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Estimation of physical properties of bottom sedimentary deposits using seismic data*

Y.N. Bushenkov, A.N. Kremlev,
A.J. Golmshtok, and M. Vanneste†

In this paper, a technique for estimating diverse physical properties of bottom deposits is discussed. The methodology is based on the evaluation of reflection coefficients of stratigraphic boundaries using the amplitudes of bottom and multiple acoustic reflectors by the so-called quotient method in combination with the regression equations of Hamilton. For practical application of this technique, the determination of the reflection coefficient and its accuracy in the case of non-vertical incident acoustic waves are considered. By means of theoretical modeling of seismic traces, the relationship between average sediment properties and estimated values was investigated for thin layered media. It is shown that the average thickness is defined by 1/4 of the length of the first main phase of the acoustic signal in the time domain.

The described technique was applied on two seismic profiles with distinct characteristics: a low-frequency multi-channel airgun-array profile and a high-frequency single-channel sparker profile, both acquired in the Southern Basin of Lake Baikal, Siberia. The results obtained using the low-frequency data suggest the presence of an average 4.8 m thick sand-silt-clay layer, while the high-frequency data detail the upper 40 cm layer of the lake bed deposits of Lake Baikal as a silt-clay one. These conclusions are in good agreement with the deep water drilling results in the region.

The estimation of various physical properties of bottom sediments in seas and deep lakes, and subsequent sorting of bottom areas based on these data, are important for regional research of water basins, for solution of tasks of engineering geophysics and geotechnical problems and for geological research of sediments by means of core sampling.

Introduction

In this paper, a technique for determining physical properties of sediments using seismic data is presented. This technique is based on the results obtained by Hamilton who found that the bulk density, the porosity, the seismic compressional wave velocity and hence the reflection coefficient of

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a stratigraphic boundary are determined by the average grain size of the sedimentary unit [1]. Because of this, all mentioned physical properties could be computed via one of these quantities, of which the reflection coefficient – if known with high enough accuracy – is the most convenient one.

Numerous observations show that sedimentary deposits often consist of thin layers with different thickness, grain size and main mineral elements. By means of mathematical modeling, the opportunities of the suggested technique for estimating physical properties of a layered medium were investigated for two kinds of layered sequences. It is revealed that for these layered samples, the model gives average values of the diverse sedimentary properties and the thickness of an "effective" layer is determined by the length of the first main phase of the acoustic signal in the time domain. Furthermore, it is shown that for sand-silt-clay thin layered sediments, the estimated quantities differ not more than 3% from the average ones.

This methodology is tested on different seismic data sets. The offset, i. e., the distance between the acoustic source and the nearest receiver or hydrophone during seismic data acquisition, varies from several tens of meters (single-channel seismic survey) up to several hundreds of meters (multichannel seismic survey). Due to the offset-dependent reflectivity, the accuracy of the determination of the reflection coefficient by means of the quotient method was investigated for different incident angles.

A special software program realizing the mentioned technique was written at the Institute of Computational Mathematics and Mathematical Geophysics (SB RAS) in Novosibirsk. Seismic profiles with different acquisition layout and frequency spectrum of the Southern Basin of Lake Baikal were processed and reflection coefficients were determined. The results of the evaluation of the calculated physical properties are compared with results from deep water drilling data (Baikal Drilling Project – BDP).

1. Reflection coefficients

The quantitative evaluation of the reflection coefficient from the lake or sea floor sediments forms the basis of the proposed methodology. Amplitudes of the primary bottom reflection and its multiple, observed on minimal offset seismic traces, are used. The reflection amplitude at normal incidence A_s is proportional to the bottom reflection coefficient R_f and to an unknown factor k describing source and receiver. This amplitude is also inverse proportional to the wave propagation distance (due to geometrical divergence) which is equal to the product of the acoustic wave velocity in water v_0 and the travel time t_0. Thus, we obtain the following relationship:

$$A_s = \frac{kR_f}{v_0 t_0}. \qquad (1)$$

For the amplitude of the multiple of the sea or lake floor reflector A_d, we have the similar equation:

$$A_d = -\frac{kR_f^2}{2v_0t_0}, \tag{2}$$

where the minus-sign takes into account the reflection of the acoustic energy at the water-air interface acting as a perfect mirror, R_f^2 because of the double reflection at the bottom and factor 2 in the denominator since the total propagation distance of the multiple reflection is double.

Taking the ratio of these amplitudes, we obtain the expression for the reflection coefficient of the sea or lake floor [2, 3]:

$$R_f = -\frac{2A_d}{A_s}. \tag{3}$$

It is worth noting here that, after the reflection coefficient is obtained, formula (1) permits to define the unknown factor k which completely describes the properties of the acoustic source and the receiver for normal waves. This calibration factor permits us to evaluate reflection coefficients via strong reflection amplitudes.

2. Physical properties of bottom deposits

After analyzing numerous observations and experimental data of bottom sediment properties, Hamilton has established that their density, porosity and compressional wave velocity can be expressed by general functions versus average grain size [1]. Furthermore, these quantities only depend on the sedimentation environment, subdivided into shelf areas and continental slopes, abyssal planes and abyssal hills. We restrict our consideration to the shelf and continental slope environments because these are the areas of our main interest.

Average physical characteristics of all possible kinds of deposits in the shelf and continental slope environment are listed in the table. We see there that the density and compressional wave velocity have maximum and minimum values for sand and silt-clay sediments respectively. Reflection coefficients in function of density, observed for different sedimentary environments, is shown in Figure 1, taken from [4].

Combining Hamilton's regression relations and converting them into functions of the reflection coefficient, we obtain the following formulas:

$$\rho = 2.5840R_f + 0.9985, \qquad (\sigma = 0.026), \tag{4}$$

$$\varphi = 100.48 - 150.15R_f, \qquad (\sigma = 1.5), \tag{5}$$

$$s = 2.0960 - 1.5857\rho + 1.1572\rho^2, \qquad (\sigma = 0.06), \tag{6}$$

$$v_p = 2.3304 - 1.2570\rho + 0.4877\rho^2, \qquad (\sigma = 0.01), \tag{7}$$

Density, porosity and compressional acoustic wave velocity of continental terrace (shelf and slope) sediments, taken from [1]

Sediment type	Density, g/cm^3	Porosity, %	Velocity, m/s
Sand			
Coarse	2.034	38.6	1836
Fine	1.962	44.5	1759
Very fine	1.878	48.5	1709
Silty sand	1.783	54.2	1658
Sandy silt	1.769	54.7	1644
Silt	1.740	56.2	1615
Sand-silt-clay	1.575	66.3	1582
Clayey silt	1.489	71.6	1546
Silty clay	1.480	73.0	1517

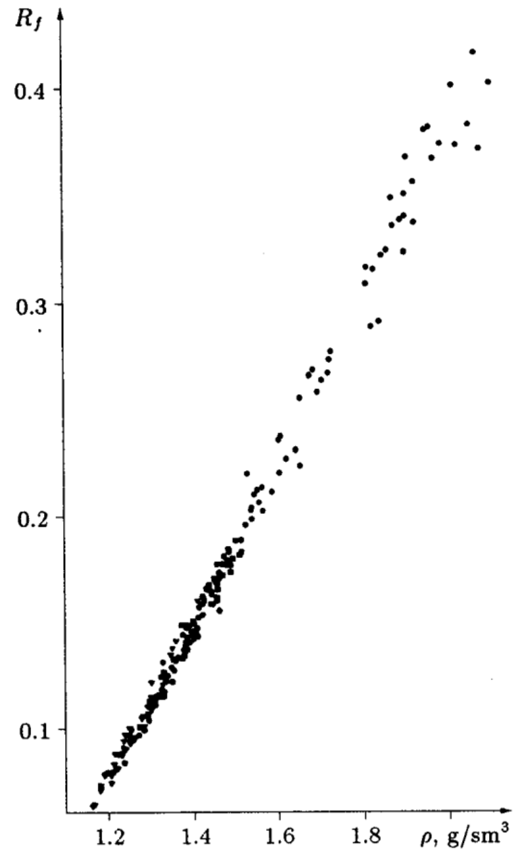

Figure 1. Density and reflection coefficient at normal incidence, all environments [4]

which makes it possible to compute density ρ (g/cm^3), porosity φ (%), acoustic impedance s (g/cm$^3 \cdot 10^5$) and compressional wave velocity v_p (km/s) via reflection coefficient. Here σ is the mean standard error.

3. Accuracy of reflection coefficient estimation

During seismic data acquisition, the minimal source-receiver offset may vary from tens of meters (single-channel surveys) up to hundreds of meters (typical for multi-channel seismic surveys). This implies that the acoustic waves have no vertical incidence on the sea or lake floor. Therefore, we evaluate the reflection coefficients obtained by the quotient method for different incident angles.

The amplitudes for the bottom reflector A_s and its multiple A_d were calculated for different incident angles using the formulas for reflection of acoustic plane waves in elastic media, mentioned in [5]. The reflection coefficient was estimated by the ratio (3) and compared with the reflection coefficient for a normal incident wave. Relative errors of this procedure are shown in Figure 2 for sand and silt-clay deposits. Errors for other types of sediment lay between these curves. So, we can state that the errors do not exceed 4% for angles less than 25 degrees for all kind of deposits.

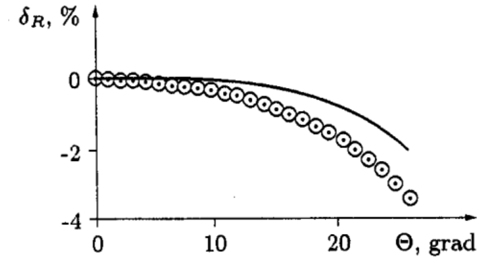

Figure 2. Error of reflection coefficient estimation by quotient method versus incident angle

4. Estimation of the physical properties of layered sedimentary sections

Sediment core sampling and deep water drilling show that deposits often consist of thin layers distinguished by their thickness, average grain size and mineral composition. According to Wides [6], the acoustic energy is reflected from a layer with thickness of approximately one wavelength. This thickness equals 1–2 m for a high-frequency single channel sparker source and 30–70 m for a middle-frequency multi-channel airgun-array source. In this section it is shown by means of mathematical modeling that for thin layered media the suggested technique gives averaged sedimentary physical characteristics. The thickness of the "effective" layer and the accuracy of the estimations are also investigated.

Synthetic seismic traces for a normally incident 16 ms Ricker-pulse, i. e., a zero-phase wavelet, are calculated using the Baranov–Kunets algorithm for two different models of layered media. Then, the amplitudes A_s and A_d were picked and the reflection coefficient using the quotient method (3) was worked out. After this, the effective physical quantities given by (4)–(7) were calculated and compared with the corresponding average model values.

The first type of layered model was set by alternation of pairs of sand and silt-clay sediments, being the most acoustically contrasting sediment types (see the table). The thickness of each layer varied from 0.06 m up to 1.7 m which is small compared to the wavelength of the incident acoustic wave. For each model, average sand thickness h_s and clay thickness h_c were fixed and their sum did not exceed 2.4 m. The thickness of layers in each pair number i were obtained using random values ξ_i and η_i: $h_{si} = \xi_i h_s$, $h_{ci} = \eta_i h_c$. These random values ξ and η have the uniform distribution in interval $[0, 1]$ with average value equal 0.5. The total thickness of the sample was larger than the wavelength of the incident pulse. For such models, average density and velocity are defined by the ratio of h_s and h_c and fall between the corresponding values for sand and clay.

In the second model type, the compressional wave velocity increases linearly with depth according to

$$v(z) = v_0 + Gz, \tag{8}$$

with gradient G between $1.2\,\mathrm{s}^{-1}$ – typical for terrigeneous deposits [8, 9] – and $10\,\mathrm{s}^{-1}$. The sediment density was calculated using formula (7). The average model density and velocity were computed using the formulas

$$\bar{\rho} = \frac{1}{h}\int_0^h \rho(z)dz, \qquad 1/\bar{v} = \frac{1}{h}\int_0^h \frac{dz}{v(z)},$$

where h is the effective thickness of the layer through which the sound waves are transmitted.

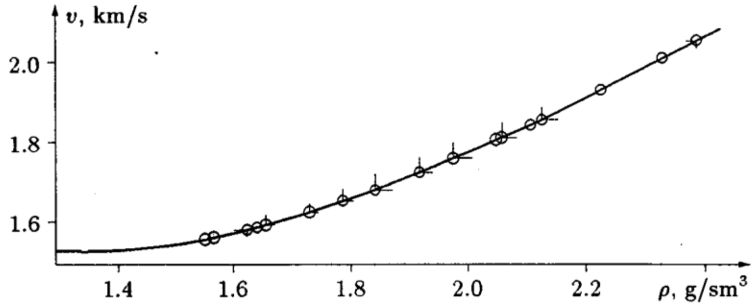

Figure 3. Effective and average values of density and compressional wave velocity mathematical modeling results

Numerical experiments show that the difference between the effective and the average values are minimal if the effective thickness h equals $vT/4$, where T is the length of the first main phase of the reflected wave in the time domain.

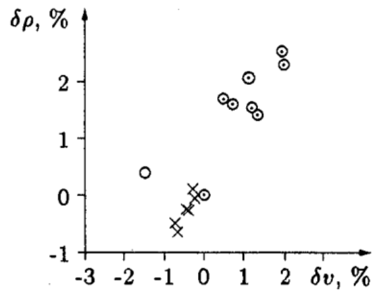

Figure 4. Errors of effective and average density and compressional wave velocity, mathematical modeling results

The effective and average values of the density and the compressional wave velocity calculated for the two different models are shown in Figure 3. The effective values of these quantities satisfy equation (7) and lay on the continuous curve (circle points). Effective and average values corresponding to the same model are joined in triplets, where the end of the horizontal segment gives the average density and the end of vertical segment gives the average velocity. This means, the lengths of these segments give the difference between the effective and average values. Relative errors of effective and averaged values for density and velocity for different models are shown in Figure 4. We see that the errors do not exceed 3% for typical marine sediments.

5. Estimation of physical properties of lake floor sediments in the Southern Basin of Lake Baikal, Siberia

In this section, we present some estimates of the physical properties of lake floor sediments in the Southern Basin of Lake Baikal, using multi-channel low-frequency airgun-array and single-channel high-frequency sparker seismic data.

A special instrumental program for seismic data processing based on the given technique was elaborated at the Institute of Computational Mathematics and Mathematical Geophysics in Novosibirsk. It gives the possibility to visualize seismic traces, pick the target waves (in our case the reflection from the lake floor and its multiple), calculate bottom reflection coefficient by applying the quotient method, compute sedimentary physical parameters using equations (4)–(7) and store the results in the table. The low-frequency seismic data were obtained in 1992 during the joint Russian–American expedition of the South Branch of the P.P. Shirshov Institute of Oceanology and the US Geological Survey [10, 11]. The processing results for Line 92–1, averaged over the 5 nearest traces, are represented in Figure 5. The average reflection coefficient of the lake floor for the whole profile equals 0.25, the sediments porosity is 60%, the bulk density is 1.65 g/cm^3, and the compres-

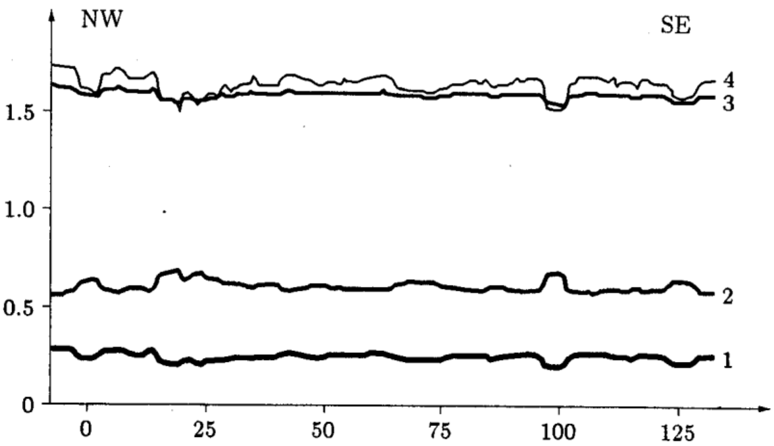

Figure 5. The low-frequency seismic data, 1992, line 92–1: 1 – bottom reflection coefficient; 2 – porosity; 3 – compressional wave velocity; 4 – density

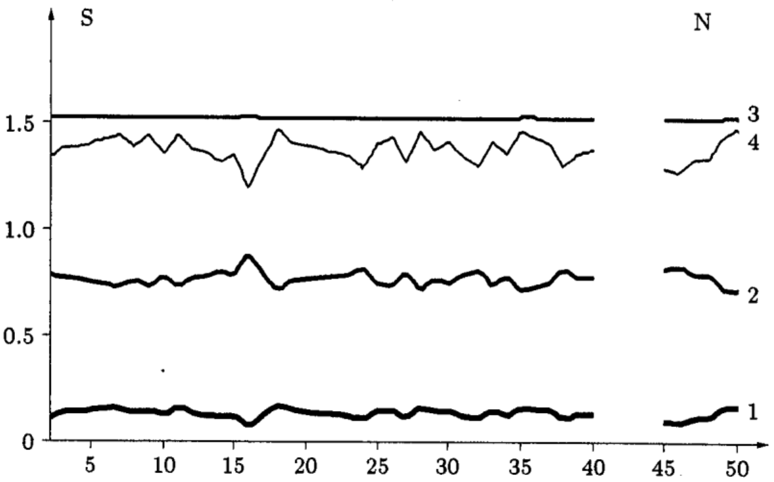

Figure 6. The high-frequency sparker data, 1997: 1–4 at Figure 5

sional wave velocity equals 1.6 km/s. The duration of the first (main) phase of the bottom reflection equals 12 ms, so the effective thickness is 4.8 m.

Figure 6 gives the processing results of the high-frequency sparker data, acquired during 1997 by the joint Russian–Belgian expedition of Limnological Institute of SB RAS in Irkutsk, the United Institute of Geology, Geophysics and Mineralogy of SB RAS in Novosibirsk and the Renard Centre of Marine Geology of the University of Gent, Belgium. The main phase of the acoustic pulse equals approximately 1 ms, so in this case the effective thickness equals 40 cm. The average value of the reflection coefficient for this layer equals 0.15 while the calculated porosity is 80%, the bulk density is 1.4 g/cm^3 and compressional wave velocity is 1.5 km/s.

According to Hamilton, typical sediments with average physical characteristics, obtained for a 5 m layer are sand-silt-clays while an upper 40 cm layer should represent silt clays. These conclusions are in good agreement with the deep water drilling results in this region [12].

6. Conclusions

In this paper, we investigated the quotient method applied on processed seismic traces for modeling and determining reflection coefficients, also in the case of non-vertical incident acoustic waves. It appears that this methodology gives good results. It is shown that for typical sand-silt-clay deposits, the error does not exceed 4% for incident angles less than 25 degrees.

Quantitative estimates of the reflection coefficients can be used to calculate physical properties of sediments, for example, the density, acoustic impedance, compressional acoustic wave velocity, and porosity, using the regression equations of Hamilton. The results allow us to make a guess of the kind of deposited material on the sea or lake floor. Using high-frequency and low-frequency acoustic records of Lake Baikal, we find that the bottom sediments should be silt clays or sand-silty clays. Here, the duration of the first main phase of the incident acoustic pulse can not be ignored. Moreover, it defines the thickness of the sounded deposits.

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