Shear-wave velocities in shallow marine sediments
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Summary
Shear-wave velocities in shallow (0 to 130 m deep) marine sediments are obtained from offshore Brazil. The data, acquired in-situ, consisted of both direct velocity measurements and indirect (geotechnical) predictions. Expressions to correlate $V_S$ and depth for shallow marine sediments were derived empirically. We find that $V_S=48z^{0.44}$ ($z$ is in m and $V_S$ in m/s) fits the data closely. This equation describes the sediment shear velocity in the 130 m directly below the ocean floor. This expression predicts values similar to those by Hamilton (1976), but matches very shallow data more closely.

Introduction
Analyses of marine seismic data acquired using the ocean bottom cable (OBC) technique generally require some knowledge of the physical properties of marine sediments. The shallow sedimentary section may be especially important, as dramatic changes in elastic parameters are common over small distances. This may affect various algorithms, as for example P-P and P-S wave separation, static corrections, and velocity analysis. In this paper, geotechnical data are used, through correlation to direct $V_S$ measurements, to obtain values for shear-wave velocities in shallow marine sediments. The values obtained in this work were used, together with additional literature data, in analyses of mode-conversion (P- to -S and S- to -P), for both up- and down-going seismic energy at sea-bottom and in shallow marine sediments (Rodriguez-Suarez et al., 2000).

Physical properties of marine sediments: overview of literature data
Hamilton (1976,1979) has one of the first overviews of S-wave velocities in marine sediments. In the earlier paper, he obtained empirically the expressions ($z$ is depth in meters, $V_S$ in m/s), for silt clays and turbidites,

\[ V_S = 116 + 4.65z \quad 0 < z < 36 \]
\[ V_S = 237 + 1.28z \quad 36 < z < 120 \]

In the second paper, he found an empirical relation between $V_P$ and $V_S$ (and $V_P/V_S$ values) for marine sediments. In both articles, he used in-situ measurement data from different geographical locations, water depths, and lithologies. For siliciclastic sediments, he found $V_P/V_S$ ratios of around 13 for shallow sediments, decreasing to around 2.6 at a 1 km depth. For sands, $V_P/V_S$ ratios have high gradients in the first metres, from around nine at 5 m and decreasing to six at 20 m. He had no measurements for unconsolidated or soft limestones. As a final remark, he reiterated that very shallow sediments might have very high $V_P/V_S$ ratios. He reported a value of 46, and believed that even higher values might be found. The hypothesis of very high values for $V_P/V_S$ ratios is possible when the porosity goes over 60%, as the material is not unconsolidated sediment anymore. Instead, it is a suspension of grains in salty water; in such case, $V_S$ approaches zero.

It should be pointed that although Hamilton expected very low $V_S$ values in very shallow (less than 10 m) marine sediments, the use of his equations gives values consistently higher than real data measurements (Richart et al., 1970; Breeding et al., 1991; Lavoie and Anderson, 1991; this report). This may be due to rapid vertical changes in physical properties of very shallow sediments regarding shear-wave propagation, not considered in his empirical derivations.

For very shallow marine sediments, Breeding et al. (1991), Briggs (1991), and Richardson et al. (1991) report Biot (1956a,b) poroelastic and Bryan and Stoll (1988) models to have better agreement with measurements.

Richardson et al. (1991), analyzing the upper two meters of sediments in shallow water, conclude that the shear modulus is controlled by consolidation for sands, but for fine-grained sediments, other processes are important. Again, according to the authors, $V_S$ values predicted by Hamilton (1976) and Bryan and Stoll (1988) near the sea bottom are often higher than measured values. Theilen and Pecher (1991), using core analyses and in-situ measurements from the upper nine metres of sediments in the Barents Sea, found small variation in $V_P$ but a rapid increase (from 10 to 40 m/s) in $V_S$. Duennennier and Sutton (1995) consider a value of 20 m/s appropriate for $V_S$ in high-porosity shallow marine sediments in ocean bottom seismometers (OBS) coupling problem analysis. They relate $V_S$ values between 10 and 40 m/s from the literature. Ayres and Theilen (1999) present data for near-surface sediments (upper 9 m) from the continental slope of the Barents Sea. S-wave velocities are much more sensitive to lithology changes than P-wave (which has a narrow range of velocity values). Sandy clays, marls, and oozes cover most of the floor of Barents Sea continental slope. The sediments have unexpected over-consolidation in the upper meter. $V_S$
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varies between 9 and 47 m/s.

S-wave velocities from offshore Brazil: direct measurements and geotechnical data

The data used in this section to obtain elastic parameter came from: 1) direct \( V_S \) measurements and 2) geotechnical data, both obtained from offshore Brazil. The ocean-bottom data were acquired at water depths varying from 20 to 2,000 m and with lithologic compositions varying from sand to shales and oozes to limestones. Depths from zero to 132 m below the sea floor were analyzed at 30 different locations.

The direct \( V_S \) measurements used the seismic cone penetrometer technique, a small VSP-like survey. In this survey, it is possible to combine standard geotechnical tests with in-situ \( V_S \) measurements in the same acquisition. Shear waves, generated in the sea floor by a hydraulic driven spring hammer, are recorded by two orthogonal geophones, mounted horizontally in a piezocone penetrometer. Responses from both geophones are considered in the velocity calculation. An umbilical cable connects the geophones to a seismograph. In general, the shear-wave source is activated several times for a constant geophone depth, to increase signal-to-noise ratio. Interval velocities are obtained directly between two successive measurement depths. An acquisition scheme is shown in Fig. 1. More information about this technique can be found in Robertson et al. (1986) and de Lange (1991).

In the Brazilian data, velocity measurements were obtained at approximately every five metres. Direct measurements of \( V_S \) were performed in six different locations over distinct Brazilian offshore oil and gas fields. Pure geotechnical data (without \( V_S \) measurements) from 24 locations, also over Brazilian oil and gas offshore fields, were also used in the analyses presented here. The geotechnical data was acquired to support analyses of offshore installations (drilling and production platforms and pipelines) on the sea bottom. Density information was available in all 30 locations.

To use pure geotechnical information as a source of shear-wave velocity, it is necessary to establish a correlation between the 'geotechnical' shear modulus (also called shear strength, or \( S_U \)) and the 'dynamic' shear modulus, or Lame’s constant, \( \mu \). The dynamic shear modulus defines shear-wave velocity according to the well-known expression

\[
V_s = \sqrt{\mu/\rho},
\]

where \( \rho \) is density.

The dynamic modulus derivation is based on very small strain (less than \( 10^{-6} \)) and a linear stress-strain regime (Hooke's Law is valid). Geotechnical (or the engineering) modulus, however, in general is related to the material break point, involving much larger strains, where Hooke's Law may not be applicable (the strain-stress relation is not linear anymore). Nevertheless, some relation between the two parameters is intuitively expected. Richart (1975), based on land data, found that \( V_S \) measurements in-situ could be used as an indication for \( S_U \). Some published discussions about this correlation are presented below. In general, the authors are interested in the inverse problem – to obtain geotechnical parameters from seismic measurements. 

Fig. 1 – Schematic diagram of offshore system for acquiring \( V_S \) and conventional geotechnical data (after de Lange, 1991).

Theilen and Pecher (1991), analyzing cores from the upper nine metres of sediments in the Barents Sea, found a linear correlation between in-situ estimations of geotechnical and dynamic modulus – the dynamic values being around 200 times higher than the geotechnical ones (Fig. 2). The authors believe specific
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correlations may be obtained for distinct kinds of sediments. Baldwin et al. (1991) also obtained $S_U$ and $V_S$ (using a 1.5 kHz signal) in samples of marine clays from the Canadian Beaufort Sea (50 m water depth) and Portsmouth (New Hampshire, USA). Unlike the data presented here, their measurements were not in-situ. They also found linear relation between $S_U$ and $V_S$, but by a factor that was a function of sediment consolidation.

In the data presented here, depth-variant correlation factors were obtained by averaging information from the six locations where both $S_U$ and $V_S$ were acquired. These factors $f$ were calculated simply by the expression

$$ f = \frac{\mu}{S_U} $$

The results, shown in Fig. 3, were used for $V_S$ calculations in the remaining 24 locations where only $S_U$ was available. The picture shows that shear strength decreases remarkably compared to shear modulus for very shallow sediments, which would be intuitively expected. It also shows that the correlation factor value of 200, obtained by Theilen and Pecher (1991) for depths between 0 and 9 m, occurs here around 10 m, being higher for shallower sediments.

The velocity values obtained from averaging $V_S$ from all 30 locations are presented in Fig. 4. Also shown, for comparison, are the values expected from Hamilton expressions. In general, there is a reasonable agreement between Brazilian sediments values and Hamilton results. The most remarkable discrepancies are around 35 m and in the very shallow (less than 10 m) section. At 36 m Hamilton defined a boundary, using one expression for sediments above it and another for sediments below. Regarding sediments above 10 m, it has already been mentioned that values from Hamilton expressions are higher than what is generally found in the literature. Simple inspection of his equations indicates that, immediately below the sea floor, $V_S$ is over 100 m/s, what, in general, is not observed in most marine sediments (Hovem et al., 1991).

Using the measurements from all 30 locations, an empirical second-order equation, based on least-square best fit, was obtained. Also empirically derived was an exponential expression. They are:

$$ V'_S = 91.68 + 4.46z - 0.017z^2 \quad (1) $$

$$ V'_S = 48z^{0.4387} \quad (2) $$

$z$ is depth in meters from 0 to 130 m, $V_S$ is in m/s.

Values from both equations are presented in Fig. 4. The two empirical expressions give closer results. Values from the 2nd order equation are higher than measured data in the very shallow (above 10 m) sediments, while the exponential expression deviates from the measurements trend below 100 m.

It should be stressed that these equations are general, and do not consider aspects that may be important, such as lithology, consolidation, water depth, and so on. Nevertheless, they provide an excellent first guess for $V_S$ in shallow marine sediments. This may be especially true for geological environments similar to offshore Brazil – namely, extensional marine basins younger than Jurassic.
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Fig. 4 – $V_s$ obtained from averaging in-situ direct and indirect (geotechnical) data in 30 locations offshore Brazil (continuous line). Also shown for comparison are values expected from Hamilton (dashed) and 2nd order (dash-dot) and exponential (dotted) fit equations of the continuous line data.

Conclusions

Shear-wave velocities in shallow marine sediments were calculated from direct velocity measurements and indirect (geotechnical) data from in-situ measurements offshore Brazil. Using best fit, empirical expressions correlating $V_s$ to depth were derived. These equations give values similar to Hamilton but predict shallower velocities better.

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References


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