Scattering and reflection from soft gassy sediments: Geoacoustic modeling approach

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Abstract: *Presence of even a small volume fraction of gas bubbles can significantly change acoustic properties of underwater sediments, particularly, their effective sound speed and attenuation. In this paper, a geoacoustic modeling approach which, after corrections in input parameters for gas content, is used for estimating the reflection loss and scattering strength, major characteristics describing geoacoustic bottom interactions. One of these corrections is discussed in more detail and shown to be significant in a strong volume scattering regime, which seems a reasonable assumption for gassy sediments with bubbles and voids or with stronger fluctuations of sound speed caused by spatially varying concentration of bubbles. Results of numerical simulations of angular dependences of reflection loss and backscattering strength for soft gassy sediments are presented.*

Keywords: *Reflection and scattering coefficients, methane bubbles, rough interfaces, volume heterogeneity, intrinsic and scattering attenuation.*

1. INTRODUCTION

There is extensive literature on geoacoustic modeling of underwater sediments aimed at predicting reflection loss and scattering strength, major characteristics describing sound-bottom interactions, see e.g. [1,2] and references therein. Soft water saturated sediments in these models are usually treated as effective fluid media whose input parameters are density, sound speed and attenuation. For instance, GABIM [2], Geoacoustic Bottom Interaction Model, presents results for canonical classes of granular sediment, each with a representative set of these parameters defined by their empirical relationships with the mean grain size [1].

One of the limitations of such approach is that this modeling relies on accuracy of the mentioned empirical relationships, which however have been well established only for gasless sediments [1]. This limitation can be essential as it is known that even a small volume fraction of gas bubbles may significantly change sound speed and attenuation in the sediment. There are various models to quantify these changes and provide theoretical relationships of sound speed and attenuation with gas content, see e.g. [1,3-5]. In this paper, Wood's model is used simply to provide a representative example of such relationships.

Various approaches to consider reflection loss and scattering strength of gassy sediments were discussed in literature [5-12]. For instance, the effect of methane bubbles on bottom reflection was observed in Lake Kinneret and its treatment was given using an effective model of gassy sediments [5-8]. Effects of gas bubbles on scattering strength of soft sediments was considered in [1,2,9-12]. In this paper, we suggest that geoacoustic modeling approach developed for gasless environments, such as that used in GABIM, is applicable to estimating the reflection loss and scattering strength of gassy sediments as well once the values of input parameters are corrected to account for these changes. One of these corrections is discussed in more detail and shown to be significant in a strong volume scattering regime, which can be a reasonable assumption for sediments with such strong discrete scatterers as gas bubbles and voids or with stronger fluctuations of sound speed cased by continuous spatial variations of bubble concentration.

2. GEOACOUSTIC MODEL INPUT PARAMETERS

GABIM [2], Geoacoustic Bottom Interaction Model, presents comparison of results for 10 "canonical" sediment classes, defined by their different mean grain size, with a set of geoacoustic input parameters whose values are determined empirically as representative for each class. In this paper, we consider only soft sediments with inputs for two classes, Fine Sand and Clay, given in Table 1, defined in [2] and used here in calculations.

Sediment type	a_ρ Density Ratio	a_c Sound Speed Ratio	δ Loss Tangent	q Volume Scattering Ratio	Roughness Spectral Exponent	Roughness Spectral Strengths
Fine Sand	1.936	1.1536	0.01669	0.002	3.25	0.000016
Clay	1.410	0.9892	0.00149	0.001	3.25	0.000016

Table 1. Representative canonical parameters taken from [2] and used as inputs in calculations for gasless sediments.

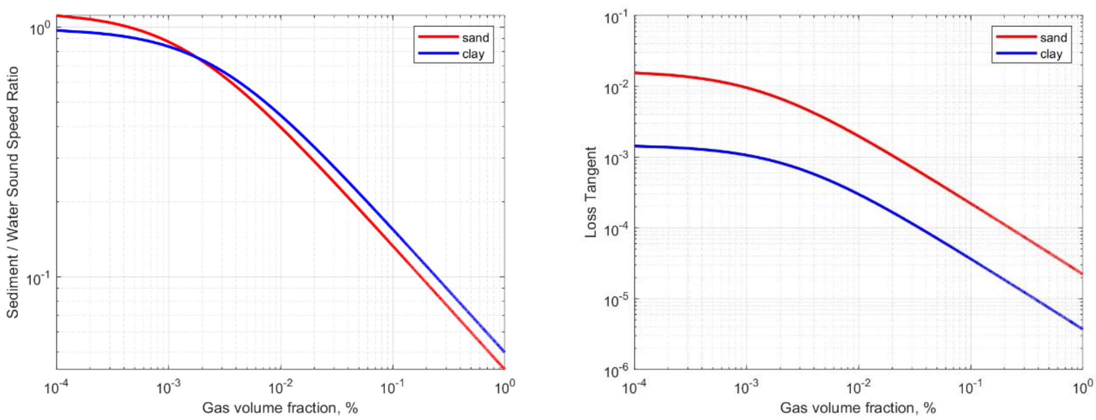
The inputs include sediment/water density and sound speed ratios, a_ρ and a_c, and loss tangent (attenuation parameter) δ. This is sufficient for predictions of the reflection coefficient, V, and bottom reflection loss, $20 \log|V|$, for soft sediments. The model also includes 3 additional parameters, volume scattering ratio q (a ratio of volume scattering and attenuation coefficients), and roughness spectral strength and exponent, which are needed for predictions of the so-called equivalent surface scattering coefficient,

$$M_S = M_{Sr} + M_{Sv} \tag{1}$$

where M_{Sr} and M_{Sv} are its roughness and volume scattering components. Bottom scattering strength is defined as $10 \log M_S$.

It is known that even a small volume fraction of gas bubbles may significantly change sound speed and attenuation, and therefore at least two of these inputs, a_c and δ, should be corrected in the case of gassy sediments. There are various theoretical relationships of effective sound speed and attenuation with gas content and bubble size (see, e.g., [1, 3-5]). Here, in this paper, for a demonstration of the geoacoustic approach, a Wood's model is chosen. The model accounts for additivity of density and compressibility in the sediment that includes two components, gas bubbles inclusions and the host gasless surrounding sediment, to derive the effective sound speed of the mixture. This requires adding only one parameter, volume fraction of gas bubbles, α, which may provide significant corrections for the sediment sound speed and attenuation but practically does not affect density (at small α typical for gassy sediments). The model is known to be sufficiently accurate at low frequencies or small enough bubbles (microbubbles) where resonance effects controlled by bubble size are negligible. Including additional parameters, such as the bubble size and shape, is similar, and, although allows accurate accounting for resonance and other effects, does not change the approach in general.

In Figure 1, Wood's model results are given for effective sound speed ratio and loss tangent of sand and clay sediments with methane bubbles as functions of gas volume fraction assuming that values of methane density and sound speed are 0.717 g/l and 330 m/s respectively. This provides Wood's model-based values to input parameters, summarized in Table 2, for numerical simulations presented in following sections of this paper.



(a) (b)

Fig.1: Sound speed ratio (a) and attenuation parameter (b) for gassy sand and clay sediments as functions of gas volume fraction according to Wood's model.

α, %	0	0.002	0.005	0.1
a_c , Fine Sand	1.1536	0.7319	0.5315	0.1331
a_c , Clay	0.9892	0.7383	0.5723	0.1550
δ , Fine Sand	0.01669	0.0067	0.0035	0.00022
δ , Clay	0.00149	0.00083	0.00050	0.000037

Table 2. Wood's model-based values for sound speed ratio, a_c , and attenuation parameter, δ, given different gas volume fractions α (in %) used in calculations for fine sand and clay sediments.

3. BOTTOM REFLECTION LOSS AND ROUGHNESS SCATTERING STRENGTH

The following calculations are aimed at illustrating quantitatively significant effects of gas bubbles (particularly microbubbles) in the sediment, which particularly change contrasts of parameters (effective density, compressibility, sound speed, attenuation, and impedance) at interfaces, affecting bottom reflection and rough interface scattering.

Figure 2 shows the magnitude of reflection coefficient vs incidence angle for gassy sand (a), and gassy clay (b) sediments using inputs given in Tables 1 and 2 at different gas volume fractions according to Wood's model. The deep minima of the magnitude of reflection coefficient are caused by reduction of sound speed and corresponds to angles at which the water-sediment interface is nearly transparent, that is it has a minimal contrast of angular dependent impedances (zero if attenuation is ignored).

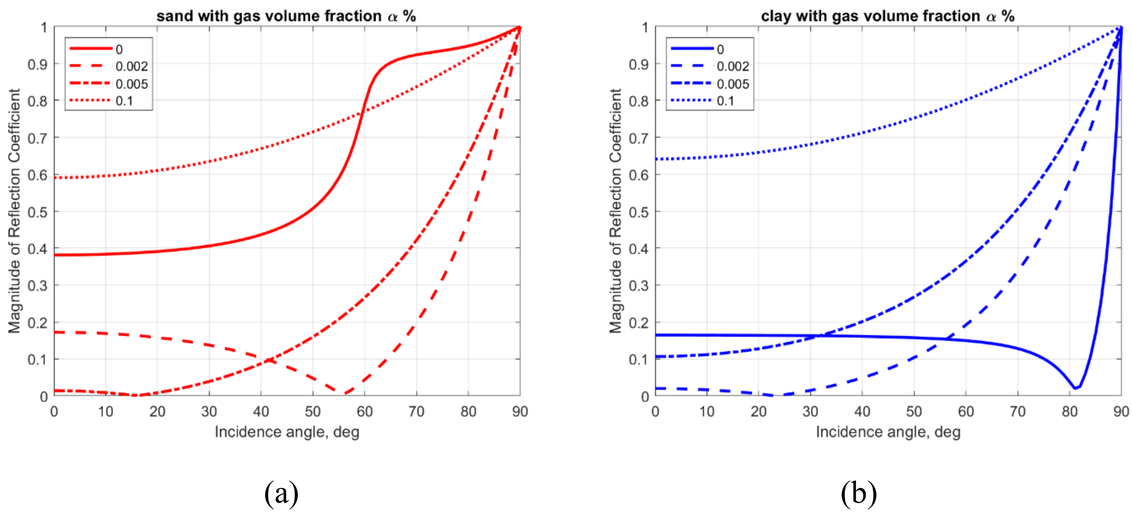
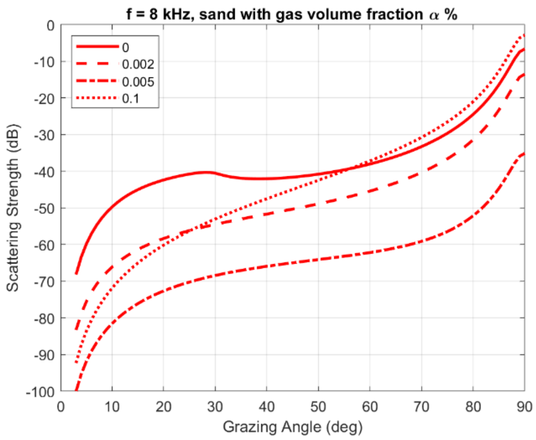
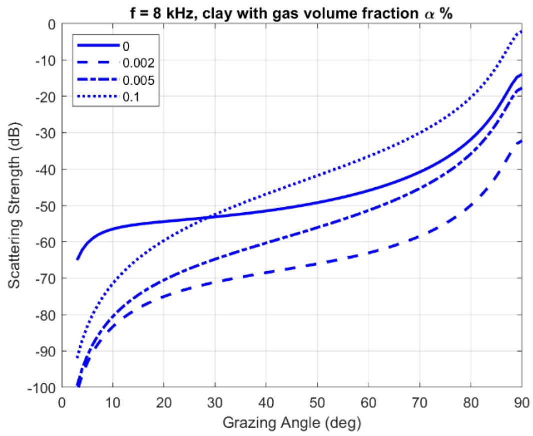


Fig.2: Reflection coefficient vs incidence angle for gassy sand (a), and gassy clay (b) sediments at different gas volume fractions.

In [9], numerical examples are given for angular dependences of rough bottom scattering strength to show the effect of a reduced sound speed typical for a small presence of gas in the sediment. Here, in this paper, we apply the same approach and same expressions for the scattering coefficient M_{Sr} as in [1,9] but use different inputs, gasless sediment canonical parameters and Wood's model-based parameter corrections given in Tables 1 and 2. As in [9], we assume that roughness parameters are the same as in the gasless case. Results are given in Figure 3 which shows the roughness backscattering strength as a function of grazing angle.



(a)



(b)

Fig.3: Roughness backscattering strength of gassy sand (a) and clay (b).

4. VOLUME SCATTERING MODEL

Presence of gas bubbles and voids may significantly affect both mechanisms of volume scattering in the sediment, its continuous and discrete heterogeneity [10]. For discrete scattering, this particularly results from changing the contrast between parameters of the bubble and surrounding effective host medium, and, for continuous scattering, this is due to enhancing fluctuations of sediment effective parameters (caused by spatial variations of bubble volume concentration).

Consider the volume component of equivalent surface scattering coefficient, see Eq.(1), which for backward directions in the case of the sediment half-space, using expressions given in [1,2,9], can be presented as follows:

$$M_{Sv} = \frac{|W|^4 \mathrm{Real}(\gamma)}{2a_\rho^2} q \tag{2}$$

$$\gamma = \sqrt{(1 + i\delta)^2 - a_c^2 \sin^2 \theta} \tag{3}$$

$$W = 1 + V = \frac{2a_\rho a_c \cos\theta}{a_\rho a_c \cos\theta + \gamma} \tag{4}$$

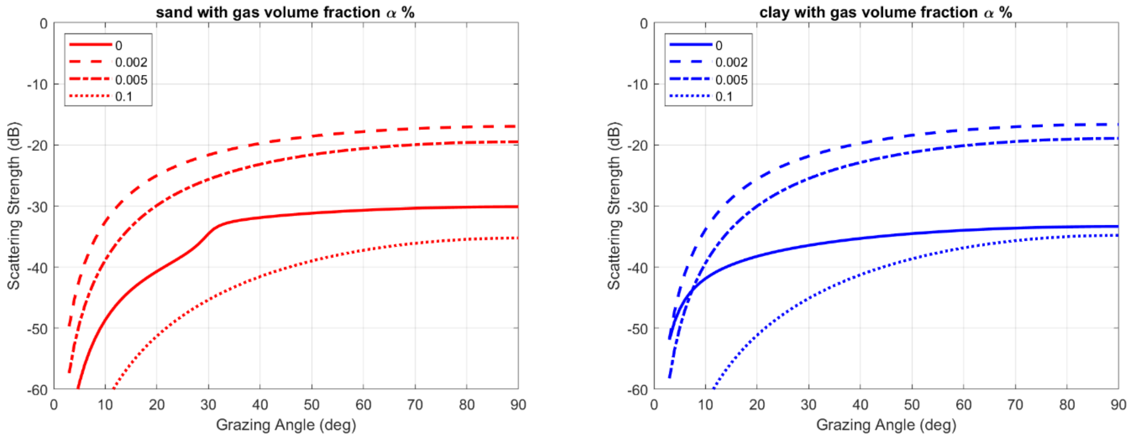
where $V(\theta)$ and $W(\theta)$ are the reflection and transmission coefficients at the water-sediment interface as functions of incidence angle θ, and other parameters are defined earlier and given in Tables 1 and 2. In particular, $q = m_v/\beta$ is the ratio of volume backscattering coefficient per unit volume, m_v, and the attenuation coefficient in the sediment, β. The attenuation parameter includes two components, intrinsic loss and total volume scattering loss (integrated over all directions of scattering)

$$\beta = \beta_0 + \beta_v\,, \qquad \beta_v = \oint m_v d\Omega \tag{5}$$

The result is significantly dependent on the ratio of these two components, μ, and the scattering indicatrix, ψ,

$$q = \frac{\mu}{1+\mu}\psi, \quad \mu = \beta_v/\beta_0\,, \quad \psi = m_v/\beta_v \tag{6}$$

Strong scattering regime corresponds to the case where scattering loss mechanism is dominating compared to intrinsic loss, $\mu \gg 1$ and $q = \psi$. Note, that according to Wood's model, intrinsic loss of the gassy sediments is significantly lower than for gasless ones, see Fig.1 and Table 2. For isotropic scattering, $\psi = (4\pi)^{-1}$, and therefore, in the case of strong isotropic scattering in the sediment, equation (2) can be used only with $q = (4\pi)^{-1}$. Results are shown in Figure 4.



(a) (b)

Fig.4: Volume backscattering strength of gassy sand (a) and clay (b).

Note that in Table 1 parameter q is fixed and very small, $q \ll (4\pi)^{-1}$. According to first equation in (6), this is possible in two different cases. First, this may correspond to the case where scattering is isotropic but very weak with $\mu = (4\pi)q$, i.e. is μ = 0.025 and 0.0125 for sand and clay respectively. Otherwise, or in the second case of strong scattering ($\mu \gg 1$), one should assume $\psi \ll 1$, that is scattering is very anisotropic, which may be not applicable to small discrete inclusions, like microbubbles in gassy sediments. The case of anisotropic scattering may need an additional consideration due to possible effects of non-spherical shape of large enough bubbles which usually present in soft sediments [5].

5. ACKNOWLEDGEMENTS

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REFERENCES

[1] **D.R. Jackson and M. Richardson**, *High-Frequency Seafloor Acoustics*, Springer Science, NY, (2007).

[2] **D.R. Jackson, R.I. Odom, M.L. Boyd, and A.N. Ivakin**, A Geoacoustic Bottom Interaction Model (GABIM), *IEEE J. Ocean. Eng.*, 35(3), 603-617, (2010).

[3] **A. L. Anderson and L. D. Hampton**, Acoustics of gas-bearing sediments. I. Background, *J. Acoust. Soc. Am.* 67(6), 1865–1889 (1980).

[4] **A.L. Anderson and L. D. Hampton**, Acoustics of gas-bearing sediment. II. Measurements and models, *J. Acoust. Soc. Am.* 67(6), 1890–1903 (1980).

[5] **R. Katsman, A. Lunkov, E. Uzhansky, B. Katsnelson**. Effective model of gassy sediments and acoustical approach for its verification, *Proceedings of Meetings on Acoustics*, Vol. 44, 005001 (2021).

[6] **E. Uzhansky, B. Katsnelson, A. Lunkov, R. Katsman, A. Ivakin**, Estimating bubble size in Lake Kinneret through reflection of wideband sound signals from gas rich sediment environment, *Proceedings of Meetings on Acoustics*, Vol. 50, 005001 (2023).

[7] **E. Uzhansky, R. Katsman, A. Lunkov, B. Katsnelson**, Integrated methodology for gas content assessment and prediction in shallow muddy lake sediments: acoustic mapping and correlation analysis, *MethodsX* , 13, 102799, (2024).

[8] **B. Katsnelson, R. Katsman, A. Lunkov, and I. Ostrovsky**. Acoustical methodology for determination of gas content in aquatic sediments, with application to Lake Kinneret, Israel, as a case study. *Limnology and Oceanography: Methods*, 15(6), 531-541, (2017).

[9] **A.N. Ivakin**, Models of scattering for remote acoustic sensing of the seafloor, in *Acoustical Oceanography,* T.G. Leighton, G.J. Heald, H.D. Griffiths, G. Griffiths (eds.), *Proceedings of the Institute of Acoustics*, v.23: Part 2, pp. 268-275, (2001).

[10] **A.N. Ivakin**, Modeling of acoustic backscatter for remote detection and characterization of oil and gas in marine environment, in, *Proceedings of the Institute of Acoustics*, v.34: Part 3, pp.1202-1209, (2012).

[11] **L. Fonseca, L. Mayer, D. Orange, and N. Driscoll**, The high-frequency backscattering angular response of gassy sediments: Model/data comparison from the Eel River Margin, California, *J. Acoust. Soc. Am.* 111(6), 2621–2631 (2002).

[12] **F. Boyle and N. Chotiros**, A model for high-frequency acoustic backscatter from gas bubbles in sandy sediments at shallow grazing angles, *J. Acoust. Soc. Am.* 98(6), 531-541 (2001).