INVESTIGATION OF BOTTOM SEDIMENT STRATIFICATION

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The main goal of this paper is to find a method to assess remotely the type of sediments on the basis of the signal received using the parametric echosounder. The images of the sea bottom sediments taken by a parametric echosounder show the fine structure of the upper layer of the bottom sediments. The depth of penetration depends on the type of sediment, in fact on the attenuation of acoustic wave. In the paper the method of distinguishing the sediment layer basing on interpretation the received bottom signal is proposed. The knowledge on acoustic parameters of different type of sediments obtained in laboratory condition or using the literature data, allows to predict the composition of upper layer of the bottom. The considerations are illustrated by the results recorded from the bottom of the Gulf of Gdansk.

INTRODUCTION

The most appropriate method for remotely sensing the sea floor is the transmission, reception, and finally the interpretation of an acoustic echoes. The acoustic characterization of seabed sediments have been ongoing since the 1970's. Traditionally, these were accomplished by interpretation of grey scale echograms collected using an echo sounder. In the 1980's dedicated seabed classification was introduced which processed the analog signals and generated values representing the acoustic response from a integration of the sea-bottom echoes [11]. With the introduction of high speed digital processors, a more sophisticated approach to signal processing and echo shape characterization is possible [3].

The strength of acoustic energy reflected from the seabed with single beam sonar could be used to classify the type of the bottom using the acoustic ground discriminating systems. The basis of this technique is that different amounts of energy will be reflected or scattered from the sea floor based on the contrast in acoustic impedance between the bottom type and the water column. For example, a soft bottom such as mud will have a different reflection signature than a hard bottom such as rock and exposed archaeological material will have a different response to the undisturbed seabed. A number of methods have been proposed for analyzing the acoustic signal properties in terms of seabed classification including the work of Jackson and Briggs [6], Orlowski [10], Burns et al. [1], and Sternlicht and de Moustier [12].

All these methods provide data on the seabed, on the material at the border between water and bottom. The new type of equipment used in underwater measurements, a parametric echosounder allows to obtain data also from the structure of an upper layer of bottom sediments [14, 7, 5]. Images of the bottom are specific. The fine structure of the bottom is well visible [9]. No other acoustic device used in the study of underwater subspace has such research possibilities. Most often the upper layer of the sediment is recognized, but the question regarding the type of sediments creating successive layers is still open.

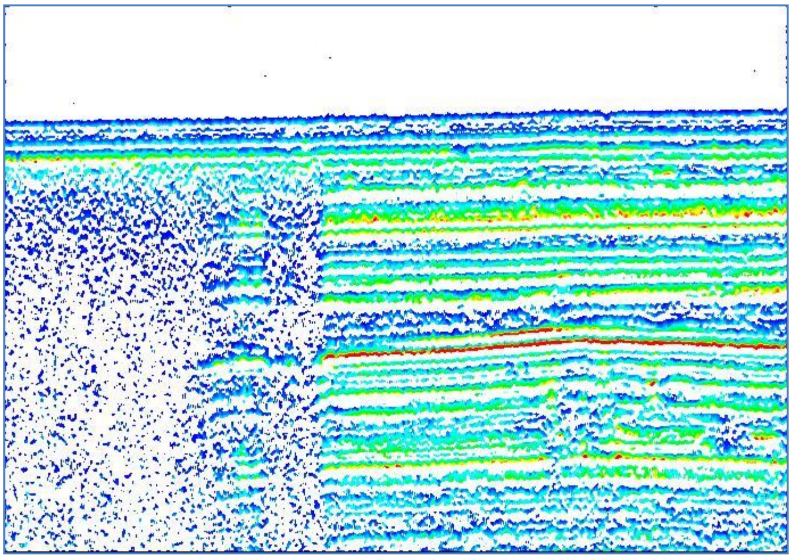

Fig. 1. Image of a sea bottom at the Gulf of Gdansk recorded by a parametric echosounder

1. SEABED SEDIMENTS CLASSIFICATION

Acoustic seabed classification is the organization of the sea floor and direct subsurface into seabed types or classes based on characteristics of an acoustic response. The amplitude and shape of an acoustic signal reflected from the sea floor is determined mainly by the sea bottom roughness, the density difference between water and the sea floor, and reverberation within the sediments.

Remote classification of the sea bottom requires an acoustic data acquisition system and a set of algorithms that analyze the data, determine the seabed type and relate the results of the acoustic classification to the physical properties of the marine sediments.

For example, the RoxAnn classification system is based on the energy contained in the first and second echoes. The second echo refers to the bounce of the original sound pulse reflecting again off the sea surface and the seabed for the second time [2].

Another solution was presented by Tęgowski [13]. He introduced a parametric analysis of the echo signals and applying the algorithm distinguishing 83 characteristic magnitudes representing various aspects of the signal envelope (energetic, statistical, spectral, continuous wavelet transform, fractal for the envelope shape), which next could be applied as parameters in the detailed computations.

An important element of classification is the determination of the acoustic regime defining a seabed class. There are two basic approaches: supervised and unsupervised classification [4].

Supervised classification defines boundaries of an acoustic class by processing a series of echoes from a known seabed type and establishing the boundaries based on those signals alone. Supervised classification requires a calibration or training data set from specific seabed types. The second approach is unsupervised classification. This is accomplished in post-processing when a subset of all data are sampled (e.g., one trace out of every ten) and acoustic classes are defined using clustering analysis. This approach enhances resolution by minimizing the covariance of the points within each class, resulting in classes that are as "compact" and discrete as possible. The clusters identified are assembled into a catalogue of seabed types that is used to classify the full data set.

Seabed classification systems require user input to relate the acoustic signal to the physical nature of the seabed. The ultimate accuracy in relating acoustic classification to bottom typing is contingent upon several issues: the frequency of the acoustic signal, the beam pattern of the transducer, and the type of ground at the calibration site. The frequency of the transmitted pulse will determine which features of the seabed strata will have the greatest influence on the acoustic response. Typically, high frequencies penetrate the seabed less but are more discriminating, while lower frequencies penetrate deeper into the seabed but are less discriminating. Beam pattern and, in particular, the width of the beam will determine the size of the acoustic footprint. A larger footprint will yield a signal that has been averaged over a larger volume of seabed, thus the level of sea floor heterogeneity will be important

The type of ground will influence the accuracy of seabed classification. For example, if only sediment grain size data is available, the seabed classes could be described according to the Wentworth Scale or to the standard of the soil classification PN-EN ISO 14688:2006.

However, this may not fully account for the acoustic diversity because other seabed characteristics such as sediment porosity, density, and presence of benthic organisms influence the signal. Ultimately, the accuracy of the final map product is limited by the ability to describe in detail each of the sites used for calibration. Therefore, rigorous site description using standard descriptions for sediments and biota are a prerequisite to classification. In addition to classification of individual echoes, ensembles of echoes produce estimates of line scale variability, which can be used to define a bottom type.

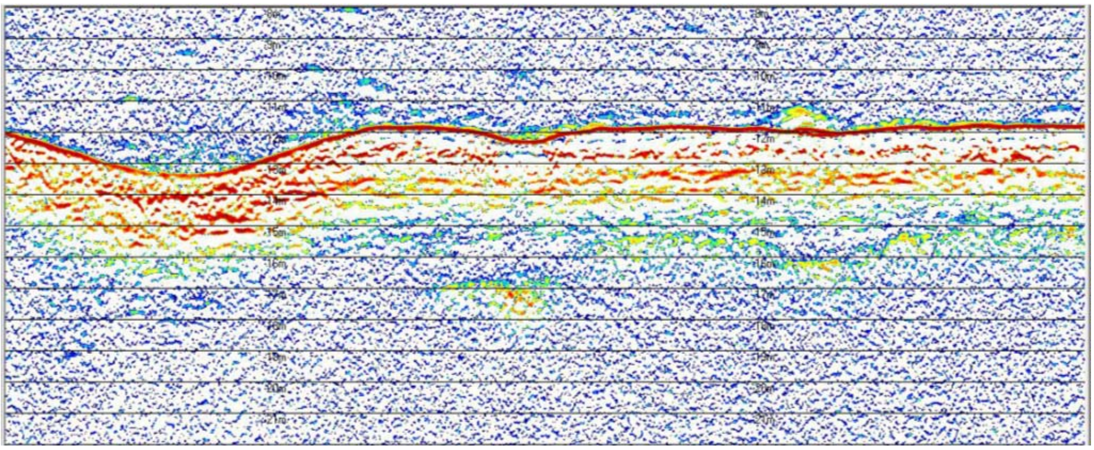

Fig. 2. Image of the bottom structure with biological scatterers (likely) at the sea floor

2. GEOACOUSTIC PARAMETERS AND GRAIN SIZE

Knowledge of the environment properties is very important for solution of many of the problems of sea bottom investigation. The main parameters are sediment mass density, sound speed, and acoustic attenuation. Moreover, it is needed information on the seafloor volume heterogeneity and surface roughness.

Physical property of some sediments, such as mass density (referred also as "bulk density"), are used directly as input parameter in acoustic theory and models. Others, such as sediment type or mean grain size, are used indirectly as empirical predictors of acoustic behavior [12]. In many applications a value of mean grain size is all that is required. Grain size is one of the most commonly measured sediment properties, and is usually given as equivalent particle diameter, either in millimeters or in logarithmic units. Logarithmic units are convenient, because many grain-size distributions are approximately lognormal. If the grain size is d mm, the grain size is recalculated into base-two logarithmic units as follows:

$$\emptyset = -log_2 d \tag{1}$$

In Table 1, comparison of grain size as well as geoacoustical parameters of main types of sediments is presented.

Table 1. Some geophysical parameters of sea bottom sediments [12]

Sediment	Symbol	Grain size [mm]	Φ	Dimensionless sound speed	Dimensionless density	Absorption coefficient [dB/m/kHz]
fine gravel	FGr	2.0	-1	1.338	2.4923	0.4556
coarse sand	CSa	0.630	0.66	1.243	2.2047	0.4718
fine sand	FSa	0.20	2.32	1.0364	1.2236	0.6958
medium silt	MSi	0.0063	7.31	0.9841	1.147	0.0763
clay	Cl	0.002	8.97	0.9801	1.1449	0.0537

The particle size of sediments acts like irregular surfaces working at different scales. At a certain acoustic wavelength, clays and silts are smooth compared to sands and gravel, however, differences are less noticeable between closer sediment classes like sandy clays and fine sands. Grain size also affects the porosity and interstitial water content that in turn control compressional-wave velocity.

3. METHOD OF RESEARCH

A method proposed by us could be treated as the unsupervised classification according to Collins and Lacroix definition [4]. But it is based on the experimental measurements of geoacoustical parameters of particular sediments determined in laboratory conditions.

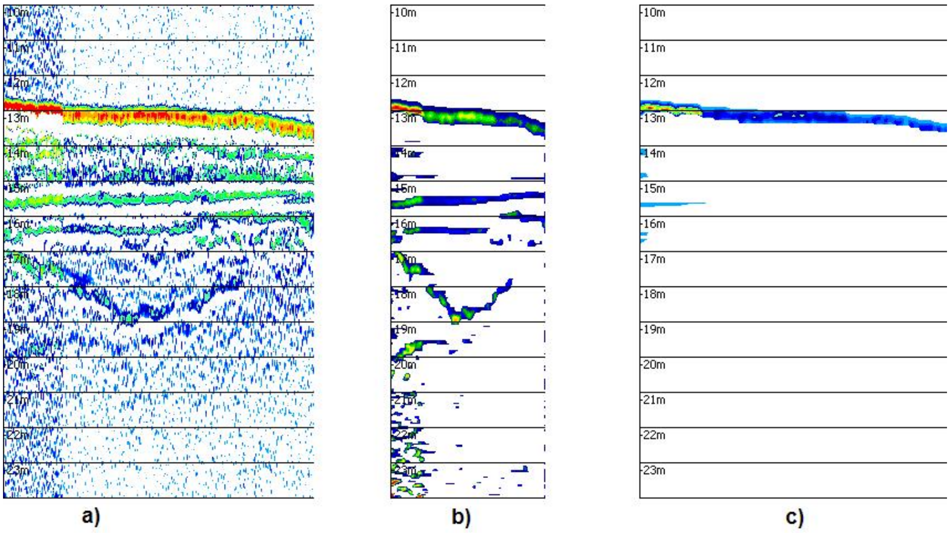

Fig. 3. Impact of the signal processing on the image of the same part of bottom (Gulf of Gdansk)

The image shown in Fig. 1 after processing of the data from the sea bottom structure obtained using of the parametric sounding [8] can be presented in the form shown in Fig. 4.

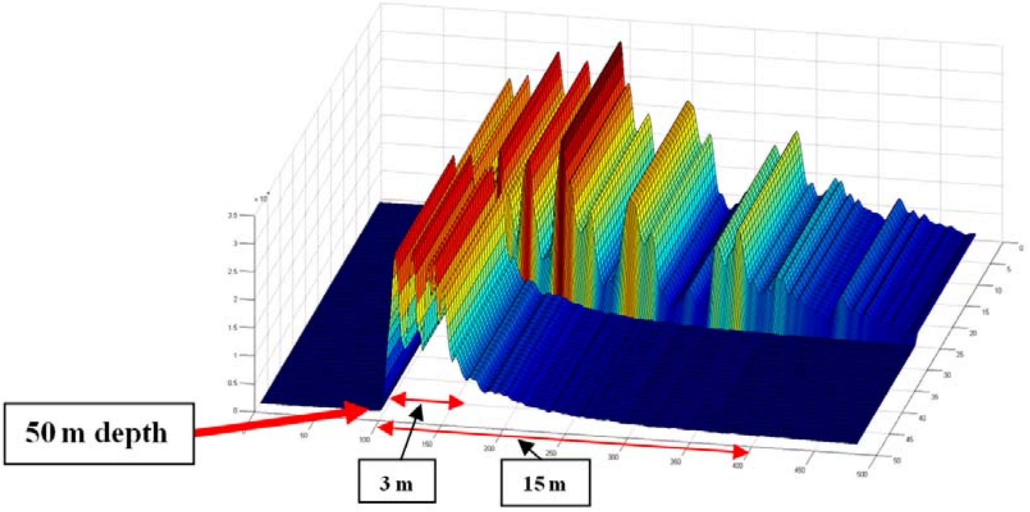

Fig.4. Changes in pressure during seabed penetration

The pressure of wave reflected at the borders between the layers of sediment is shown as a series of peaks. The value of successive peak depends on:

- reflection coefficient at given border;
- attenuation of the acoustic wave within the layer preceding the border;
- parameters in on-line and off-line processing as for example amplification TVG

The product of compressional wave velocity v and saturated bulk density ρ of sediment gives a measure of a material's resistance to an acoustic wave; this is called acoustic impedance. Differences in impedance between two layers determine, in part, the behavior of an acoustic pulse. This relationship is represented in the following expression (only for normal incidence):

$$R_0 = \frac{\rho_1 v_1 - \rho_2 v_2}{\rho_1 v_1 + \rho_2 v_2} \tag{2}$$

where R_0 is the reflection coefficient for two kinds of sediments (1 and 2) with velocities v_1 and v_2 and densities ρ_1 and ρ_2 , respectively.

In most cases, only the type of sediment from the upper layer of the bottom is known. Its impedance and attenuation, as well as speed of sound, can be assessed basing on experimental or literature data. Some parameters of the layers have to be known, such as acoustic impedance of both layers, speed of sound in the first layer, depth of the first layer, attenuation coefficient for the first layer, to determine the relative change in value of the successive peak in comparison to the previous one. If the second layer is unknown we must solve the inverse problem.

4. ACOUSTIC WAVE REFLECTION AT THE BORDERS OF LAYERS

On the border a part of acoustic energy is reflected and the remaining part penetrates the successive layers. It could be assessed using the knowledge on the sediment creating the upper layer of the sea bottom. The values of the reflection coefficient at the interface of water determined for the typical kind of sediments are given in the table 2.

Table 2. Reflection R and transmission T coefficients determined for pressure of acoustic wave at the water-sediment interface

	c[m/s]	ρ [kg/m3]	Z[Rayl]	R [vs water]	T [vs water]
water	1500	1000	1500000		
fine gravel	2007	2492	5002046	0,5386	0,4614
coarse sand	1865	2205	4110663	0,4653	0,5347
fine sand	1555	1224	1902209	0,1182	0,8818
medium silt	1476	1147	1693144	0,0605	0,9395
clay	1470	1145	1683175	0,0575	0,9425

The relative amplitude of wave penetrating the border layer of sediment varies from 0,46 up to 0,94 of pressure amplitude of incident wave.

The reflection on a particular border creating interface between different type of sediments depends on the acoustic impedance of both layers. The values of the reflection coefficients determined for the chosen types of sediments are given in Table 3. It is assumed the composition of sediments is not predictable and each layer may be adjacent to any other.

It can be easily noticed that the highest values of reflection coefficient are when the wave is transmitted to fine gravel or coarse sand. It means that the echo signal is the highest while the transmission of energy into the next layer is the least.

An example of changing the pressure amplitude of the incident wave and the reflected one on the way of penetration through the set of sediments typical for the Gulf of Gdansk is shown in Fig. 5.

Table 3. Reflection coefficient determined for pressure of acoustic wave at the interface of the different types of sediments

	Consecutive layer				
	fine gravel	coarse sand	fine sand	medium silt	clay
First layer ↓					
fine gravel	0,000	-0,098	-0,449	-0,494	-0,496
coarse sand	0,098	0,000	-0,367	-0,417	-0,419
fine sand	0,449	0,367	0,000	-0,058	-0,061
medium silt	0,494	0,417	0,058	0,000	-0,003
clay	0,496	0,419	0,061	0,003	0,000

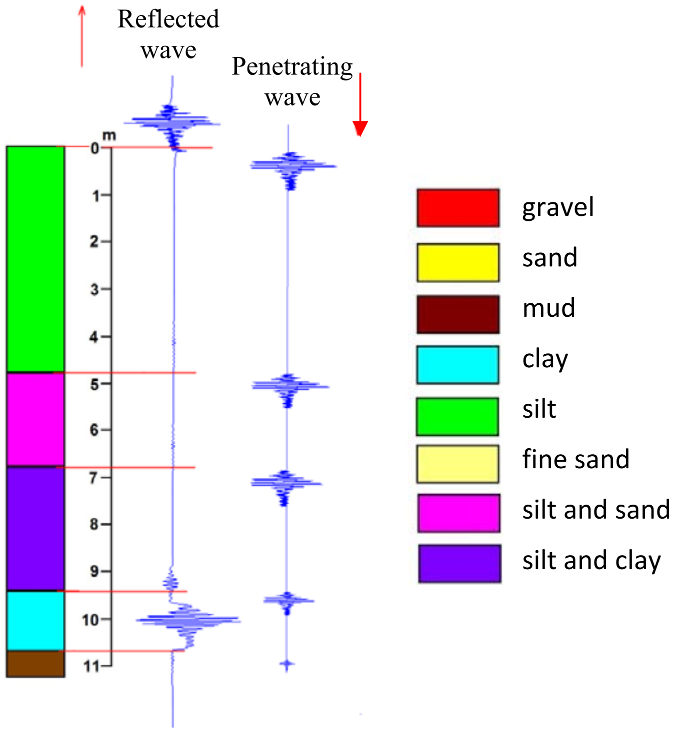

Fig. 5. Changes in shape of reflected and penetrating pulses during penetration of a bottom (an example of a core taken from the bottom of Gulf of Gdansk)

5. ATTENUATION OF ACOUSTIC WAVE IN SEDIMENTS

The quantity of acoustic energy transmitted into the bottom depends on the impedance of the consecutive layer of sediments. But the attenuation caused by the absorption is also very important factor that has an impact on the range of bottom penetration. It depends strongly on the frequency of wave.

The secondary waves used in parametric echosounder for seabed investigation are of rather small frequencies, from several up to 20 kHz. Therefore the wave of such frequency can reach the depth up to 30-40 meters for the least attenuating materials. The values of absorption coefficients for chosen types of bottom sediments are given in Table 1 [12]. On this basis, the relative change in pressure on a way equal to 1m, 5m, 10m, 20m or 30m for each of material was determined assuming that the wave frequency is 6 kHz. The analysis of these data allow to conclude that the range of penetration for wave of considered frequency in homogeneous layer will change from about 5 meters for sand up to about 30 meters in silt or clay.

Table 4. Relative diminution of acoustic pressure on the way from 1 to 30 meters in different types of bottom sediments

Type of sediment	Absorption coefficient	Absorption coefficient for 6 kHz	Relative diminution of pressure				
	dB/m/kHz	dB/m	1 m	5m	10m	20m	30 m
	1	2	3	4	5	6	7
fine gravel	0,4556	2,7336	0,730	0,207	0,043	0,002	0,000
coarse sand	0,4718	2,8308	0,722	0,196	0,038	0,001	0,000
fine sand	0,6958	4,1748	0,618	0,090	0,008	0,000	0,000
medium silt	0,0763	0,4578	0,949	0,768	0,590	0,348	0,206
clay	0,0537	0,3222	0,964	0,831	0,690	0,476	0,329

6. REAL DEPTH OF LAYER

Another question related to the interpretation of the seabed echograms is the real depth of particular layers. The image is composed of set of lines basing on the changes in time of received signal, as for example shown in Fig.6. The vertical scale on the image is proportional to the depth assuming that the speed of sound has the same value in water and in sediments.

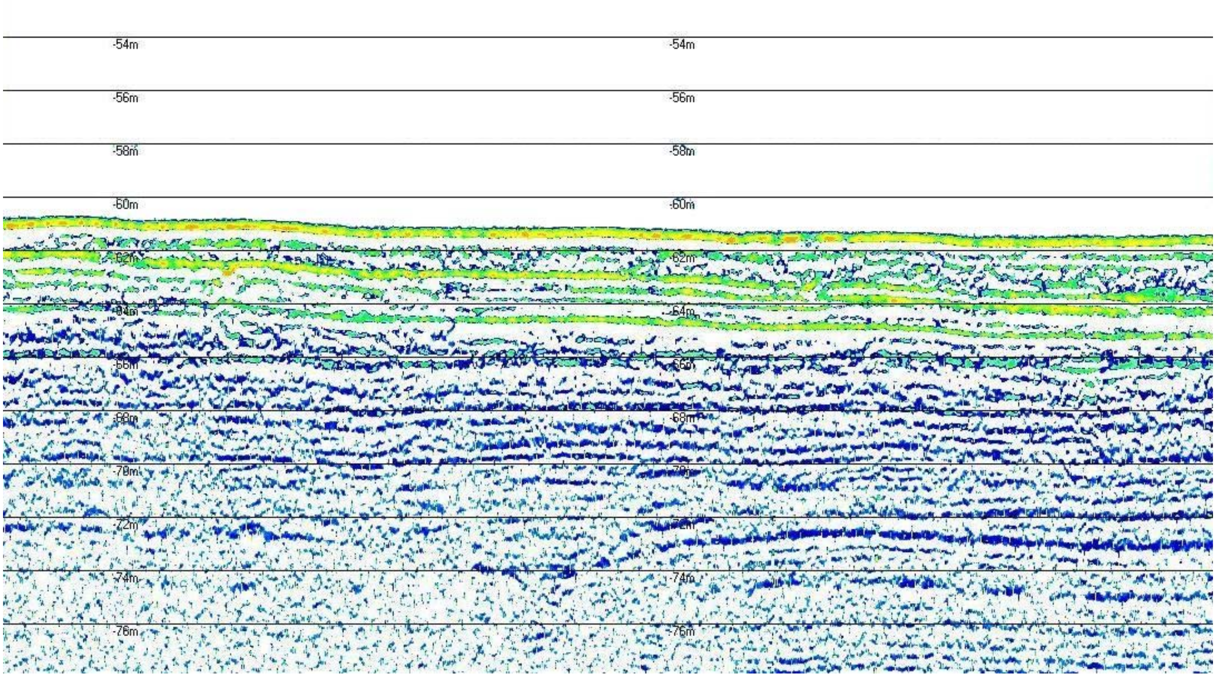

Fig. 6. Typical image obtained using the parametric echosounder

The speed of sound in sediments differs up to about 25% from the speed of sound in water. Usually, it is higher, but for some type of sediments as silt or clay it can be lower than in water. The indicative values of speed in typical type of sediments are shown in Table 5. The error rate of measurement of sediment thickness is given in the last column. It means that at certain circumstances the real thickness may be even 20-25% greater than it is shown in the echogram.

The consequence of it is further diminution of echo signal caused by the absorption on the additional wave (see chapter 5). This fact has to be taken into account in assessment of seabed structure.

Table 5. Error in measuring the thickness of the various layers of sediment assuming a constant propagation speed in the considered environment

Type of sediment	Dimensionless sound speed	Percentage error of measurement of sediment thickness based on echogram
fine gravel	1,338	25,259 %
coarse sand	1,243	19,542 %
fine sand	1,118	10,575 %
medium silt	0,984	1,614 %
clay	0,98	2,032 %

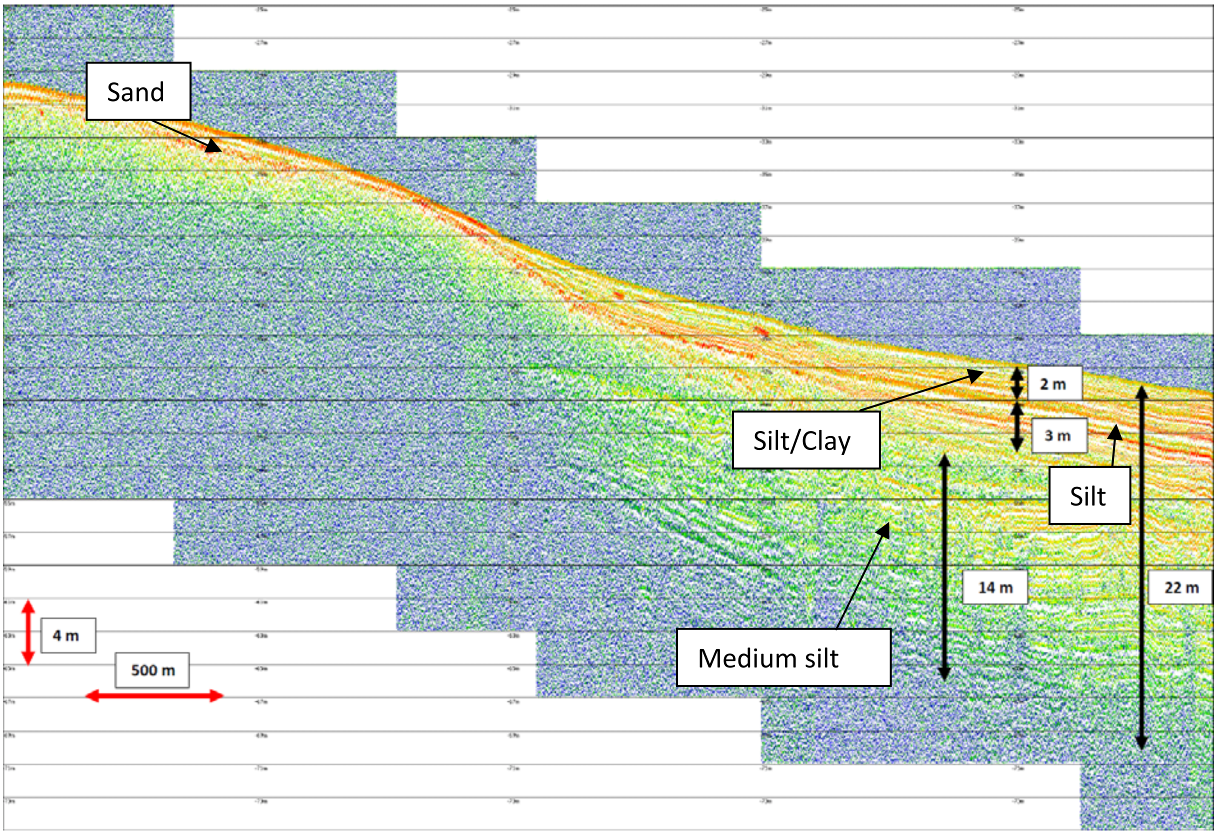

Fig. 7. The bottom sediments at the Gulf of Gdansk

CONCLUSIONS

Taking into account all the factors described above: reflection of a part of acoustic energy at the borders of layers, a great absorption in particular type of sediments, real thickness of the layer and, moreover, the amplification of a reflected signal in the receiving section of the echosounder, we can try to assess the types of consecutive layers based on the relative changes in the subsequent echoes pressure peaks.

Determination of the structure of bottom sediments can be performed using an invasive method. It gives the results estimating locally accurate sediment stratification.

This method is not recommended as a way to a widespread usage due its complexity and the limited range of applications. Therefore, the use of remote sensing and noninvasive methods offers greater prospects for practical application. Unfortunately, the results are difficult to be interpreted.

Considering the fact that the beam is perpendicular to the bedding slightly simplifies the interpretation, however, the procedure is still very complex. Multiple reflections in a stratified environment do not allow for unambiguous interpretation.

Nevertheless, the proposed method, though still requires further improvements, presents a significant step forward in the systematic determination of the parameters to the bottom sediments.

The usage of parametric echosounder allows for further development of diagnostic tools for non-invasive bottom structure research.

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