Proceedings of the Institute of Acoustics

SEDIMENT DENSITY PROFILES FROM REFLECTIONS OF BOOMER PULSES

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1. INTRODUCTION

Boomers have been used for many years as sound sources for sub-bottom profiling. Often the output has been a record on a graphics recorder, and the combined effects of monochrome recording, limited dynamic range of the paper medium, and non-traceability of run-time settings such as TVG has meant that only qualitative interpretation has been possible.

This paper describes a signal processing scheme for obtaining quantitative density data from the echoes of pulses from a commercial sub-bottom profiling system based around a boomer.

Our interest is in geotechnical properties of the sediment, particularly density and shear strength of soft sediments to depths of about 1 m. On the other hand the process of acoustic reflection is mediated by acoustic impedance, Z, given by

$$Z = \rho c$$

where ρ is the density and c the sound speed. The acoustic system measures impedance profiles, so ultimately the required geotechnical properties must be inferred from observed correlations between impedance and other properties.

2. SIGNAL PROCESSING TO OBTAIN IMPEDANCE PROFILES

To identify the requirements, we proceed from a first (oversimplified) approximation, via successive relaxations. The intention is to form a kind of "checklist" of the effects that should be considered.

2.1 First Approximation: Flat Homogeneous Sediment

The acoustic (amplitude) reflection coefficient, r, for the water-sediment interface is given by the Rayleigh formula (for normal incidence),

$$r = (R-1)/(R+1) \tag{1}$$

where R is the ratio of the acoustic impedance of the sediment to that of sea water. This reflection coefficient is independent of frequency.

The sediment impedance can be measured by determining r, and inverting equation (1). Spherical or other spreading of the sonar beam, TVG, and water column attenuation must be known, but apart from these requirements there are minimal constraints on the sonar.

Normal incidence reflections do not give the density and sound speed individually. They can be separated using the greater complexities involved in reflections over a range of angles, but at a cost in engineering and signal processing terms.

2.2 Relaxed Approximation: Thick Homogeneous Layers
The sonar must now have good enough range resolution (i.e sufficient acoustic bandwidth) to resolve the interfaces between layers. The impedances of the layers may be obtained by inversion of equation (1) successively at the interfaces. But there are extra considerations for the signal processing:
i) Attenuation of echoes from deep layers due to the overlying sediment;
ii) Additional signal structure in the echo due to multiple reflections among the sediment layers.

Attenuation in the sediment depends on sediment composition. It generally increases with increasing frequency [1-3].

Multiple reflections are a well-known problem in the processing of seismic signals, and algorithms exist for their removal [4,5].

2.3 Further Relaxation: Limit of Thin Layers
As the layers become thinner, tending in the limit to a continuously changing vertical profile, they will no longer be resolved as discrete layers. Deconvolution techniques become necessary to estimate such a continuous reflectance profile.

2.4 Further Relaxations: Undulating layers, Inhomogeneities
Undulations have the effect that the curvature of the reflected wavefront is modified, and with it the spherical spreading of the wavefront. The result is that the echo amplitude, as measured some distance away (e.g. near the sea surface) may be different from the case of a flat sediment layer.

Inhomogeneities may cause incoherent scattering, introducing signal components that are uncorrelated as the sonar is moved transversely. When processing specular reflections from sediment layers, scattering introduces a source of noise. However the scattered signal may in its own right contain valuable information about the sediment.

3. THE DSE SYSTEM

At DSE, we have developed a processing method for estimating shallow density profiles. The system uses as a sound source a boomer that is part of a Ferranti-O R E Geopulse sub-bottom profiling system . The boomer generates short very broadband intense pulses, at a sound pressure level that is typically above 212 dB (rel. 1 μPa at 1 m). The boomer equipment is deployed at the sea surface. This, and the fact that water depths to 100 m are of interest, means that the most easily acquired signals are closely normally-incident.

3.1 Hardware Used in the DSE System
The boomer is carried on a catamaran that is towed behind the survey vessel, at a speed of typically 4 knots.

The signal processing that we use requires the actual waveform transmitted by the boomer to be known. We find that this waveform is slightly variable, particularly in choppy sea conditions, probably associated with the very shallow depth of deployment. Thus it is necessary to monitor the transmitted pulse. The catamaran has been modified by adding a pole that positions a hydrophone approximately 2 m below the boomer. The hydrophone (nominal sensitivity -189 dB) monitors both the transmitted pulse and the delayed echo from the sediment.

The hydrophone signals after appropriate amplification are digitised using a plug-in analogue-to-digital converter board in an IBM-compatible PC. All subsequent signal processing is carried out digitally in the computer, in real time.

3.2 Signal Processing
The processing exploits the broad bandwidth of the sound source. Frequencies in the band 650 Hz to 15 kHz are processed. Figures 1 to 3 trace the progress of the signals through the various stages of processing.

Figure 1 shows examples of transmitted and echo waveforms. Note that the echo waveform has been amplified by (in this case) 420 times relative to the transmitted waveform, and the time offset between them is in reality (again in this case) 59 ms.

The first main step is deconvolution of the echo pulse against the transmitted pulse, resulting in an estimate of the impulse response that characterises the sediment reflection process. The deconvolution is effected in the frequency domain, by forming the quotient of the Fourier transforms of the echo and the transmitted pulses. The result is transformed back to the time domain.

Figure 2 (solid curve) shows the impulse response resulting from the deconvolution, that relates the two waveforms of Figure 1. Its amplitude has been adjusted to compensate for the relative amplifications of the waveforms of Figure 1, and for spherical spreading.

The impulse response at this stage represents a vertical sampling of the reflectance profile, which is in the most general case continuously varying. But it may still be distorted by multiple reflections within the layering. To remove multiples, we use a version of an algorithm that has been used in

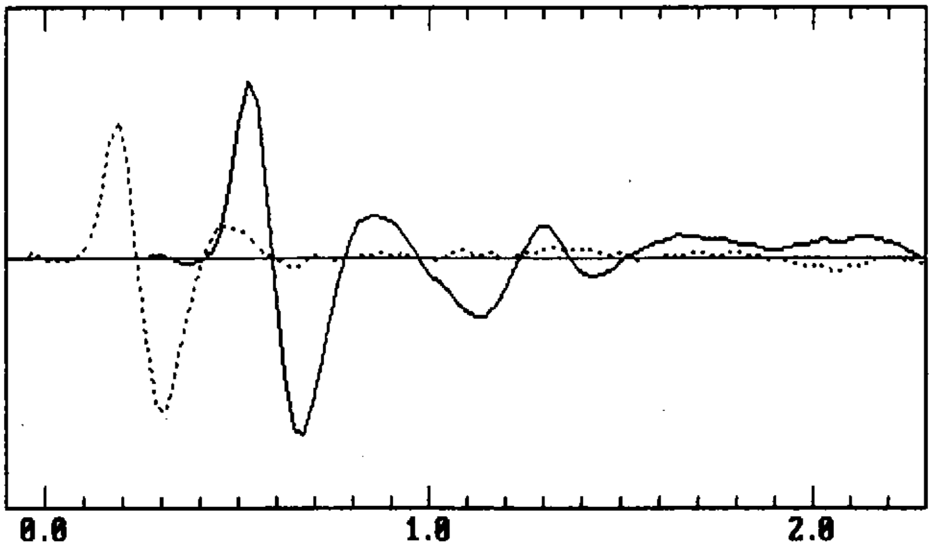

Figure 1: The transmitted (dotted) and sea floor reflection (solid) waveforms, as captured by the computer. The time scale is in milliseconds. Note that the arrival times indicated are arbitrarily offset; the true arrival times are 1.2 ms and 59 ms respectively.

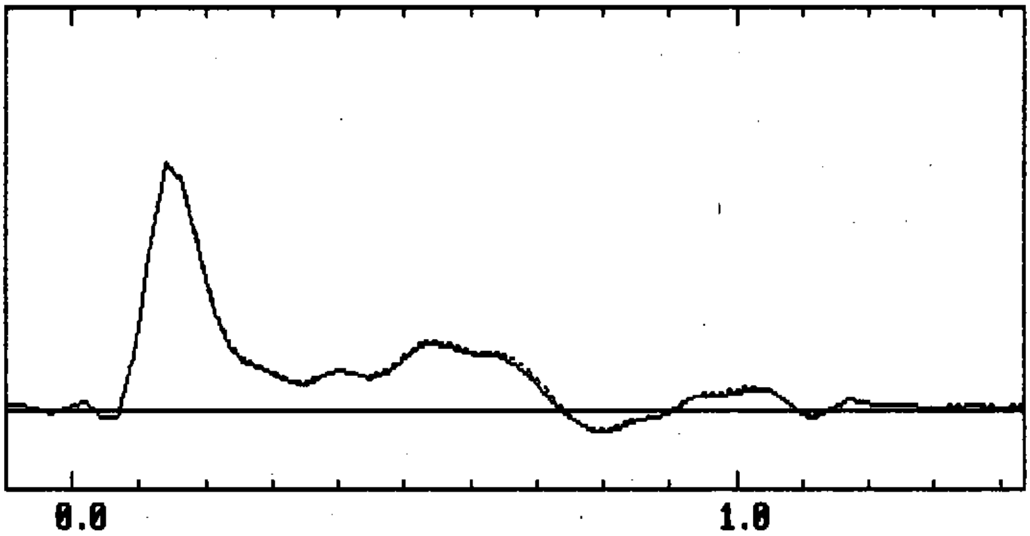

Figure 2: The sediment impulse response function (solid curve) that relates the two waveforms of Figure 1. Also shown (dotted) is the same function after correction for multiple reflections (see text). The timescale is milliseconds. The vertical scale has units of inverse time; full scale is 3330/s.

processing of signals from geophysical seismic explorations [4]. The dotted curve in Figure 2 is the reflectance function that has been obtained by subtraction of the multiples from the impulse response. (In this particular case the two curves are nearly indistinguishable.)

The final stage in forming an impedance profile is to use the inversion of equation (1) successively, working down through the reflectance profile solving for the impedances. The solid curve in Figure 3 shows the impedance profile derived from Figure 2.

It may be noted that in this impedance calculation no allowance has been made for attenuation in the sediment. The justification for this is that the broad features of the impedance profile are related to the low-frequency structure in the impulse response of Figure 2. In our case, these low frequencies are below 1 kHz. The results of measurements of sediment attenuation [1-3] indicate that for all reported sediment types, the attenuation at frequencies below 1 kHz is less than 0.6 dB per metre. Usually most of the sound is reflected from depths in the sediment of much less than the full 1 m depth of our profiles (refer Figure 2). For reflections from a depth of say 0.5 m, and an attenuation of 0.6 dB/m, the wave amplitude is reduced by about 7%. In most cases (i.e lower attenuation and shallower reflections) the effect will be less. The error induced in the impulse response will thus be limited to a few percent. There will however be a greater loss of signal at higher frequencies, resulting in a loss of detail in the resolution of deeper structure. The effect will be one of blurring the deeper parts of the profiles.

The processing described is usually carried out not on individual pulses but on averages of typically 10 to 100 pulses, gathered over a distance of up to 100 m. The reason for this is to reduce the effects of undulations and scattering that were mentioned above. Over some distance where the sediment is on average nearly flat (but not necessarily level) the curvature effects may be expected to average to smallish values. Likewise the incoherent averaging of scatter reduces its strength relative to the coherent averaging of echoes from layers.

3.3 From Acoustic Impedance to Geotechnical Properties

Finally, we proceed to estimate the properties of interest from the impedance profiles. For this, we must depend on observed correlations between impedance and other parameters.

3.3.1 Density: Sediment density is known to be highly correlated with impedance [6]. Figure 4 shows a compilation of density and impedance measurements from various sources [7,8]. All of these results are from core samples of coastal sediments. The high, but non-linear correlation is evident, although there are a few outliers.

The solid piecewise linear curve is the relationship that we have adopted to estimate density from acoustic impedance. The dotted profile in Figure 3 is

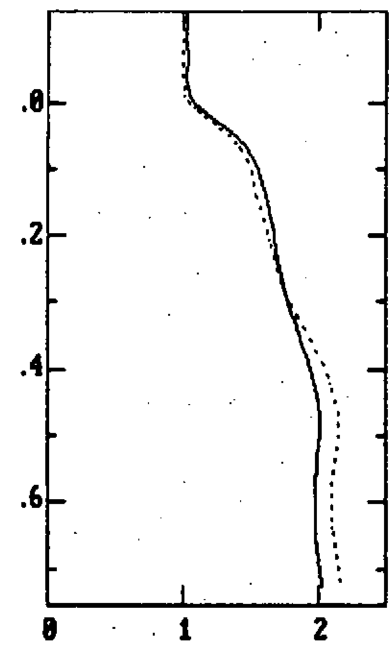

Figure 3: The vertical profiles of acoustic impedance (solid curve) and density (dotted curve) derived from Figure 2. The vertical scale is metres. The horizontal scale units are, for the impedance profile, impedance relative to sea water; for the density profile, density in g/ml.

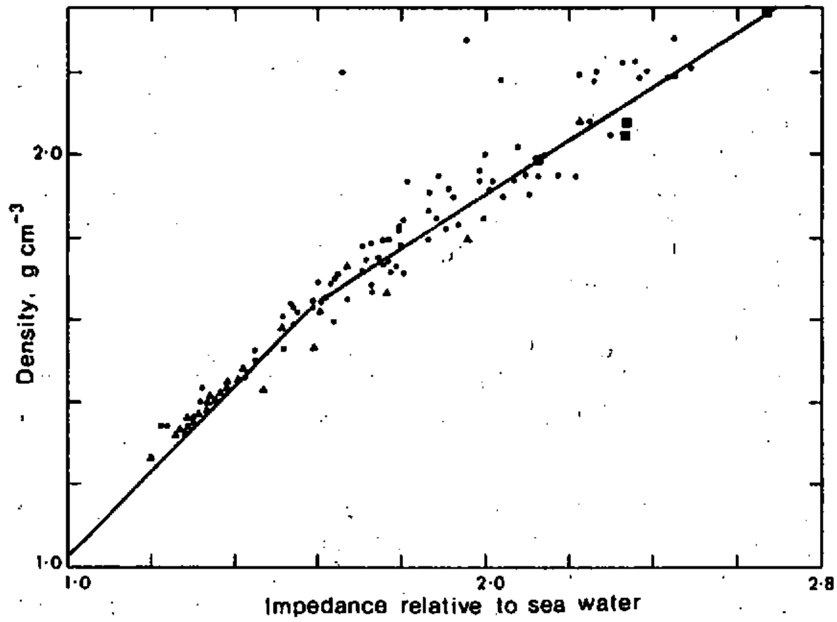

Figure 4: A compilation of measured sediment densities and impedances. Circles are from reference [7], triangles from reference [8] and squares are DSE unpublished measurements. The solid line is the relationship we use to estimate density from impedance.

the density profile associated with the impedance profile shown in the figure.

3.3.2 Shear Strength. During DSE's program of port surveys, measurements have been made of sediment shear strength using penetrometers. Figure 5 shows shear strength plotted against density (measured acoustically), as measured at a number of sites all within approximately 30 km of the port of Auckland. It is evident that there is substantial correlation between the two quantities, with a correlation coefficient of 0.85. The linear regression line is also plotted. Generally the correlation is tighter at low densities and shear strengths. The correlation is high enough to be useful in our investigations. The result however may not be valid at sites with sediments of different origin, or for higher densities.

4. EXAMPLES OF PROFILES

Two example profiles from among the thousands we have gathered are shown in Figure 6. The first was obtained on the crest of a rocky outcrop, recognised as such by the normal sub-bottom profiler record. The second was obtained about 100 metres away from the first, off the edge of the outcrop.

5. REFERENCES

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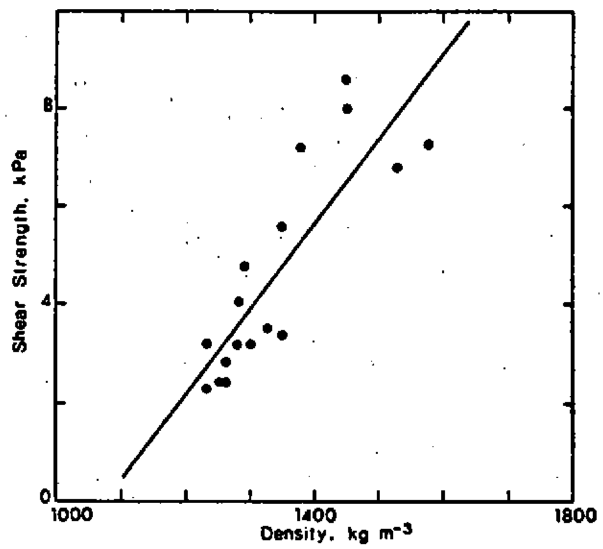

Figure 5: The empirical relationship between sediment density and shear strength, for sites in the vicinity of the port of Auckland.

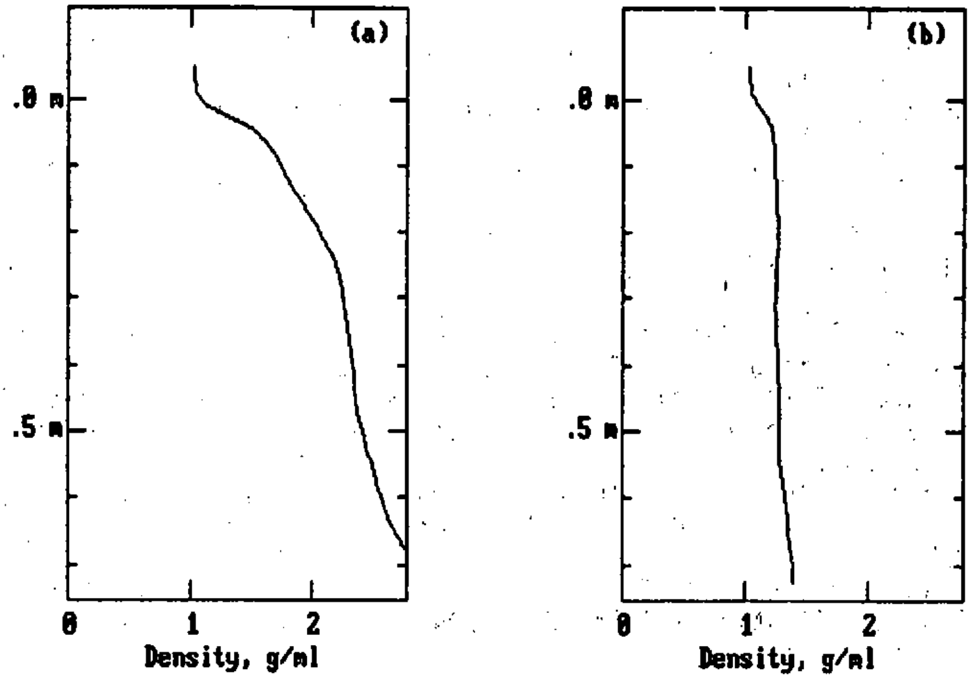

Figure 6(a & b): Two profiles obtained close to Auckland, from sites approximately 100 m apart. The high-density profile (a) is from on top of a rock outcrop. The profile (b) is off the edge of the outcrop.