint experiment under the title Noble Mariner 2012 in cooperation with the NATO Centre for Maritime Research and Experimentation (CMRE) was successfully completed. An example of the variations in the bottom reflection loss measured off the coast of France is shown in the figure below, which shows reflection loss variations of around 10 dB, signifying spatial variations in the acoustic properties of an otherwise flat seabed. The apparent undulations in the plot are not due to the bottom but to the variation in the altitude of the ROV platform. The large variation in the reflection loss indicate that the acoustic properties of the seabed are patchy.

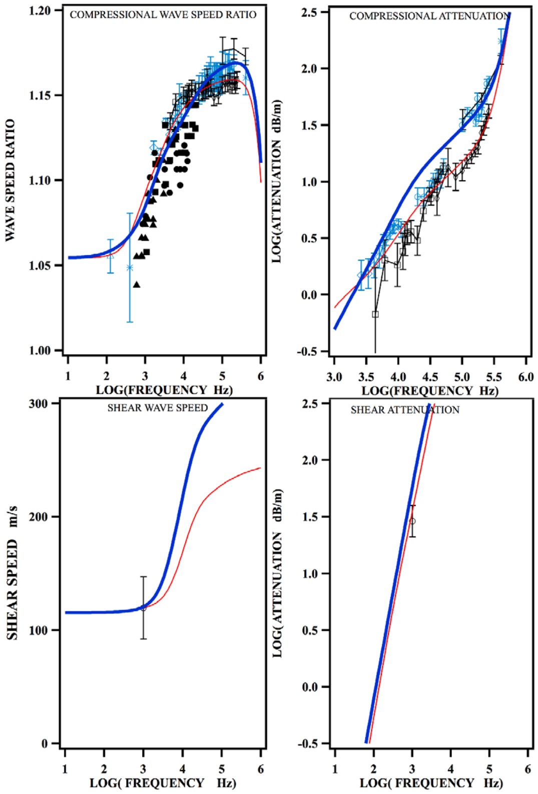

Fig. 4. Measurements from SAX99 (blue) and SAX04 (black) showing the sound speed ratio (top left), sound attenuation (top right), shear speed (bottom left), and shear attenuation (bottom right) as a function of frequency. The measurements are compared to two models with different pore size distributions that match different frequency slopes of the compressional wave attenuation (top right panel).

[The top left panel shows compressional wave attenuation as a function of frequency. The top right panel shows the compressional wave speed a function of frequency. The bottom left panel shows the shear wave attenuation as a function of frequency. The bottom right panel shows shear wave speed as a function of frequency.]

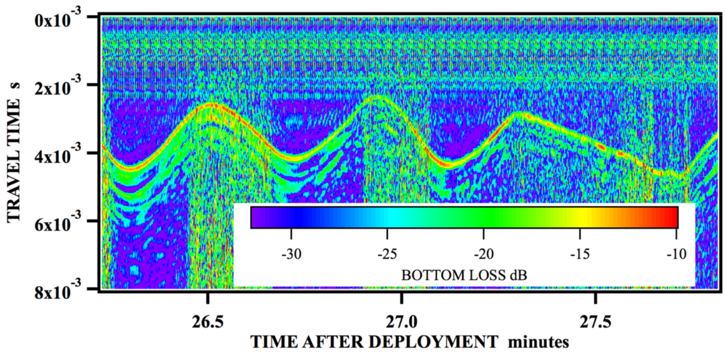

Fig. 5. Initial measurements from the Noble Mariner 2012 Experiment showing reflection loss measurements from a ROV moving slowly over the seabed. The seabed was flat but the ROV altitude was changing, hence the apparent undulations. The image shows reflection loss varying between 10 and 20 dB.
[A water-fall display of signal level as a function of time after transmission (vertical) and time after ROV deployment (horizontal) corrected for one-way spreading loss, source level and receiver sensitivity, yielding reflection loss in decibels at the water-seabed interface.]

IMPACT/APPLICATIONS

The results will impact Navy underwater acoustic propagation models, particularly where reflection and penetration of sound at the seabed are concerned. It will also impact the future structure of oceanographic databases maintained by Navy offices, including the Naval Oceanographic Office (NAVO). Predictions of sediment wave speeds and attenuations will need to be revised. In addition, the spatial variability of sediment properties will impact the accuracy of sonar performance models.

TRANSITIONS

Work on sediment variability is being transitioned to the active sonar trainers via the High-Fidelity Active Sonar Training (HiFAST) project and to future projects to improve the HFBL database. Some aspects of the ocean sediment model, particularly the frequency dependence of sediment attenuation, have been used in the Ocean Bottom Characterization Initiative (OBCI) project. This work will be used in the new project titled “Seafloor Spatial Variability Mitigation” funded by SPAWAR, for the benefit of NAVO.

RELATED PROJECTS

This project is closely related to most projects under the ONR Underwater Acoustics: High Frequency Sediment Acoustics and Shallow Water Thrusts.

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