Acoustic Propagation in Gassy Sediments

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Abstract: Measurements of values of sediment physical properties, bubble volume, and bubble size distribution are used to predict frequency-dependent sound speed and attenuation in the fine-grained, gassy sediments of Eckernförde Bay, Baltic Sea. Predictions are based on a modified version of the propagation model first presented by Anderson and Hampton [1-3]. Given the highly variable spatial distribution of bubble volume and size, the agreement between theory and measurement is remarkably good over the frequency range of 5-400 kHz. Model sensitivity studies suggest that small bubbles (< 0.25 mm radius) are either absent or occur in such a low fractional volume as to little effect acoustic propagation in Eckernförde sediments. Therefore, remote acoustic quantification of bubble volume and size appears possible.

BACKGROUND

Gas bubbles are ubiquitous in the organic-rich, muddy sediments found in coastal waters and shallow adjacent seas [3]. The presence of these bubbles impedes acoustic characterization of sediment below the gas horizon and acoustic turbidity degrades the effectiveness of high frequency sonar. The presence of free gas (usually methane) can reduce sediment stability leading to blow-out hazards during seafloor drilling, possible catastrophic destruction of seafloor structures, major down slope transport events, and burial of objects on the seafloor. Accurate estimates of gas volume, bubble size, rates of biogeochemical processes, and gas transport dynamics are required to predict this sediment behavior as well as to estimate the contribution of shallow-water methane to climatic cycles. In soft organic-rich sediment acoustic wave speed, attenuation, and scattering can theoretically be used to estimate gas volume and bubble size distribution [1-3]. In this paper, we compare predictions of those propagation models to in situ observations of bubble size distribution, and in situ measurements of compressional wave speed and attenuation.

METHODS

Interrelationships among environmental processes, sediment structure and the resultant sediment geotechnical, geoacoustic, and physical properties were studied in gas-rich sediments of Eckernförde Bay, Baltic Sea as part of the Office of Naval Research's Coastal Benthic Boundary program [4]. Estimates of the volume and size distribution of these gas bubbles were made with x-ray computed tomographic (CT) scans of core samples retained at in situ pressures [5]. Speed and attenuation of compressional waves was measured over the frequency range of 5-400 kHz using a variety of laboratory and in situ acoustic systems [3]. Sediment physical properties such as porosity, grain and bulk density, permeability, and sediment shear modulus were measured both in situ and under laboratory conditions. These data provide an opportunity to test models of acoustic propagation under in situ conditions.

RESULTS

Bubbles resolvable by CT scans range from 0.4- to 5.0-mm in equivalent radius with 0-2% (mean 0.1%) gas by volume. Dispersion of measured compressional wave speeds suggests that the upper limit of bubble resonance lies between 20-25 kHz [3]. The lowest effective bubble size is therefore 0.3 mm. Bubble concentrations (by volume, number of bubbles and size distribution) as well as normal incident acoustic backscattering shows considerable variability over horizontal scales of meters to kilometers. Bubble concentrations as well as compressional wave speed and attenuation vary vertically over centimeter scales. At acoustic frequencies above resonance (> 25 kHz) compressional wave speed is unaffected by bubbles and scattering from bubbles dominates attenuation. At frequencies well below resonance (< 1 kHz) "compressibility effects" dominate, speed is much lower (250 m s⁻¹) and attenuation is dominated by scattering from impedance contrasts. Between 1-25 kHz bubble resonance greatly affects compressional wave propagation and scattering and compressional speed and attenuation is highly variable.
Bubble concentration (volume and size) measured from CT images of a typical core collected from the central part of Eckernförde Bay was used to predict sound speed and attenuation over the frequency range of 0.5 to 100 kHz (Fig. 1). The most striking result of this modeling is the strong sensitivity of both the sound speed ratio and attenuation to gas volume and bubble size distribution. The size of the perturbations in sound speed and attenuation is most sensitive to the percent gas. At 40-50 mm, with only one bubble, we see virtually no effect on sound speed, a larger effect at 160-170 mm, and the largest effects at 80-90 and 120-130 mm. We also note that the frequency of the acoustic anomaly varies with the bubble size. The small bubbles (< 1.0 mm) at 80-90 mm depth generate a peak effect at 10-50 kHz, while the larger bubbles from 120-130 mm generate an effect that peaks at 1-20 kHz. It appears that a few large bubbles may cause significant variations in the sound speed ratio, but less so in the attenuation. This makes the limits, or shoulders of the attenuation curve a more robust indicator of fractional gas volume and size distribution, although measurements of attenuation at these extremely high levels may be quite difficult.

![Graph showing sound speed ratio and attenuation](image)

Figure 1. The number and volume of gas bubbles is used to calculate the sound speed ratio (ratio of sound speed in bubbly to gas-free sediment) and attenuation for sediments collected in Eckernförde Bay [core P2 in ref. 5]. Calculations are based on modifications [2,3] of the gassy sediment propagation model developed by Anderson and Hampton [1]. Physical property data is presented in [3]. Note the sensitivity of sound speed and attenuation to bubble volume and size distribution.

CONCLUSIONS

Frequency dependent behavior of compressional wave speed and attenuation is sufficiently sensitive to gas volumes and bubble size distributions to allow the remote acoustic characterization of these important properties in gas-rich sediments. Larger bubbles (> 1.0 mm radii) dominate propagation, especially at the lower frequencies (< 25 kHz) used by most seafloor classification systems. High compressional wave speeds (> 2500 m s⁻¹) predicted near resonance for a single-sized population of bubbles were not measured using in situ acoustic techniques. Speeds based on bubble size distributions measured with CT-scans are, however, in agreement with in situ acoustic measurements. Model sensitivity studies suggest that small bubbles (< 0.25 mm radius) are either absent or occur in such a low fractional volume as to little effect acoustic propagation in Eckernförde sediments.

REFERENCES