ACOUSTIC EXPRESSION OF SEDIMENTARY PROPERTIES

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1 INTRODUCTION

There is no unique relationship between an acoustic signature and a type of seabed. Such a statement shows how complex this field is, and explains the large number of studies being conducted in it. The acoustic methods of sediment characterisation used in sedimentology and the acoustic systems used in marine physics are both based on similar systems, the main difference being the emission incidence angle. It is therefore not easy to use acoustic data for studies in sedimentology, or sedimentary data to develop acoustic models. We demonstrated the importance of combining several systems to qualify the seabed; by increasing the number of applications, in order to refine the accuracy of data, we gradually extended the frequency domain of the acquisition systems used, but this domain is still too small compared with what is actually necessary; but managing all the systems used is costly and interference between the different systems forces us to limit the number of sensors. Characterisation of the sea bottom therefore involves the acquisition of three-dimensional multi-frequency acoustic data. This characterisation is not only the name of sediments, but is the sum of the morphology and roughness of the seabed, the nature and granularity of sedimentary particles, the nature and proportion of interstitial fluid, the lateral and vertical organisation of the sedimentary bedding.

These four elements act on sediment physical properties, namely wet density, porosity, conductivity and resistivity. Since the velocity and absorption of acoustic waves are only rarely measured, the acoustic behaviour of the seabed is generally modelled using transfer formulae which enable the name of the sediment, its porosity or mean grain size to be transcribed as seabed acoustic parameters. The last parameter taken into account is the thickness of the sediment covering the substratum. The first models represented the seabed as a single sediment layer of continuous thickness above the flat bedrock. Over the last decade, more complex models have been developed which can integrate the notion of multilayers and gradients. At the present stage in our research, it appears that the difference between the seabed acoustic models and sedimentary data comes essentially from the classification used to describe sediments, which is too reductionist to deal with their complexity. An improvement in studies requires a classification of sediments which takes into account not only central granulometric parameters, but also the mode of deposit and specific regional or local features. The nature of interstitial fluid and particle shape, which is difficult to gain information on, is given indirectly by physical parameters like density and porosity.

2 TECHNOLOGICAL CONTRIBUTION TO THE RENEWAL OF SEDIMENTOLOGY

2.1 General modelling concepts

The modelling of a phenomenon begins with a mathematical approach whose objective is to resolve a problem using a formulation as complete as possible. Due to the complex nature involved and the fact that computer processing cannot take everything into account, it is usually necessary to simplify the physical model so as to obtain a more theoretical model that only takes into account the range of possibilities considered as representative. In any case, the model is based on adjustment points derived from field measurements, or on correspondence tables (e.g. grain size - friction coefficient).

Numerical models taking into account sediments were until recently characterised by excessive simplification. Sediment models generally consist of adjusting a theoretical physical model using a more or less complete dataset. A large number of sediment models have been developed in this manner:

- Sandbanks, sandbank saturation
- Displacement of dunes, sandbars and other sedimentary structures
- Seabed acoustic properties of sediments
- Burial phenomena and other geotechnical aspects
- Characterisation of sediment deposits through remote optical or acoustic satellite sensing
- Mapping of sediment distribution or properties

Most of these models ignore the multiplicity of processes involved and the complexity of marine sediments. They have yielded good results for applications for which they were originally intended and in environments where they have been validated. The common mistake is to globalise them, i.e. to use them in domains or environments for which they were not intended.

There is a gap between Sedimentology which is closer to reality and modelling techniques which can be used to better characterise certain sedimentary phenomena. Among the many possible examples, let's consider the deviations between the physical model derived from seismic reflection data and the naturalistic model based on core data. The reflector patterns observed on seismic profiles can be attributed to the characteristics of sediments, but they are also and mostly due to the acoustic characteristics of the source. In order to determine sediments based on seismic reflection data, all the phenomena involved need to be assessed and automatically translated into sedimentary layers with homogeneous physical properties. The confrontation of acoustic models derived from seismic reflection data with deposition models derived from sediment core data has led to the refinement of sequential stratigraphy methods and to questioning the congruence of core samples.

2.2 Seabed modelling through remote acoustic sensing

Sampling data seems to be the most necessary and systematically relevant data, but sediment mapping usually needs also accurate geomorphologic data. This data can be used to characterise sedimentary processes and therefore to create a conceptual model. In order to proceed further, refinement data must be added, i.e. underwater acoustic, seabed classification systems and video imagery (surface approach), seismic data (vertical variability), measurement of physical sediment properties and near-seabed currents, chemical analysis of particles and fluids, etc.

Side-scan sonar and MES imagery have brought about significant changes in the mapping of surface marine sediments:

§ rapid exploration of the seabed surface,
§ good definition of the boundaries of rocky sectors (poorly identified by sampling),
§ detection of contacts between some sedimentary structures (identification of sedimentary structures, whether longitudinal (streaks, ribbons, veils, furrows, comet tails) or transversal (megaripples, sand dunes, etc.)

These systems revealed very diverse sedimentary structures and allowed a qualitative approach to the study of sediment transport. It must nevertheless be noted that characterisation of granularity of sediments do not come from the only analysis of these images, but is a synthesis of regional knowledge, solid expertise, and observations of present and geologic formations. This cognitive aspect of sedimentology has led to the belief that the side-scan sonar data itself contains all the information necessary for its interpretation and the automatic classification of sediments. The variability of the backscattering coefficient makes direct processing of sonar images unsuitable for sediment classification purposes and therefore resort to calculating a broad set of parameters (variance, entropy, energy, homogeneity, etc.), achieving an innovative classification system[1].
The remote classification sediment systems[2] give the possibility of distinguishing between sediment classes based on backscattering data, these systems are based on the digital processing of a

signal received by bathymetric sounders. The RoxAnn system has been used by the SHOM to observe pockmarks field, changes of sediments over sand dunes, underwater telephone cable, small rocky areas, to identify fine variations in seabed characteristics, etc. But in fact, the changes observed do not only correspond to variations of granularity. For example, in the case of a sounder with a frequency of less than 50 kHz, the signal may be modified due to rock rising up when the sedimentary layer amounts to less than one metre. Moreover, the impact of rock formations near the surface varies according to the signal absorption capacity of the sediments and the frequency of the sounder. These semi-automatic seabed classification systems currently appear as the most effective for sedimentologists seeking to identify homogeneous deposition zones. Although they do not actually define the nature of the sea bottom, they provide parameters that can be transcribed in terms of sediments, algae fields, gas-rich deposits, sand mega ripple fields, etc. Post-processing with sampling data usually allows improvement of classification accuracy and to have a high-resolution seabed characterisation when used in conjunction with acoustic images. They are acoustic systems, and therefore very useful for detecting phenomena potentially affecting seabed reflection and reverberation, like roughness for example.

2.3 Contribution of sample analyses

Samples are used to identify sediment types and thereby produce maps based on descriptive classifications and a wide range of granulometric parameters. Maps based solely on sample analysis are characterised by the often ovoid shape of the surfaces plotted. These maps concern parameters of granularity, nodule distribution, etc. The scientific literature is full of articles and books on the advantages and disadvantages of the various parameters useful for mapping: median grain size, sorting, skewness, Trask Index, etc, derived from sieving analyses. Sedimentologists have sought finer and finer descriptions, whereas specialists from related sciences have almost always taken into account the mean grain size. The existence of very heterogeneous and bimodal sediments, in coastal environment, shows that the use of this parameter is frequently not justified. In fact, it seems to be an absence of a single classification combining all relevant sediment characteristics[3].

Until a few years ago, sediment maps were intended to show seabed constituents and provide records of information available at the time of publication. With the availability of databases, their main purpose must now be to satisfy the needs of users, experts and scientists with dated and georeferenced accurate data. Unlike bathymetric maps which always show depth data, sedimentary maps may include varied information, e.g. particle size, chemical components, physical processes, geomorphology, geology. In addition, these maps use widely varying scales and are based on data largely heterogeneous in terms of quality and quantity. Different classification schemes have been developed, allowing the integration of largely varied data and the production of maps specifically tailored for each of the requirements. However, increasingly large deviations are observed between two extremes cases:

- Maps based exclusively on grab samples, i.e. diagrams offering the best possible sediment classification accuracy, but poorly delimiting boundaries between sediments
- Physiographic maps based on imagery and morphology, clearly identifying main structures and boundaries but poorly characterising seabed properties

Between these two extremes, there are maps using descriptive classifications based on multiple data sources, samples, numerical elevations models, etc. and dissociated from the acquisition systems used. They are sometimes supplemented with appendix maps so as to satisfy different requirements. These maps are not directly usable for hydrodynamic or seabed acoustic modelling, and are usually transcribed into mean grain size values.

New classifications will continue to be created to meet specific requirements and benefit from scientific and technical developments. The complexity of seabed does not allow for a single universal standard suitable for all studies and scales. But maps must be unambiguous, explicit and based on a standardised code. The standardisation of sediment maps should first and foremost consist of classifying the various possible maps and establishing rules for validating them.

Certain seabed constituents are not shown in maps, namely fluids contained within pores and potentially representing over two-thirds of the volume of sedimentary layers. This porosity could be correlated with granularity. However sand particles tend to organise differently depending on their deposition mechanism[4]. The real uncertainty is not the accuracy of porosity or parameters of granularity, but rather the effect of variations in these parameters on physical models. The relative importance of the parameters used to characterise seabed properties varies depending on the application, certain parameters play a crucial in dune dynamics models, others influence acoustic wave backscattering, etc.

3 ACOUSTIC EXPRESSION OF SEDIMENTARY PROPERTIES

Initial research on the physical properties of sediments goes back to the early XX century with the determining of the Atterberg limits defining the limits of sediment liquidity and plasticity; then, around 1925, Terzaghi's experiments gave rise to soil mechanics. The first programme concerning seabed acoustic properties was started in the late 50s by the US Navy Electronics Laboratory. A lot of research was then carried out on the subject. At the time, the sound velocity in sediment cores was measured by transmission, but also by resonance and the creation of stationary waves In order to overcome disturbances due to coring, in-situ measurement systems were also developed. Chassefière[5] and Wilson[6] then questioned the validity of results published before 1970, as well as the measuring equipment and laboratory methods used until then.

In parallel with field and laboratory measurements, an experimental approach to Biot's theory was developed by Plona[7]. The method, considered too theoretical, was replaced by a macroscopic approach to propagation phenomena[8], consisting of replacing the theoretical porous environment by a homogeneous environment equivalent in terms of given properties. The overly simplistic sediment model was thus replaced by a homogeneous linear viscoelastic environment, better suited to assimilating the phenomena brought into play during the propagation of a mechanical wave in the seabed. Such an approach is based on acoustic models as well as information provided by geologists. This method, while it represents real progress, nevertheless remains reductionist given the complexity of natural sediments.

In Biot's approach, reformulated by Stoll, the description of the sedimentary environment is based on eleven parameters[9]:

- the sediment is characterised by grain density (ρ_d) and mass (K_d);
- the interstitial fluid Is expressed by fluid density (ρ_f), mass (K_f) and viscosity (η),
- the Interstices are given by porosity θ, permeability (K), a parameter of pore dimension characterisation (a) derived from mean grain size and an indicator of pore shape (a');
- the elasticity of the sediment is characterised by its density (K_m) and rigidity (μ_m).

In theory for a homogeneous environment, by obtaining sound velocity and density values, the physical parameters necessary for the development of acoustic models can be found.

There are, in fact, three methods for drawing up propagation models. The first corresponds to the empirical relations obtained by repeated acoustic and measurements of granularity on batches of sediments. The second is based on combining the physical parameters and acoustic properties of seabed constituents by a viscoelastic model or, for porous elastic environments such as sand, on a model starting from Biot's theory and completed by Kirchoff's approximation to take account of roughness. The third is based on inverse methods by which the lithological environment can be reconstituted and reflection coefficients directly determined by analysis of the acoustic waves emitted by a dedicated system.

The three methods require knowledge, to varying degrees, of the physical parameters of sediments crossed by acoustic waves. The data used as input for the models, frequently called actual sediment characteristics, is generally limited to the name of the sediment, extracted from seabed maps and transcribed as a mean grain size value; at the second stage, empirical formulae can be used to calculate the physical parameters sought. Using a series of transfer functions, acoustic wave reflection and reverberation can be modelled from data provided by sedimentologists.

The difference between the sedimentary model and the data used as input for geoacoustic models (C_p, d), looks very great. In order to converge towards more effective models, we are conducting acoustic parameterisation studies since the 1990s in order to:

- assess the acoustic impact of the seabed. This is only possible by comparison between real data from surveys dedicated to this problem and simulations. Specific expertise has been acquired in order to make a clear distinction between problems coming from the nature of the seabed and from other environmental parameters.
- quantify seabed parameters. Beyond the characterisation of the seabed using acoustic or seismic imagery systems, we have tried to obtain acoustic parameters by remote sensing. Sedimentology and acoustic studies have been carried out in order to achieve convergence between the methods and models to ensure appropriate processing of the signal and more relevant descriptive parameters of the seabed.

Our studies therefore cover the physical properties of sediments, the digital processing of the acoustic signal of systems conventionally used in sedimentology (side-scan sonar, sediment penetrator, multibeam echo sounders) and inverse models, as well as the impact of variations in the seabed on propagation models.

3.1 Acoustic propagation in the seabed

Marine sedimentology is the analysis of the combination of several systems to qualify the seabed, by increasing the number of applications, in order to refine the accuracy of data, we gradually extended the frequency domain of the acquisition systems used. This domain is still too small compared with what is actually necessary. But managing all the systems used is costly and interference between them forces us to limit the sensors of the same carrier. Analysing the systems used for each area of research has shown that to properly assess the variability of the seabed (algae, pockmarks, horizontal and vertical changes) a whole range of systems must be used, with wave lengths ranging from a few hundred kilos to several hundred Hertz, even if we limit ourselves to the first decametres of sediment. Characterisation of the sea bottom therefore involves the acquisition of three-dimensional multi-frequency acoustic data. By merging multi-frequency data, it seems possible to refine the characterisation of parameters directly related to frequency such as attenuation and surface roughness.

Reverberation is affected at high frequencies by underwater vegetation. As frequency decreases, wave penetration in sediment grows, and the capacities to classify sediments increases. Beyond a limit in the region of 20-30 kHz, acoustic waves can cross several sediment layers or even reach the underlying rock; the acoustic parameters obtained therefore correspond to a mix of different pieces of information and become increasingly difficult to interpret. Acoustic wave penetration is influenced by internal inhomogeneities like burrows, gas bubbles, seashells, and porosity variations. For VHR seismic system the unstability of the signal and the difficulty in obtaining sufficient data pose many problems. In addition the result obtained with this kind of system is very closely related to acquisition system performance (Figure 1). The characterisations obtained from these systems are bound to be different in terms of number of sedimentary layers and their acoustic properties. The result being dependent on frequency, it would only be suited to applications with similar frequencies.

Figure 1: The same seismic profile with three different sediment penetrator. Left: Sparker 50J: 0,2-1,2 kHz, Middle: Sediment penetrator TR109: 2,5-4,5 kHz, right: Boomer IKB Seistec: 1-10 kHz.

3.2 Measuring velocity in situ and on sediment samples

The sea bottom can be defined by the morphology and roughness of the seabed, the nature and granularity of sedimentary particles, the nature of interstitial fluid, the lateral and vertical organisation of the sedimentary bedding. These four elements act on sediment physical properties, namely wet density (ρ_h), porosity (n), conductivity and resistivity. The main seabed acoustic properties affecting the propagation of an incident acoustic wave on the seabed are, according to Hamilton[10, 8]:

- the velocity C_p of compression waves, or longitudinal velocity, or P (primary) waves,
- the velocity C_s of shear waves, transverse velocity or S (secondary) waves,
- the damping coefficients of these two waves or associated attenuations α_p and α_s correspond to intensity losses per unit of wave length (in dB/m).

The precise characterisation of sediment physical properties is difficult to define since it depends on measuring methods for acoustics as well as sedimentology. The method of qualifying the physical and acoustic properties of sediments very frequently consists of using various formulae to obtain sound velocity, density or porosity from granularity. Considerable differences between the results so obtained and the measurements taken in the laboratory have led us to look in detail at the studies in this area. Even if the measurement is made on board when the coring has just been carried out, the causes of inaccuracy remain:

measurement on poor quality sediments (pistoning, etc.),
absence or poor calibration of sound velocity sensor,
the effects of burial, temperature and pressure,
corrections due to laboratory measuring conditions.

A measuring protocol is therefore necessary, it should include measuring methods, the characteristics of the equipment used, as well as a description of the sediments and the qualification of the sample being measured.

Our research is presently focused on understanding the relative variations observed between velocity values and other physical and granulometric parameters, since these relationships appear to be more complex than what is indicated by classical empirical formulae. Laboratory measurements performed on a series of core samples taken in the Arabian Sea show that the relationship between the mean grain and sound velocity is not unique, with two relationships clearly apparent in Figure 2. These research showed that several core samples taken from a given sedimentary zone, governed by a unique deposit process, allowed correlations to be made between the velocity and granularity measured, as well as acoustic imagery. In this example, the MES light grey zone shows velocity peaks, coming from levels of hardened silt. The MES dark grey zone shows the same sediment at the surface, the first silty bed is nearer the surface and the underlying clay contains a greater proportion of silt. So these variations does not characterise the surface sediment but two regional deposit modes. These differences show how detailed the sedimentary description must be to determine the physical properties of the seabed.

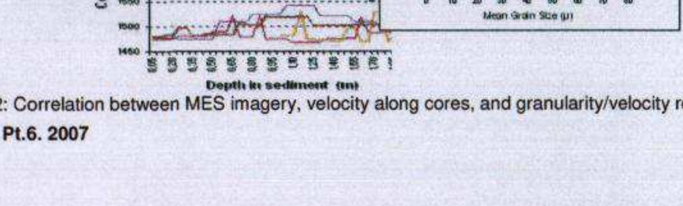

Figure 2: Correlation between MES imagery, velocity along cores, and granularity/velocity relations.

3.3 The limits of empirical models

All the empirical formulae have the same form, but give results which are sometimes very different because of the diversity of the study sectors on which these formulations were validated. The domains of validity of geoacoustic models are often limited by granularity, depth, etc. The formulae of Hamilton and Bachman[11] for example are only applicable for fine sediments since the studies mainly concerned deep seabeds; there are, moreover, technical difficulties in studying sandy sediments since measuring velocity would require the use of low frequencies incompatible with the conventional width of sediment cores and boreholes. The measuring systems and data available therefore exclusively concern sediments with mean grain size below fine sand. So most of the models, are therefore virtually unusable in the Channel or North Sea where fine sediments represents less than 10% of sediment cover.

The notion of a sedimentary process impact does not seem to be included in any model. However, this factor inevitably has great influence on porosity and density and therefore on velocity and it is possible to improve models by taking better account of the sedimentary processes. Establishing such regional formulas seems to be developing to the detriment of universal models. This is the case for the study on the coasts of Korea[12] which resulted in the creation of the following models: Velocity (Cp)/porosity (C_p=a-bn+cn^2), Cp/mean grain size (C_p=a-bGM+cGM^2) and Cp/percentage of mud (C_p=a-bV). These authors note that certain sectors of their study show good similarity with the formulae proposed by Hamilton on the north Pacific continental shelf, but they define the most appropriate coefficients a, b and c for each of the three provinces of their study, resulting in nine formulae for the calculation of compressional-wave velocity.

To evaluate the performance of the different geoacoustic models, enabling the variation in sedimentology parameters (D50, porosity, etc.) to be correlated with physical parameters (sound velocity, density, conduction, impedance, attenuation) we realize an initial study including a campaign of measurements at sea, a sedimentary analysis and an acoustic modelling[13], and then we developed a simulator to compare the different models proposed in the literature, and assess the impact that sedimentary variation could have on acoustic models. Such an approach is limited since geoacoustic models generally reduce the translation of sediment to its simplest expression. Nevertheless, the simulator allows evaluation of the impact of modifications to the input parameters on propagation models. This tool takes account of the adjustment of laboratory physical measurements in order to have "real" values corresponding to in situ conditions. In order to be able to study the performance of the acoustic acquisition systems used by sedimentologists, as well as the impact of sediments on the sonar data, the simulator covers a wide range of frequencies and emission angles. For example, we have analyses the influence of the burial of a silty layer in a clay environment on the reflection coefficient and the reverberation index, etc.

4 CONCLUSION: RELATIONSHIP BETWEEN SEDIMENTARY AND ACOUSTIC MODELLING

By using acoustic systems, it is now possible for sedimentologists to have an accurate description of megaripples, pockmarks, erratic blocks, algae fields, acoustic turbidity from gas, mud volcanoes, variations in seabed type, tectonic and anthropic imprints, etc. But to reach such a determination, a multitude of systems must be used with very variable emission properties. Each study combining acoustic data with sedimentary data adds a level of requirement, causing greater complexity in the systems to be implemented and a greater need for expertise. Consequently, the greater the progress in studies on remote sensing of ground and seabed geoacoustic properties, the more necessary detailed studies of sediments and their characteristics become.

The naturalistic approach consisting of acquiring data to produce digital maps is the same as that used by physicists to adjust modelled physical processes by means of field data. Sedimentologists produce seabed sediment models based on varied data and prior knowledge acquired through training or experience. The contributions of imagery, sediment penetrator and supervised classification systems and the improvement of associated data have reduced the need for interpretation and improved the quality of the models obtained. It is now possible to produce highly refined descriptions of all types of sedimentary environments and to measure the importance of sediment-forming process on physical properties. Sedimentary investigation of the seabed has made considerable progress in recent years, although this has not been taken into account in related sciences such as geoacoustics[9]. The differences found between the different geoacoustic models proposed, seem to show that there is no universal law. This is essentially due to the fact that the sand on a Mediterranean beach does not have the same properties as that of an Atlantic turbidite or sediment resulting from monsoon in the Indian Ocean, even if these sediments have the same mean grain size or the same porosity. There are many sources of differences between various environments: abrasion of grains, cohesion, nature of heavy minerals, presence of seashells or gas, proportion of organic carbon etc. At the present, it appears that the differences between the acoustic models and sedimentary data comes also from the classification used to describe sediments, which is *too reductionist* to deal with their complexity. An improvement in studies requires a classification of sediments which takes into account not only parameters from granularity, but also the mode of deposit and specific regional or local features.

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