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MARINE SEDIMENT NONLINEARITY

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This paper is dedicated to the memory of my teacher and friend, Dr. R. W. B. Stephens.

1. INTRODUCTION

High-intensity sources of sound are used extensively for engineering and scientific purposes in relation to oil prospecting, to off-shore constructions and to the study of bottom and subbottom materials and profiles for instance. The penetration of high-power signals into the seabed leads to nonlinear acoustic processes like formation of higher harmonics and thus to signal distortion, to excess absorption and for underwater explosions being used as sources of sound near the seabed, also to acoustic saturation effects.

The most important parameter necessary in order to evaluate the magnitude of the nonlinear effects influencing signals in marine sediments is the second-order, acoustical nonlinearity ratio B/A [1]. The experimental determination of this ratio and comparison of the experimental results with theoretical predictions is the aim of this paper.

2. THEORY

Water-filled marine sediments may be considered to be consisting of mineral grains forming a skeleton frame which surrounds fluid-filled pores. The elastic moduli of importance to sound propagation through water-filled marine sediments are for instance (a) the bulk modulus of water B_w, (b) the bulk modulus of the solid grains B_s and (c) the bulk modulus and the shear modulus of the skeleton frame B_f and μ, respectively. In an earlier paper [2] Hovem developed an expression for the compressional wave velocity in water-filled marine sediments given by:

$$C^2 = \frac{B + \frac{4}{3}\mu}{\rho} \qquad (1)$$

where

$$B=B_s\frac{B_f+Q}{B_s+Q}$$

with

$$Q=\frac{B_w(B_s-B_f)}{\Phi(B_s-B_w)}$$

and where Φ expresses the porosity of the marine sediments. The density ρ is the weighted density of the water ρ_w and the solid ρ_s expressed by:

$$\rho=\Phi\rho_w+(1-\Phi)\rho_s \qquad (2)$$

The expressions (1) and (2) formed the basis in [2] for the development of B/A expressed as the weighted sum of contributions from all four elastic moduli, assuming that the pressure dependence of the compressional velocity, only, would influence the values of B/A.

Based on a thermodynamical expansion of the equation of state of a fluid, originally suggested by Beyer [3] based on an interpreta-tion by Rudnick [4], it is possible to write B/A as:

$$B/A=2\rho_o C_o\left[\left(\frac{\partial c}{\partial p}\right)_T\right]_{\rho=\rho_o}+\left(\frac{2C_oT\beta}{C_p}\right)\left[\left(\frac{\partial c}{\partial T}\right)_P\right]_{\rho=\rho_o} \qquad (3)$$

In (3) ρ_o and C_o denote the ambient density and the compressional signal velocity of the sediments, respectively. T and p denote absolute temperature and pressure, respectively, while β is the isobaric coefficient of volume expansion given by:

$\beta = (1/V)(\delta V/\delta T)_p$ with $V = 1/\rho$

C_p is the specific heat at constant pressure of the sediments. The determination of the derivatives of the compressional signal velocity with respect to p and T for constant T and p, respectively, forms the most crucial part of the use of (3) for determination of B/A of water-filled marine sediments. As shown by Bjørnø [5], the term involving the derivative of C with respect to T for constant p is much smaller than the pressure dependent term for water-filled marine sediments. This result was used in [2] for the development of B/A based on the four elastic moduli.

Due to the fact that water-filled marine sediments may be considered
to consist of a porous, gas-free, uncemented mineral structure, being fully saturated with water and being macroscopically isotropic, the differential or effective pressure assumed in [2] to act on the skeleton frame may be neglected and only the pore pressure acting on the water and the mineral grains is contributing essentially to the acoustical nonlinearity of the water-filled marine sediments. By lack of contributions from the skeleton frame the B/A expression in [2] reduces to:

$$B/A=\left[\frac{\Phi B_g}{\Phi B_g+(1-\Phi)B_w}\right]^2\cdot\frac{1}{\Phi}\frac{\partial B_w}{\partial p}-1 \qquad (4)$$

3. EXPERIMENTAL STUDIES AND DISCUSSIONS

Two experimental procedures have been used for determination of the B/A-values of several water-filled marine sediments of various porosities. These procedures comprise (a) a thermodynamical procedure based on expression (3) and (b) a finite-amplitude wave procedure based on the determination of the formation of the second harmonic to an originally finite-amplitude, monochromatic signal propagating across known distances in the sediments. Due the considerable influence of absorption in sediments at elevated frequencies, see Bjørnø [5 & 6], only short distance propagation was studied.

Samples of sediments were taken from a seabed and from a small hill a few kilometers from the coast. Before being studies in the laboratory these two types of sediment test samples were characterized as medium sand and very fine sand, respectively, according to the Wentworth scale, due to their predominant contents of mineral grains of a medium size fitting with these levels of the scale.
After being sieved in the laboratory a subdivision of the two test samples into five test samples was performed, each sample having a medium diameter of the mineral grains matching with one of the levels of the Wentworth scale, see table 1. These five test samples formed the basis for the subsequent studies.

SEDIMENT TYPE	POROSITY n. %	ρ_o kg/m^3	c_o m/s	B/A
Medium sand	39.5	2010	1765	11.78
Fine sand (beach)	42.7	1980	1720	10.89
Fine sand (hill)	40.9	1990	1740	11.21
Very fine sand	46.2	1930	1710	10.56
Silt	50.1	1820	1650	9.62

Table 1. Characteristic physical qualities of the sediment types studied. The B/A values are based on the thermodynamical procedure using expression (3).

In order to remove dissolved gas, to kill bacteries and to wash-out prospective salts each sample was saturated with distilled water and boiled for several hours. Gas bubbles, in particular, had been a source of errors during some introductory studies reported elsewhere [7]. These bubbles could either be introduced during the preparation of the test samples before the experiments or they could be introduced by bubble growth in an acoustic field during the insonification of the sediments. Moreover, break-down of organic materials could lead to bubble formation. However, the boiling of the sediments turned out to be an efficient way to avoid influences of bubbles during the experiments. Minor samples of the sediments were taken out and weighed before being dried in a kiln for 5 hours at 120 °C in order to remove all water from the pores.

A new weighing of the dried samples formed basis for determination of the porosity, n, of the samples. Using standard laboratory procedures ρ_o, C_p and β for the samples were determined.

Measurements of the compressional signal velocity as a function of static pressure at constant temperature (20 °C) was performed in a thick-walled steel tube forming a test chamber of a length of 10 cm which was closed at both ends by a transmitting and a receiving transducer, respectively. A phase difference of 180° between the transmitter and receiver, measured by means of a B&K phasemeter, was obtained by varying the frequency of a tone generator driving the transmitter close to resonance via a power amplifier.

Measurements of the compressional signal velocity as a function of temperature at constant pressure (10^5 Pa) was performed using the same transmitter, receiver and electronics, but after having replaced the thick-walled steel tube with a thin-walled, perforated plastic tube, surrounded by a water-jacket allowing constant temperature distilled water to be circulated through the sediments during the tests. The temperature was stabilized with an accuracy better than 0.1 °C during the measurements.

The velocity of sound as function of pressure and temperature was first determined for pure water, thus making possible a calibration of the test chambers and a comparison of the experimental results with the ones found by others [8].

The ambient compressional signal velocity and its derivatives with respect to p and T for constant T (= 293 °K) and p (= 10^5 Pa), respectively, were determined on basis of the experimental data of compressional signal velocity as a function of pressure and temperature. These derivatives, forming the most crucial factors in (3), were used for the calculations of the B/A values given in table 1 for various sediment types. As also found for pure water, **the pressure derivative term (first term in (3)) is predominant in sediment acoustic nonlinearity.**

Moreover, the derivatives of the compressional signal velocity with respect to p and T at constant T and p, respectively, have about the same values as found for pure water at 20 °C and 10^5 Pa. This shows that the water-filled marine sediments, and thus sediments in the surface layers of the seabed, will display a change in compressional velocity with pressure and temperature **mainly arising from the pore water and not from the mineral structure of the sediments**, while the moderating influences on the ambient values of the compressional signal velocity and the density of the water-filled marine sediments arising from the mineral structure lead to an increasing value of the first term in (3) compared to this terms value in pure water.

The second procedure for determination of B/A of water-filled marine sediments was based on measurements of the formation of the second harmonic in the finite-amplitude wave distortion course arising when originally sinusoidal waves propagate away from the source. Two frequencies were used, 10 kHz and 100 kHz. The measurements at 100 kHz were performed in a test cell having the dimensions 50 cm x 50 cm x 10 cm. The cell walls were formed by 1 mm thick rubber plates and the transmitter and receiver were mounted in 50 cm x 50 cm perspex baffles situated 10 cm apart. The receiver could be moved along the acoustic axis of the transmitter. The 10 kHz messurements were performed in a steel box (0.6 m x 0.6 m x 1.0 m) filled with the sediments to be studied. The same facilities were used for absorption studies at the fundamental and at its first harmonic [5]. Special minihydrophones were used for measurements of absorption and formation of second harmonics at frequencies above 100 kHz, while a B&K hydrophone (type 8103) was used for reception at all frequencies below 100 kHz. For signal processing was used a HP 3585A spectrum analyzer.

The measured second-harmonic amplitudes as a function of distance from the source were plotted and extrapolated back to the position of the transmitter surface (x = 0). The values thus found together with the physical qualities of the various sediments - compressional signal velocity, density and absorption - were used for a calculation of B/A for the sediments studied exploiting the following expression derived from a modified version of Thuras et al's [9] plane wave expression [10]:

$$P_2(X) = \frac{(2+B/A)\pi f}{2\rho_o C_o^3} x P_1^2(0) \left(\frac{e^{-\alpha_2 x} - e^{-2\alpha_1 x}}{2\alpha_1 - \alpha_2} \right) \qquad (5)$$

In (5), α_1 and α_2 denote the absorption coefficients for the fundamental and its first harmonic, respectively.

The experimental values of B/A as a function of the porosity of the water-filled marine sediments are shown in figure 1. The figure shows a good agreement between the B/A values measured using the two different experimental procedures and for comparison is shown the B/A dependence on porosity calculated using expression (4).
The good agreement between the theoretical predictions and the experimental data from different experimental procedures seems to give evidence to the conclusion that only the pore pressure acting on the water and the mineral grains is contributing essentially to the acoustical nonlinearity of the water-filled marine sediments, while the skeleton frame influence is vanishing.

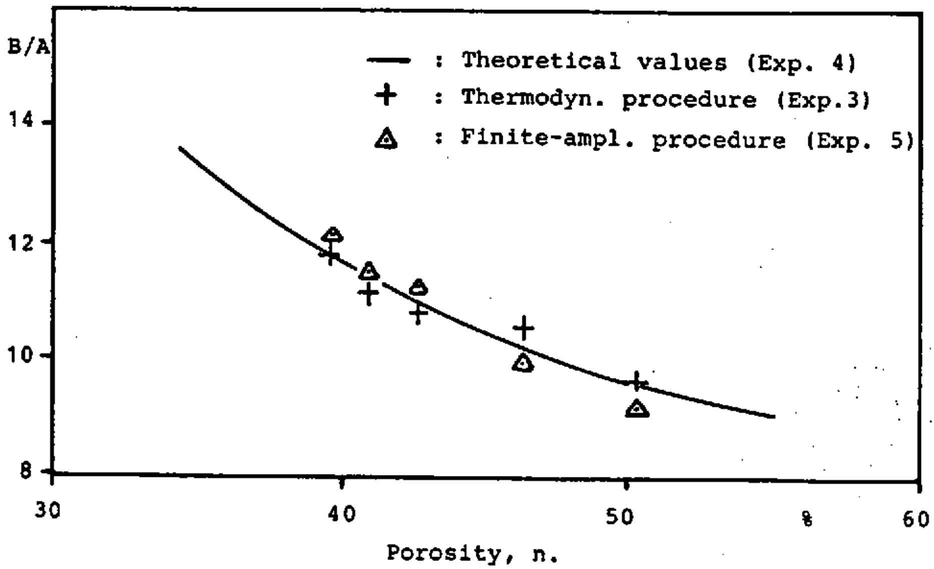

Figure 1. Measured (2 procedures) and calculated values of B/A as a function of porosity

4. CONCLUSIONS

Experimental as well as theoretical evidence has been created for the statement that the acoustic nonlinearity of water-filled marine sediments having a porous, gas-free, uncemented mineral structure and being fully saturated with water is mostly governed by pore pressure influence on water and mineral grains and that the pressure influence on the nonlinearity is considerably stronger than the temperature influence.

5. REFERENCES

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