The significance of seabed reflection coefficient derived from high frequency seismic data to marine sedimentary environment

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Abstract. In this paper, the physical and practical significance of seabed reflection coefficient are studied based on the seismic convolution model, which reveals that high frequency signal is sensitive to the acoustic impedance changing. Then based on the seismic data acquired in the west coast of Taiwan Strait used for case study, the seabed reflection coefficient is calculated in the light of sound pressure level and seabed reflected wave. In comparison with the results of geological sampling and analysis, the overall trend of fine particles correspond to lower reflection coefficient and coarse particles correspond to greater reflection coefficient. In addition, the abnormal values of the calculated reflection coefficient could indicate some abnormal phenomena at or near the seabed, which could also be identified from the seismic profile. In brief, the seabed reflection coefficient derived from high frequency seismic data could be used for studying the modern marine sedimentary environment. The reflection intensity might be a good indicator of hydrodynamics of sedimentation.

1. Introduction

Marine surface sediment is an important medium to reflect modern marine sedimentary environment. The physical and chemical properties of marine sediment have profound implications for the study of marine sedimentary environment.

High resolution sub-bottom profiler systems have been widely used for several decades. Generally, the sub-bottom profilers are used to produce high resolution images of the near-surfaces. In addition, sub-bottom profilers are also used for marine sediment classification and abnormal object recognition [1-6]. Recently, however, high resolution sub-bottom profilers are often regarded as ideal tools for revealing the geo-acoustic properties of surficial marine sediment. Typical case studies include the Sediment Acoustics Experiment in 1999 (SAX99) [7, 8] and in 2004 (SAX04) [9], the Asian Sea International Acoustic Experiment in 2001 (ASIAEX) [10], the Shallow Water Acoustic Program in 2006 (SW06) [11], the Quantifying, Predicting, and Exploiting Uncertainty Initiative Experiment in 2009 (QPE09) [12].

There are many factors that control the propagation and scattering of high frequency acoustic signal at or near the seabed, such as biological, biogeochemical, geological, and hydrodynamic processes operating at the benthic boundary layer [4, 13]. Bioturbation of sediments by benthic animals (burrowing, ingestion, defecation, tube building, biodeposition, cementation and metabolic activities)
affects the physical properties of marine sediments [14]. Conversely, the physical properties of marine sediments might be the indicators of benthic activity. Hence, there are also many studies dedicated to integrate the biological and physical data for marine habitat mapping and classification [14-17].

The study of marine sediments and their physical properties can also provide an important scientific basis for pre-marine development projects such as the laying of submarine cables and pipelines, the design and construction of the oil drilling platform and so on. However, the traditional method of sediment sampling and laboratory analysis is time and labor consuming. Geo-acoustic inversion is a promising solution to this situation and many related researches have been carried out as stated above. Reflection coefficient is one of the fundamental geo-acoustic parameters that could be deduced from seismic data, which could be used to reveal the physical properties of the surface sediments in some way.

2. Studying from seismic convolution model

2.1. Modelling the source signature

Sub-bottom profilers could be classified into many versions according to their operating principle or manufacturer. In this paper, the operating principle of sub-bottom profilers was described based on EdgeTech 3200XS, which is one of the versatile wideband frequency modulated (FM) sub-bottom profilers. The system transmits an FM pulse that is linearly swept over a full spectrum frequency range (also called “Chirp pulse”).

Generally, the FM pulse is calibrated to generate a spectrum with a Gaussian shape. It should be noted that Sinc shape and Cosine shape are also used frequently for the other version of profilers. In this paper, however, the “Chirp pulse” represents the linear frequency modulated signal with a Gaussian shape. In Figure 1, (a) presents the 5ms Chirp pulse from 1-10 kHz, which is used in the real data as an example; (c) presents the autocorrelation of the Chirp pulse, which is also called Klauder wavelet; (b) and (d) are the corresponding amplitude spectrum of (a) and (c). As showed in Figure 1(b) and Figure 1(d), the theoretical center frequency of the 5ms Chirp pulse from 1-10 kHz is 5.5 kHz.

![Figure 1](image-url) (a) The 5ms Chirp pulse, linearly sweeping from 1-10 kHz. (b) Amplitude spectrum of the Chirp pulse. (c) The autocorrelation of the Chirp pulse (Klauder Wavelet). (d) Amplitude spectrum of the Klauder wavelet.
2.2. Modelling the seabed reflector

As noted in the literature [4], there is an interlayer transition zone in the range of 0.05-0.3m thickness at the seabed. The thickness of the transition zone determines the acoustic impedance gradient. Figure 2 summarizes the results for a transition zone at the seabed. The thickness of the transition zone in the model ranges from 40 μs (approximately 0.032 m), 160 μs (approximately 0.128 m), 280 μs (approximately 0.224 m), to 400 μs (approximately 0.32 m), as showed in (a)-(d). The reflection coefficient in (e)-(h) are derived from the acoustic impedance in (a)-(d). The seismic trace in (i)-(l) are synthesized by the Chirp pulse described above and the reflection coefficient in (e)-(h), which are after matched filtering. The curve showed in (m)-(p) are the corresponding amplitude spectrum of the synthetic trace in (i)-(l).

Figure 2. Effects of acoustic impedance gradient at the seabed on the waveform and the amplitude spectrum of the matched filtered record (Modified from Bull’s model [4]).

The simulated results reveal that the acoustic impedance gradient at the seabed has a great influence on the waveform and the amplitude spectrum of the reflected wave. Since the seabed sediments are water-filled, the acoustic impedance of the seabed would mainly depend on the properties of solid particles.

According to the effective density fluid model developed by Williams et al. [7], the seabed reflection coefficient is weakly frequency dependent. For seabed reflection coefficient calculation from seismic data in practical examples, however, the reflected waves we picked for computation are always the response of the surface seabed zone instead of the ideal water/sediment interface. Hence, it is obviously that the seabed reflection coefficient derived from seismic data would be frequency dependent.

Based on the convolution model, it is possible to calculate the dependence of the reflection coefficients on frequency, as shown in Figure 3. The calculated reflection coefficients would be frequency independent when the seabed is a step change in acoustic impedance. However, instead of
the step change, the seabed is always a gradational change with acoustic impedance gradient changing over small vertical as well as lateral distance [4]. Hence, the calculated reflection coefficients would be frequency dependent.

In a word, the Chirp pulse in the above frequency band (several kilohertz) is sensitive to the variation of the surface seabed sediments and could be used to study the marine sediments and also the sedimentary environment.

Figure 3. Calculated reflection coefficients versus frequency based on seismic convolution model. The results of (a), (b), (c), (d) correspond to the convolution models shown in Figure 2.

Figure 4. Location of the survey line used for the case study. The results of geological sampling and analysis are also shown in the figure, which are gridding with natural neighbour interpolation.

3. Case study in the west coast of Taiwan Strait

3.1. Data acquisition
Acoustic reflection data were collected using the EdgeTech 3200XS Chirp sub-bottom profiler system with the tow vehicle of SB-0512i, which was towed at the starboard over the study area (see Figure 4). The transmission signal used was frequency modulated from 1-10 kHz with a sweep time duration of 5 ms (as shown in Figure 1). The ping rate of the survey line is 5 Hz and the trace spacing is about 0.46 m. According to the technical manual provided by EdgeTech, the acoustic power (also called “sound pressure level”) of the deck unit we used in this study is about 212 dB ref 1μPa peak at center frequency. This parameter would be used as source signature to calculate the reflection coefficient at the center frequency in the following section.

3.2. Data analysis and processing
Seismic data recorded as the EdgeTech standard format (JSF) file consists of a collection of trace records, including a 16 byte message header, a 240 byte trace header and trace data. The trace data in the JSF file are usually recorded in the form of analytic signal, which could be converted into envelope data and pressure amplitude data. The envelope data is beneficial to image the stratigraphic texture, while estimating the physical and acoustic properties needs the true amplitude information. Figure 5 presents the seismic profile used for case study, which was imaged according to the envelope data. However, the following calculations are totally base on the amplitude data.
Figure 5. The seismic profile used for case study, which was obtained in the west coast of Taiwan Strait.

The effect of spherical spreading should be taken into account when calculating the seabed reflection coefficient. Then after spherical spreading compensation, the energy of the reflected wave would be determined by the seabed reflection coefficient. Figure 6 presents the results of spectral analysis of the seabed reflectors, which reveal the energy distribution characteristics in frequency domain and spatial domain. The relative energy intensity around the center frequency could indicate the magnitude of the reflection coefficient in some ways.

Figure 6. Distribution of the relative energy intensity of seabed reflection in frequency domain and spatial domain.
According to the results of geological sampling and analysis, the survey line used for case study span the surface sediment types of clayey silt, silt, sandy silt and silty sand, which transit from fine particles to coarse particles. And according to the results shown in Figure 6, the reflection intensity of coarse particles is obviously greater than that of fine particles. However, in order to estimate the physical and acoustic properties of the seabed, reflection coefficient should be quantified.

3.3. Seabed reflection coefficient calculation

Seabed reflection coefficient could be calculated based on the reflected wave and incident wave, which needs the source signature to deduce the incident wave [18]. Without the source signature, seabed reflection coefficient could also be calculated according to the primary and secondary seabed reflection [4, 5, 10, 12, 19-21]. For the seismic data acquired in shallow water, however, the results derived from the latter method are illogical.

In this paper, without the source calibration experiment, we deduce the seabed reflection coefficient in the light of the theoretical sound pressure level and also the seabed reflection. And in order to reduce the influence of random noise, the calculated reflection coefficients could be averaged with a number of adjacent traces. In addition, the reflection intensity could be denoted by the reflection loss, which represents the reflection coefficient in decibels. Figure 7 presents the seabed reflection loss measurements of the survey line, which are averaged over 101 traces (about 46 m) in the spatial domain. The relative standard deviations in every computation window are also shown in the figure.

![Figure 7](image_url)

**Figure 7.** Seabed reflection loss calculated at the center frequency (5.5 kHz).

As described above, the survey line span the surface sediment types from fine particles to coarse particles, which indicates that the fine particles (soft) correspond to a lower reflection loss (reflection coefficient) and the coarse particles (hard) correspond to a higher reflection loss. In addition, the relative standard deviations shown at the bottom of Figure 7 also indicate the properties changing over lateral distances.

It should be noted that, the results are only deduced from the amplitude information at the center frequency since lacking some details of the actual Gaussian shape. However, as aforementioned, the Chirp pulse is a wideband frequency modulated signal and hence further research should be implemented to uncover more information in the seismic data. Moreover, the calculations are based on the assumptions of source stability and also spherical spreading.
3.4. Indications of abnormal value

As shown in Figure 7, there are many abrupt change sections along the seismic line, which might indicate some abnormal phenomena on the surface seabed. Here we compare the calculated reflection coefficient with the seismic profile of the traces from No.48001 to No.53000, as shown in Figure 8.

![Figure 8](image)

**Figure 8.** The selected abnormal values and the corresponding seismic profile. The upper part is the abnormal seabed reflection coefficient and the lower part is the corresponding sub-bottom profile.

It is obvious that the abnormal seabed reflection coefficients correspond to some abnormal phenomena at or near the seabed, as shown in the seismic profile. However, we would not try to discuss more due to lack of sufficient information.

4. Discussion and conclusions

The marine sedimentary environment is influenced by many factors, such as biological, biogeochemical, geological and hydrodynamic processes. According to the results of seismic convolution model, high frequency Chirp signals are sensitivity and hence small changes in the composition or geometry of the seabed would change the characteristics of seabed reflection, including waveform, energy, amplitude, and phase etc. This sensitivity characteristic provides the ability of sediment classification and object recognition from reflection data. However, it also results
in the inaccuracy of calculated reflection coefficient since interference from the marine environment might influence the calculation.

Taiwan Strait is an ideal area for scientific research in many subjects. According to the previous studies carried out at the Taiwan Strait [22, 23], the sediment characteristic was dominated by the submarine topography, the tidal action, the rivers’ carriers of Chinese Mainland and of Taiwan Island, the Kuroshio branch, the south China sea warm current, and the east China sea circulation. The overall trend of fine particles correspond to lower reflection coefficient and coarse particles correspond to greater reflection coefficient agree with the previous studies [2, 5, 6]. The surface sediment particles at the trough of Taiwan Strait are generally coarse might due to the scour effect of the bottom flow and hence they are more firm than that at the coastal area and correspond to a greater reflection coefficient. Furthermore, the high frequency Chirp signals are sensitive not only to the vertical property changing, but also to the lateral medium changing. For instance, the abnormal values of the calculated reflection coefficient indicate some abnormal phenomena at or near the seabed, which could also be identified from the seismic profile. However, more work should be implemented to explain these phenomena.

The seabed reflection coefficient derived from high frequency seismic data could be used for studying the marine surface sediments. In order to mine information hidden in the recorded data, more attributes should be derived from the raw data.

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