**UNIVERSITY OF SOUTHAMPTON**

FACULTY OF ENGINEERING, SCIENCE AND MATHEMATICS

Institute of Sound and Vibration Research

# The *in situ* compressional wave properties of marine sediments

by

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## ABSTRACT

The inversion of compressional wave properties is presently emerging as a technique for determining the geotechnical properties of marine sediments. However, the relationships required to perform such an inversion are still under debate, with further research required to resolve the dependence of compressional wave properties on both frequency and geotechnical properties. Though the use of *in situ* probes provides the most promising manner of examining these relationships, previous work in this field has encountered a number of experimental difficulties.

This work presents a series of well-constrained *in situ* transmission experiments. These were undertaken on inter-tidal sediments using a purpose built *in situ* device, the Sediment Probing Acoustic Detection Equipment (SPADE). Compressional wave properties were measured from 16 to 100 kHz in a range of sediment types (medium to fine sands and medium to fine silts), with several closely spaced locations examined at each general site to assess the local variability in compressional wave properties. Spreading losses, which were adjusted for sediment type, were incorporated into the data processing. Also included were a thorough error analysis and an examination of the repeatability of both the acoustic wave emitted by the source and the coupling between the probes and the sediment.

The results indicate that sands possess greater group velocities, greater effective attenuation coefficients and lower quality factors than silts, while the low velocities measured in silts imply that the bulk moduli of the silt sites examined are lower than expected owing to a considerable fraction of organic matter. Significant variations were observed in compressional wave properties, which were more reliably related to variations in geotechnical properties in sands than in silts. Group velocities were observed to be independent of frequency in sands within 95 % confidence limits, with no reliable frequency-dependence being determined in silts owing to variability in the measured values. Effective attenuation coefficients were proportional to frequency within 95 % confidence limits for the majority of the sand and silt locations examined. Results indicate that compressional wave properties can be used to determine porosity, bulk density and sand fraction, while the reliable determination of mean grain diameter from compressional wave properties in inhibited by the scatter in the data.

The results from this study were also used to assess the effectiveness of Biot Theory to predict the compressional wave properties of these sediment types. In sands, the Biot phase velocities agreed with measured group velocities, while Biot absorption coefficients were less than measured effective attenuation coefficients, owing to scattering or squirt flow not accounted for in the Biot Theory. In silts, Biot phase velocities are greater than measured group velocities, while Biot absorption coefficients generally agree with or are greater than measured effective attenuation coefficients. In silts, predicted velocities are greater than those measured, while absorption coefficients generally agree with or are greater than measured attenuation coefficients. The discrepancy between the measured attenuation coefficients and predicted absorption coefficients can be explained through the over-estimation of *in situ* porosities by the geotechnical measurement techniques adopted.

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## List of abbreviations used

| | |
|---|---|
| *dS* | Surface element of source transducer |
| *EGM* | Effective Grain Model |
| DSOP | Deep Sea Ocean Probe |
| FFT | Fast Fourier Transform |
| ISSAMS | *In Situ* Sediment Acoustic Measurement System |
| $\phi$ | Phi scale |
| R1, R2 etc | Receiver locations |
| R-R separation | Receiver-to-Receiver separation |
| SNR | Signal-to-Noise Ratio |
| $S_P$ | Active surface *of* source |
| SPADE | Sediment Probing Acoustic Detection Equipment |
| S-R separation | Source-to-Receiver separation |
| TVR | Transmit Voltage Response |
| X | Field-point |

## List of symbols used

| | |
|---|---|
| $\%E_{10}$ | Percentage of useful energy retained from $f_+$ to $f_-$ (%) |
| $\%CE$ | Percentage error associated with coupling variability (%) |
| $\alpha$ | Attenuation coefficient of sediment ($dB\cdot m^{-1}$) |
| $\alpha_n$ | Attenuation coefficient of sediment ($np\cdot m^{-1}$) |
| $\beta$ | Conversion constant (dimensionless) |
| $\gamma$ | Tortuosity (dimensionless) |
| $\gamma_o$ | Empirical constant used to obtain tortuosity (dimensionless) |
| $\delta(t)$ | Dirac pulse (dimensionless) |
| $\Delta E$ | Energy loss per cycle (joules) |
| $\Delta M$ | Variability of mean grain diameter (dimensionless) |
| $\Delta t$ | Time difference between sediment and reference signals (s) |
| $\varepsilon$ | Volume strain of the fluid in Biot Theory (dimensionless) |
| $\xi(t)$ | Analytical voltage signal (V) |
| $\eta$ | Viscosity of pore water (Pa·s) |
| $\eta_1(T)$ | Viscosity of pure water (Pa·s) |
| $\theta$ | Angular dimension of source transducer (degrees) |
| $\kappa$ | Wave number ($m^{-1}$) |
| $\kappa_o$ | Dominant wave number ($m^{-1}$) |
| $\lambda$ | Wavelength (m) |
| $\mu$ | Shear modulus (Pa) |
| $\mu'$ | Imaginary part of complex shear modulus of sediment (Pa) |
| $\pi$ | 3.1416 (to 4 decimal places) |
| $\rho$ | Bulk density of sediment ($kg\cdot m^{-3}$) |
| $\rho_c$ | Mass coupling between solid and fluid ($kg\cdot m^{-3}$) |
| $\rho_e$ | Error in bulk density ($kg\cdot m^{-3}$) |
| $\rho_f$ | Density of pore water ($kg\cdot m^{-3}$) |
| $\rho_r$ | Density of mineral grains ($kg\cdot m^{-3}$) |
| $\rho_w(T)$ | Temperature–dependent density of pure water ($kg\cdot m^{-3}$) |
| $\rho_{11}$, $\rho_{12}$, $\rho_{22}$ | Coupled densities used in Biot Theory ($kg\cdot m^{-3}$) |
| $\sigma$ | Sorting ($\phi$) |
| $\sigma_m$ | Standard deviation in the gradient of linear least-squares fit |
| $\sigma_i$ | Error on ith measured value |
| $\sigma_Q$ | Error in quality factor (dimensionless) |
| $\sigma_V$ | Error in velocity ($m\cdot s^{-1}$) |
| $\sigma_\alpha$ | Error in attenuation coefficient ($dB\cdot m^{-1}$) |
| $\tau$ | Period of the dominant oscillation in the pulse (s) |
| $\tau_i$ | Period of *voltage output pulse* (s) |
| $\tau_r$ | Period corresponding to central frequency of received pulse (s) |

| | |
|---|---|
| $\phi_x$ | Grain diameter corresponding to the $x^{th}$ percentage point ($\phi$) |
| $\chi^2$ | Chi-squared value (dimensionless) |
| $\psi(t)$ | Impulse response of the transducer (dimensionless) |
| $\omega$ | Angular frequency ($rad{\cdot}s^{-1}$) |
| $\omega_o$ | Dominant angular frequency ($rad{\cdot}s^{-1}$) |
| $a$ | Pore size parameter (m) |
| $A(f,d)$ | Amplitude of received pulse at frequency $f$ and S-R separation d (V) |
| $A(x,t)$ | Amplitude of acoustic wave at distance x and time t (V) |
| $A(x_1)$, $A(x_2)$ | Peak amplitude of the waves which have propagated though distances $x_1$ and $x_2$ (V) |
| $A_C$ | Corrected amplitude (V) |
| $A_{CO}$ | Conditioned amplitude (V) |
| $A_e$ | Error in the corrected amplitude (V) |
| $A_o$ | Amplitude of acoustic wave at $t=0$ and $x=0$ (V) |
| $A_p(y,z)$ | Amplitude of predicted pressure field at field-point $(y,z)$ (V) |
| $A_{s1}$, $A_{s2}$ | Amplitudes of signals at probes 1 and 2 for propagation through sediment (V) |
| $A_{w1}$, $A_{w2}$ | Amplitudes of signals at probes 1 and 2 for propagation through water (V) |
| $b$ | Coefficient of damping in Biot Theory ($Pa{\cdot}s{\cdot}m^{-2}$) |
| $B_1$, $B_2$, $B_3$, | Constants used in processing of received amplitudes (dimensionless) |
| $B_i$ | Bandwidth of *voltage input pulse* (kHz) |
| $B_o$ | Bandwidth of *voltage output pulse* (kHz) |
| $C$ | Coupling parameter (dimensionless) |
| $c_1$ | Velocity at a frequency of zero ($m{\cdot}s^{-1}$) |
| $c_2$ | Attenuation coefficient at a frequency of zero ($dB{\cdot}m^{-1}$) |
| $c_3$ | Quality factor at a frequency of zero (dimensionless) |
| $Cl$ | Volume chlorinity ($kg{\cdot}m^{-3}$) |
| $C_m$ | Scaling factor (dimensionless) |
| $D(mm)$ | Grain diameter (mm) |
| $D(\phi)$ | Grain diameter ($\phi$) |
| $d$ | Probe separation (m) |
| $dA_1$ | Error in amplitude arising from median stack (V) |
| $dB(y,z)$ | Pressure field at field-point $(y,z)$ (dB) |
| D | Parameter used in Biot Theory |
| $D_o$ | Standard grain diameter (mm) |
| $D_{50}$ | Grain diameter of 50th percentile point ($\phi$) |
| $d_o$ | Near-to-far field transition (m) |
| $DT$ | Error in arrival time (s) |
| $dt_1$ | Intrinsic timing error of the acquisition card (s) |
| $dt_2$ | Timing error associated with cross correlation process (s) |
| $dX$ | Separation of source elements along X axis (m) |
| $dY$ | Separation of source elements along Y axis (m) |
| $e$ | Volume strain of the solid frame in Biot Theory (dimensionless) |

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|---|---|
| $E$ | Mean energy per cycle (joules) |
| $E_{10}$ | Amount of "useful" energy retained from frequencies $f_+$ to $f_-$ (joules) |
| $E_T$ | Amount of "useful" energy retained from frequencies $f_1$ to $f_2$ (joules) |
| $f$ | Frequency (Hz) |
| $f_+$, $f_-$ | Frequencies corresponding spectral amplitudes 10 % of the peak value (kHz) |
| $F_1(T)$, $F_2(T)$ | Temperature-dependent terms in *Equations A.2* ($kg \cdot m^{-3}$) |
| $f_1, f_2$ | Frequencies corresponding spectral amplitudes 1 % the peak value (kHz) |
| $F_3(T)$, $F_4(T)$ | Temperature-dependent terms in *Equations A.3* (Pa) |
| $F_5(T)$, $F_6(T)$, $F_7(T)$ | Temperature-dependent terms in *Equations A.4* |
| $f_c$ | Generic central frequency (kHz) |
| $f_i$ | Central frequency of *voltage input pulse* (kHz) |
| $f_o$ | Central frequency of the *voltage output pulse* (kHz) |
| $f_r$ | Central frequency of the received signal (kHz) |
| $f_s$ | Sampling frequency (kHz) |
| $G(f,d)$ | Spreading losses at frequency f and S-R separation d (dB) |
| $G(x)$ | Spreading losses distance x from the source (dB) |
| $G(x_1)$, $G(x_2)$ | Spreading corrections distances $x_1$ and $x_2$ from the source (dB) |
| $H$ | Height of source transducer (m) |
| $HR$ | Hydraulic Radius (m) |
| $i$ | $(-1)^{1/2}$ (dimensionless) |
| $k$ | Permeability ($m^2$) |
| $K$ | Bulk modulus of sediment (Pa) |
| $K'$ | Imaginary part of complex bulk modulus of sediment (Pa) |
| $k_A$ | Constant of proportionality in attenuation coefficient power law ($dB \cdot m^{-1} \cdot kHz^{-1}$) |
| $K_b$ | Frame bulk modulus (Pa) |
| $K_f$ | Bulk modulus of the pore water (Pa) |
| $k_h$ | Hamillton's parameter ($dB \cdot m^{-1} \cdot kHz^{-1}$) |
| $k_o$ | Constant in Kozeny-Carmen Equation (dimesionless) |
| $K_r$ | Bulk modulus of mineral grains (Pa) |
| $K_w$ | Bulk modulus of pure water (Pa) |
| $L_+$, $L_-$ | Positive and negative limit parameters (dimensionless) |
| $m_o$ | Gradient of the linear least-squares fit |
| $m$ | Integer (dimensionless) |
| $M$ | Mean grain diameter ($\phi$) |
| $M_D$ | Dry mass (kg) |
| $mean(A_{CO})$ | Mean conditioned amplitude (V) |
| $M_{max}$ | Maximum grain diameter (μm) |
| $M_{min}$ | Minimum grain diameter (μm) |
| $M_T$ | Saturated mass (kg) |
| $n$ | Porosity (%) |
| $N_1$ | Number of samples in the Blackman-Harris window (dimensionless) |

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|---|---|
| $N_2, N_3$ | Number of integration steps in pressure field model (dimensionless) |
| $N_3$ | Number of steps in FFT (dimensionless) |
| $n_e$ | Error in porosity (%) |
| $N_p$ | Number of data points to which least-squares linear fit is applied (dimensionless) |
| $N_S$ | Number of shots stacked (dimensionless) |
| $P$ | Pressure (atmospheres) |
| $P_b$ | Lamé constant in Biot Theory (Pa) |
| $P(X,t)$ | Pressure at field-point $X$ and time $t$ (Pa) |
| $P(y,z)$ | Maximum pressure at field-point $(y,z)$ (Pa) |
| $P_o$ | Maximum pressure at reference point (Pa) |
| $Q$ | Quality factor (dimensionless) |
| $Q_g$ | Correction for saturated sediment in Gassmann's Equation (Pa) |
| $q$ | Exponent of frequency in attenuation coefficient power law (dimensionless) |
| $Q_A$ | Constant of proportionality in relationship between quality factor and frequency ($kHz^{-1}$) |
| $Q_b$ | Measure of coupling between volume change in solid and fluid (dimensionless) |
| $R$ | Distance between the field-point $X$ and the surface element $ds$ (m) |
| $R_b$ | Pressure required to force a volume of fluid into aggregate (Pa) |
| $r$ | Radius of source transducer (mm) |
| $R'$ | Minimum distance between the field-point $X$ and transducer surface (m) |
| $R^2$ | Goodness of fit (dimensionless) |
| $R_e(f)$ | Frequency-dependent electronic gain of the receiving amplifiers (dB) |
| $R_T(f)$ | Frequency-dependent response of the receiving transducers (dB) |
| $S$ | Salinity |
| $S_n$ | SNR enhancement by median stack (dimensionless) |
| $S_T(f)$ | Frequency-dependent TVR of source transducer (dB) |
| $std(A_{CO})$ | Standard deviation of the conditioned amplitudes (V) |
| $T$ | Temperature ($^oC$) |
| $t$ | Time (s) |
| $t'$ | Convolution time variable (s) |
| $t_A$ | Arrival time (s) |
| $t_1$ | Propagation time from furthest point on source to field-point X (s) |
| $T_i$ | Duration of the *voltage input pulse* (s) |
| $t_l$ | Length of the pulse (s) |
| $t_{lag}$ | Unknown lag time (s) |
| $t_{ny}$ | Nyquist time (s) |
| $T_o$ | Duration of the *voltage output pulse* (s) |
| $t_R$ | Time at which cross-correlation of received pulse and *voltage output pulse* peaks (s) |
| $t_o$ | Time of initial arrival at field-point X (s) |

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|---|---|
| $t_S$ | Time taken for pulse to travel through the sediment (s) |
| $t_V$ | Time at which correlation of received signal and *voltage output signal* peaks at (s) |
| $v$ | Compressional wave velocity of sediment ($m \cdot s^{-1}$) |
| $v_A$ | Constant of proportionality in relationship between velocity and frequency ($m \cdot s^{-1} \cdot kHz^{-1}$) |
| $v_I$ | Constant term in *Equations A.1* ($m \cdot s^{-1}$) |
| $Var_E$ | Variance of data from model predictions |
| $Var_T$ | Total variance of data |
| $v_g$ | Group velocity ($m \cdot s^{-1}$) |
| $V_O(f)$ | Peak-to-peak voltage of the voltage output pulse (V) |
| $V_{ph}$ | Phase velocity ($m \cdot s^{-1}$) |
| $v_P$ | Pressure-dependent term in *Equations A.1* ($m \cdot s^{-1}$) |
| $V_S$ | Saturated volume ($m^3$) |
| $v_S$ | Salinity-dependent term in *Equations A.1* ($m \cdot s^{-1}$) |
| $v_T$ | Temperature-dependent term in *Equations A.1* ($m \cdot s^{-1}$) |
| $v_{TSP}$ | Temperature, Salinity and Pressure dependent term in *Equations A.1* ($m \cdot s^{-1}$) |
| $V_W$ | Volume of pore water ($m^3$) |
| $v_w$ | Compressional wave velocity of water ($m \cdot s^{-1}$) |
| $W(f)$ | Spectral amplitude at frequency $f$ (dimensionless) |
| $W(\omega)$ | Spectral amplitude at angular frequency $\omega$ (dimensionless) |
| $W_P$ | Peak spectral amplitude (dimensionless) |
| $x$ | Distance (m) |
| $\hat{x}(t)$ | Hilbert transform of signal x (V) |
| $x(t)$ | Voltage signal (V) |
| $Y_1$, $Y_2$ | Offset (m) |
| $Y_i$ | $i^{th}$ predicted value |
| $y_i$ | $i^{th}$ measured value |