Shallow-Water Mud Acoustics

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LONG-TERM GOALS

Goals include the development of models and methods that explain observed material and acoustic properties of different physical types of shallow-ocean mud sediments. Other goals are to assess prior data relating to the acoustic properties of mud and to provide guidance in the development and interpretation of experiments. A related goal is to construct models that will guide inversion techniques for inferring properties of mud sediments, for estimating accuracy of results, and for use in applications. These goals are science relevant to resolving long-term Naval problems of transmission loss and array response in shallow water over mud sediments and of acoustic detection, localization, and classification of objects buried in mud.

OBJECTIVES

- Develop analytical fundamental-physics models for geoacoustic properties that show their dependence on mud parameters. Properties include material density, porosity, and compressional and shear sound speeds and attenuations, with focus on depth and frequency dependence.
- Estimate the accuracy of physical mud parameters that is required for acoustic data comparisons and for making predictions in applications.
- Use modeling results to provide methodologies for inversion methods in order to determine parameters and profiles in mud sediments.

APPROACH

The technical approach builds upon that for previous ONR-supported research on the card-house structure theory of mud sediments, which we review briefly. That research, initiated at Boston

University under the leadership of William Carey (deceased) and Allan Pierce, was broadened to a collaboration with Rensselaer. Its objective was a model for the interaction of clay mineral platelets that is based on fundamental physical principles and that correctly explains and predicts geoacoustic properties of high-porosity marine muds. For example, the Mallock-Wood two-phase-medium approach can accurately estimate only the compressional sound speed in mud. In contrast, accurate first-principle predictions of shear sound speed were unknown prior to the breakthrough aggregated card-house structure developed by Pierce and Carey [1]. The first key step in the approach is formulating a hypothesized physics-based model. The electric field of each solid component, a thin platelet of clay minerals with an electric charge distribution due to its chemical, electrical, and material properties, mimics a longitudinal quadrupole aligned transversely to the platelet. This causes platelets to repel for edge-to-edge or face-to-face contact and promotes their attraction edge-to-face. The second critical step is analyzing the model to find one or more convenient formulas. Such expressions are useful for estimating the shear sound speed in terms of physical parameters of the mud and its component platelets. The inevitable third step is improving the model and the resulting formulas by refining the incorporated physics. This requires replacing the single quadrupole with a sheet of quadrupoles distributed over the platelet faces; incorporating a narrow gap, known as a Stern layer, across which platelet interactions occur; and showing that platelet elasticity has a negligible effect on the shear speed expression [2]. The fourth step is to investigate the numerical implications of the expression. The predicted shear speed values appear physically reasonable, and the expression is sensitive to only a few of its physical parameters. The final step is to compare predictions of the expression with experimental or observational results. While the intended use of the formula is with ocean data, such as is sought in the ongoing Seabed Characterization Experiment, initial tests were made with carefully controlled laboratory data [3]. The agreement between measured and predicted values was so close that the card-house theory is considered successful for pure kaolinite mud. The experiments also showed that a modified structural model is necessary for mud without card-house aggregates.

- This research is a coordinated collaborative effort with another grant directed by Allan Pierce of Boston University. Consequently the annual reports for that grant and the present one describe the same technical progress. Other colleagues who are involved in the current research for consultation and collaboration are listed under Related Projects. Additionally one current Rensselaer doctoral student is assisting with the research on both grants.

WORK COMPLETED

- This project is a new start in 2015. Current tasks and some recent previous work relevant to project objectives are summarized.

A. An important missing element in the card-house structure theory is a physically based description of edge-to-face platelet binding. It was implied [4] that short-range intermolecular (Van der Waals) forces may overcome repulsive electrostatic forces and permit attachment. At even smaller distances the intermolecular forces become repulsive, which produces a minimum potential energy identified as a platelet binding energy. A convenient formula for quantitative prediction of this energy is found using a Lennard-Jones potential, several modeling simplifications, and multiple integration over two platelets [5].

B. The hypothesized edge-to-face bond breaking mechanism [5], considered as a source of compressional attenuation in mud, can be regarded as a type of relaxation process [6]. A relaxation coefficient may be expressed in terms of other physical parameters using a thermodynamics result [7]. This leads to a consistent theoretical description of the attenuation process, which needs investigation in light of available and future data.

C. In order to specify quantitatively the effects of bubbles in mud, an extended Mallock-Wood equation is derived for the compressional sound speed in mud [8]. Bubbles in mud are distinctive in their persistence, ubiquity, and shape [9]. These features are explained qualitatively by the card-house structure theory, such as the inhibition of bubble migration and coalescence.

D. An invited review of the card-house structure theory describes its achievements to date, including explaining mechanisms for observed values of porosity, shear speed, and compressional speed [10]. Physical measurements of mud properties that are needed for improved geoacoustic modeling are listed, and research directions for explaining geoacoustic properties are specified.

E. In order to understand the behavior of attenuation in mud, and particularly its frequency behavior, the best available data set [11] is re-examined and modeled. The data is investigated for sensitivity and robustness of earlier regressions. A Perkeris waveguide formulation is used to construct a full-field (modes and continuous spectrum) solution representation, containing environmental parameters which can be varied for analysis and data comparisons [12].

RESULTS

- Initial results correspond to tasks under Work Completed.

A. When the binding energy of two platelets is comparable to the energy of fluctuations induced by the passage of an acoustic wave, platelet bond breaking and reforming occurs. This is a physical mechanism for compressional attenuation, from which its quantitative dependence on parameters might be deduced. An initial calculation [5] shows unequal energies and suggests that improved modeling of the interaction forces, along with avoiding some simplifications, is needed. One hypothesis is that platelet edge roughness is a major contributor to the discrepancy.

B. In a hypothesized process for the compressional attenuation [6], a relaxation time appears in addition to the relaxation coefficient. Completeness of the model requires determination of this parameter in terms of other physical quantities, specifically those related to the mud. In addition, investigation is needed as to whether more than one such relaxation process may have significant effects on attenuation.

C. Estimates of the volume fraction of solid material in mud can be obtained from inversions using the extended Mallock-Wood equation. Employing measurements by Carey at Dodge Pond, we found that the solid volume fraction agrees with an estimate from the card-house theory [8]. The latter is useful in explaining the characteristic non-spherical, flattened shapes of bubbles in mud.

D. Sediment physical and geoacoustical properties provide estimates of compressional sound speeds versus porosity for eight clay or silty-clay data sets [9]. While the agreement between data and Mallock-Wood predictions is quite good, there is a systematic difference of about 1% [10]. An explanation is provided by the card-house theory, because an effective pressure associated with electrostatic interactions between platelets produces just enough change in the predictions to account for the discrepancy [6].

E. Initial results [12] suggest that the data allow considerable variability in attenuation estimates and that those in [11] are roughly as good as could be expected. In addition it is suggested that shortcomings in the previous experiment should be remedied in future ones.

IMPACT/APPLICATIONS

The overarching research goals are to devise formulas and procedures for accurately estimating physical parameters of upper-sediment mud, in order to determine acoustic propagation quantities, perform data comparisons, and conduct inversion procedures. Research so directed is relevant to the Navy because it is part of the science base for three critical problems: prediction of transmission loss and array response over mud sediments, including long-range conveyance of information; detection, localization, and classification of objects buried in mud; and improvement of shallow water sonar systems and predictions with mud sediments.

RELATED PROJECTS

This research is a coordinated collaboration with research under the ONR grant, "Acoustical properties of mud sediments," directed by Allan Pierce of Boston University. The research will also be connected with other ONR projects, particularly those involving the Seabed Characterization Experiment. Collaboration is planned with colleagues at Woods Hole Oceanographic Institution (Jim Lynch, Tim Duda, and Ying-Tsong Lin), Naval Research Laboratory-SSC (Michael Richardson and Dawn Lavoie), ARL-Pennsylvania State University (Charles Holland), Seaprobe Incorporated (Richard Bennett), University of Delaware (Mohsen Badiey), ARL-University of Texas (Megan Ballard, Tom Muir, David Knobles, Kevin Lee, and Preston Wilson), and Naval Underwater Warfare Center-PC & NP (Kerry Commander, Danny Lim, David Burnett, and Joe Fayton).

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PUBLICATIONS

- Published [proceedings]: [1], [2]