THE COMPRESSIONAL WAVE AND PHYSICAL PROPERTIES OF INTER-TIDAL MARINE SEDIMENTS

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New quadratic regression equations for inter-tidal sediments are presented, which relate compressional wave properties (velocity ratio and proportionality constant) to porosity, bulk density and mean grain size. The compressional wave properties were derived from compressional wave velocities and attenuation coefficients measured on inter-tidal sediments from 16 - 100 kHz using common experimental and processing techniques. The regression equations are more robust for velocity ratio than proportionality constant. Discrepancies between the new regression equations and those derived for submerged sediments support the conclusion that the sediment structure of inter-tidal sediments differs from that of submerged sediments. This is attributed to the different physical processes which govern the supply, deposition and dynamics of the sediment in each environment.

1. INTRODUCTION

The ability to determine the geoacoustic properties of marine sediments is essential to sonar modelling techniques, such as those used for mine detection and anti-submarine warfare [1]. As both the geoacoustic and physical properties of the sediment will be determined by the sediment structure and marine environment, such properties will be inter-related [2]. This inter-related nature is typically utilised by sonar modellers, through the use

of regression equations to estimate a sediment's geoacoustic properties from its physical properties. Such an approach requires quantitative knowledge of these regression equations for a wide a range of sedimentary environments. Such information will also aid the inversion of geoacoustic properties obtained from high-resolution reflection profilers to obtain the physical properties of large regions of seabed [3].

Regression equations between the compressional wave properties and the fundamental physical properties (porosity, bulk density, mean grain size and sand/silt/clay fractions) have been presented by a number of authors, *e.g.* [2, 4-7]. Typically, in order to develop more universal regression equations, the compressional wave properties examined are carefully selected to account for certain location and experimental dependent variables. Firstly, the 'velocity ratio' v/v_w is calculated, where v and v_w are the compressional wave velocities in the sediment and pore water respectively. Secondly, extant research [5, 10-11] implies that effective attenuation coefficients α (*i.e.* frictional, viscous and scattering losses) are proportional to the insonifying frequency f, *i.e.*

$$\alpha = k \cdot f \qquad (1).$$

Hence, this research will make use of the proportionality constant k.

A number of forms of regression equation have been utilised, with single-variable quadratic regressions favoured over multiple-variable [4] and linear [6] forms. The most robust regressions [7] are derived from compressional wave velocities and attenuation coefficients measured *in situ,* at 38 kHz, using common experimental and processing techniques. Such techniques avoid the necessity of using both a compilation of geoacoustic data, obtained from a range of experimental programmes and techniques, or geaocoustic properties measured on sediment samples in the laboratory, for which sediment disturbance arguably affects the applicability of such relationships to *in situ* properties.

This work aims to expand our quantitative knowledge of the regression equations between geoacoustic and physical properties to inter-tidal sediments. Velocity ratios and proportionality constants, obtained from *in situ* compressional wave velocities and attenuation coefficients, are compared to porosities, bulk densities and mean grain sizes measured from sediment cores. The applicability of previously published regression equations determined for submerged siliciclastic sediments are investigated, namely those of Richardson and Briggs [7], Hamilton and Bachman [2] and Hamilton [5].

2. *IN SITU* TRANSMISSION EXPERIMENTS AND PROCESSING TECHNIQUES

Compressional wave properties were determined through a series of *in situ* transmission experiments that used the Sediment Probing Acoustic Detection Equipment (SPADE). This acoustic probe consists of a piezoceramic source and a pair of matched receivers. The *in situ* beam pattern of the source, which was required for the calculation of attenuation coefficient, was determined using a modified version of the impulse response method, the validity of which was confirmed though calibration water tests [8, 10].

The experimental procedure [8, 10] involved deploying the source and receivers vertically into the sediment to a common depth of approximately 1 m. A series of acoustic pulses, consisting of five shots at each central frequency from 16 to 100 kHz (in increments of 2 kHz) were emitted by the source and detected by the receivers. This procedure was repeated for between 3 and 7 source-to-receiver (S-R) separations, varying from 0.99 – 8.1 m.

The processing techniques developed have built on published acoustic transmission processing techniques, which are reviewed in [8]. A thorough error analysis was performed, in order estimate the degree to which certain assumptions (*e.g.* a homogeneous sediment and constant coupling between the transducers and the sediment) are relevant. The relevant

intrinsic errors were then incorporated into the total error budget. The group velocity was calculated from the travel time for the signal to be emitted by the source and detected by the receiver. This was measured using the correlation of the received signals with the electronic signals transmitted to the source amplifier. This approach was justified by the negligible discrepancies between the received and electronic signals [8]. In order to account for the time lag introduced by the probes and acquisition system, a linear least-squares fit was applied to travel time versus S-R separation for each frequency (the gradient of which represents the inverse of the velocity).

In order to obtain attenuation coefficient, unknown variables (such as the coupling of the transducers to the sediment and the Transmit Voltage Response of the source) must be accounted for. This was achieved by correcting the amplitudes of the received signals for spreading losses, and applying a weighted linear least-squares fit to the natural logarithm of the corrected amplitude against S-R separation (the gradient of which represents the effective attenuation coefficient) [8].

The physical properties of the sediments were obtained from push cores collected from each location. Porosity and bulk density were measured using a Multi-Sensor-Core-Logger (MSCL) [9], while grain size distributions were obtained from sediment samples using ¼ phi sieving analysis and an optical particle analyser. For each location mean values of porosity n, bulk density ρ and mean grain size M were determined, with standard deviations quoted as the relevant errors. Throughout the paper error bars for physical properties represent these standard deviations, while error bars for compressional wave properties represent intrinsic errors obtained from the thorough error analysis detailed in [8].

3. RESULTS AND DISCUSSION

A thorough examination of the frequency-dependence of the compressional wave properties of inter-tidal sediments is presented in [10]. This concludes that, in sands (within 95 % confidence limits) attenuation coefficient is proportional to frequency and velocity is non-dispersive. For silts attenuation coefficient is again proportional to frequency, while no frequency-dependence of velocity can be ascertained, owing to the observed variability of the measured velocities.
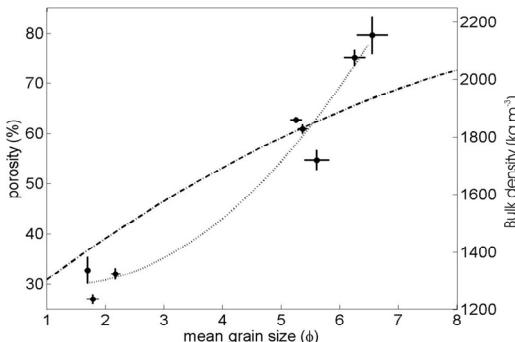

Fig. 1: The relationship between the porosity and mean grain size of the inter-tidal sites examined, including errors (crosslines), best fit regression (dotted line) and regression presented by Hamilton and Bachman [2] (dashed line). The equation of the best fit regression is presented in Table. 1.

The physical properties of the sediments are displayed in Fig. 1, along with the best fit regression between porosity and mean grain size. Discrepancies between the curvature of the current regression and that of Hamilton and Bachman [2] can be attributed to differences in grain roughness, with previous research supporting this conclusion (see Fig. 7 of ref. [12]). As the MSCL measures bulk densities from gamma-ray attenuation and determines porosity

from density using a standard equation [9], no additional information can be obtained by examining the dependence of bulk density on either porosity or mean grain size.

Variables	Regression equation	R^2
n (%) and M (ϕ)	$n=1.74 \cdot M^2-4.46 \cdot M+32.61$	0.960
v/v_w and n (%)	$v/v_w=1.03 \times 10^{-4} \cdot n^2-1.51 \times 10^{-2} \cdot n+1.53$	0.950
v/v_w and ρ (kg.m^{-3})	$v/v_w=3.92 \times 10^{-7} \cdot \rho^2-1.15 \times 10^{-3} \cdot \rho+1.82$	0.950
v/v_w and M (ϕ)	$v/v_w=9.01 \times 10^{-3} \cdot M^2-0.11 \cdot M+1.34$	0.941
k (dB.m^{-1}.kHz^{-1}) and n (%)	$k=1.82 \times 10^{-4} \cdot n^2-2.34 \times 10^{-2} \cdot n+0.892$	0.561
k (dB.m^{-1}.kHz^{-1}) and ρ (kg.m^{-3})	$k=6.93 \times 10^{-7} \cdot \rho^2-2.22 \times 10^{-3} \cdot \rho+1.918$	0.562
k (dB.m^{-1}.kHz^{-1}) and M (ϕ)	$k=9.00 \times 10^{-3} \cdot M^2-0.119 \cdot M+0.540$	0.548

Table 1: Quadratic regression equations for inter-tidal marine sediments, with goodness of fit values R^2. Parameters include porosity n, bulk density ρ, mean grain size M, velocity ratio v/v_w (where v and v_w are the compressional wave velocities in sediment and water respectively) and proportionality constant k. Limits of independent variables are: 27.0 – 79.6 % for porosity; 1356 - 2211 kg.m^{-3} for bulk density; and 1.7 – 6.3 φ for mean grain size.

Velocity ratios were obtained for the inter-tidal sediments using pore water velocities computed from measured salinities and temperatures [8]. Quadratic regression equations (Table 1) indicate that velocity ratios are strongly correlated with porosity, bulk density and mean grain size (Fig 2), which implies that these physical properties are the fundamental factors governing velocity. Because the range of porosities and bulk densities spanned by the silt sediments is greater than the corresponding range of mean grain sizes, velocities ratios fit less well to mean grain size (R^2 of 0.941) than porosity or bulk density (R^2 of 0.950).

The velocities predicted by Hamilton and Bachman [2] were converted into velocity ratios using the mean pore water velocities computed for the relevant temperature (23°C [2]) and salinities (33 to 35 [12]). These over-predict the measured velocity ratios (Fig. 2). Velocity ratios predicted from porosity using the Richardson and Briggs regressions, agree with those for inter-tidal sediments. However, values predicted from bulk density exceed measured values, while those determined from mean grain size under-predict in sands and over-predict in silts.

The discrepancies between the measured and predicted velocity ratios indicate that additional "latent" sediment properties, which differ between submerged and inter-tidal sediments, are affecting compressional wave velocities. The general over-estimation of measured velocity ratios by published regression equations can be explained through the rigidity of inter-tidal sediments being less than that of submerged sediments. Possible sources of this reduction in rigidity include different mineralogies, different rates of deposition, the geochemical alternation of submerged sediments, different clay fractions and the presence of rougher sediment grains in the inter-tidal sediments.

The quadratic regressions determined between the proportionality constants and the physical properties are presented in Fig. 3 and Table 1. These are less robust than those determined for velocity (R^2 of 0.548 - 0.562). One interpretation is that the proportionality constant is related to the fundamental physical properties through a more complex form than those investigated. Proportionality constants predicted by a more complex regression presented in the literature [5] agrees with measured values in medium to fine sands (1-2.5 ϕ) and medium silts (6-7 ϕ), Fig. 3. However, there are insufficient data to deduce the validity of this regression to inter-tidal sediments. Alternatively, additional "latent" physical properties may contribute significantly to attenuation losses, examples of which discussed in [8, 10]. These include squirt flow losses which are by affected by the clay fraction and scattering

losses which are affected by sediment heterogeneities with scales comparable to the acoustic wavelengths (>16 mm [10]) *e.g.* shells, pebbles and patches of sediment heterogeneity. Constants of proportionality predicted by the Richardson and Briggs regressions [7] do not agree with measured values, with discrepancies again attributed to different clay fractions, grain roughness and concentrations of sediment heterogeneities.
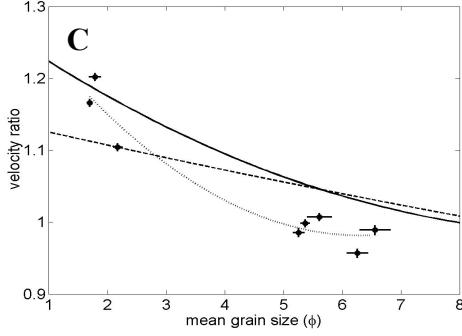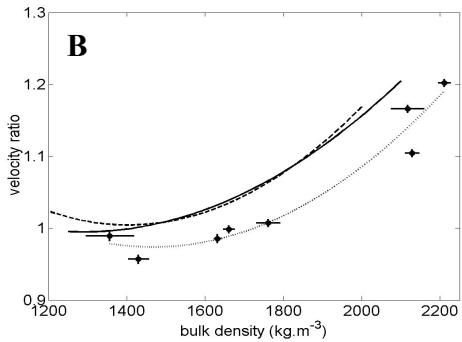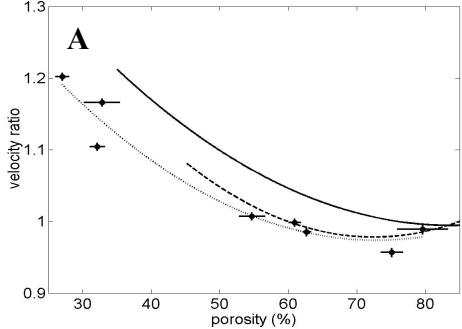

Fig. 2: The relationships between the velocity ratio and porosity (A), bulk density (B) and mean grain size (C) for inter-tidal sediments. Plots include the optimum regression equations (dotted lines), velocity ratios predicted by Hamilton and Bachman [2] (solid line) and Richardson and Briggs [7] (dashed line) and errors (crosslines).
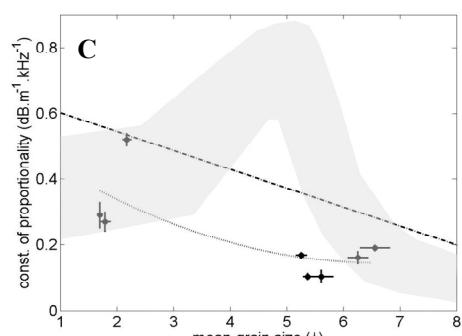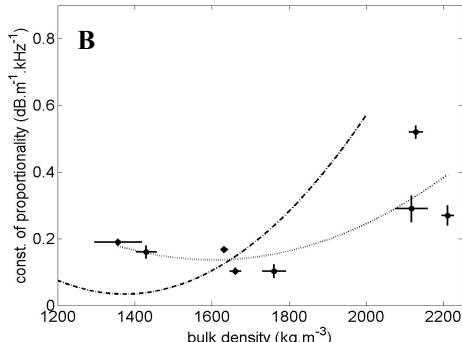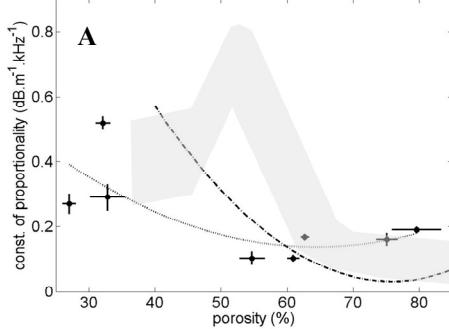
Fig. 3: The relationships between the proportionality constant and porosity (A), bulk density (B) and mean grain size (C) for inter-tidal sediments. Plots include the optimum regression equations (dotted lines), proportionality constants predicted by Hamilton [5] (shaded area) and Richardson and Briggs [7] (dashed line) and errors (crosslines).

4. DISCUSSION AND SUMMARY

This paper presents the first regression equations between compressional wave and physical properties for inter-tidal sediments, obtained using *in situ* compressional wave properties measured from 16 – 100 kHz. Discrepancies between these regressions and those previously presented for submerged sediments support the conclusion that the sediment structure of inter-tidal sediments differs from that of submerged sediments. This attributed to the different physical processes that govern the supply, deposition and dynamics of the sediment in each environment.

5. ACKNOWLEDGEMENTS

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