Sea-bottom shear-wave velocities and mode conversions

Carlos Rodriguez-Suarez and Robert R. Stewart

ABSTRACT

Elastic parameters for shallow marine sediments are compiled using literature data (e.g., Hamilton, 1976;1979) and geotechnical data from offshore Brazil. The Brazilian data showed good agreement with Hamilton's results. Analyses of transmission and reflection coefficients for compressional- and shear-wave energy mode conversion using Zoeppritz equations were performed for both sea bottom and typical Tertiary sediment interfaces. We conclude, from previous published data and our results, that most S-wave reflection data recorded on the ocean floor are related to energy upcoming energy converted at an interface at depth and not from a downgoing shear conversion at the ocean floor.

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 effect various algorithms, for example, P-P and P-S wave separation, static corrections, and velocity analysis.

In this report, we present a study on the energy mode conversion that occurs at the sea floor and compare it with reflected conversions at a representative interface of Tertiary sediments.

PHYSICAL PROPERTIES OF MARINE SEDIMENTS

Some of the first analyses of S-wave velocity in marine sediments were done by Hamilton (1976; 1979). In the earlier paper, he obtained the expression $V_S = 128z^{0.28}$ (z depth in meters) for sands and $V_S = 116 + 4.65z$ for silty clays. In the second, he found an empirical relation between V_P and V_S (and V_P/V_S values) for marine sediments. 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 meters, 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 may have very high V_P/V_S ratios. He reports a value of 46, and believed that even higher values may be found. We think this may be possible when the porosity goes over 60%, as the material then is not an unconsolidated sediment anymore, but instead, a suspension of grains in salty water. Hamilton's results are shown in Figure 1.

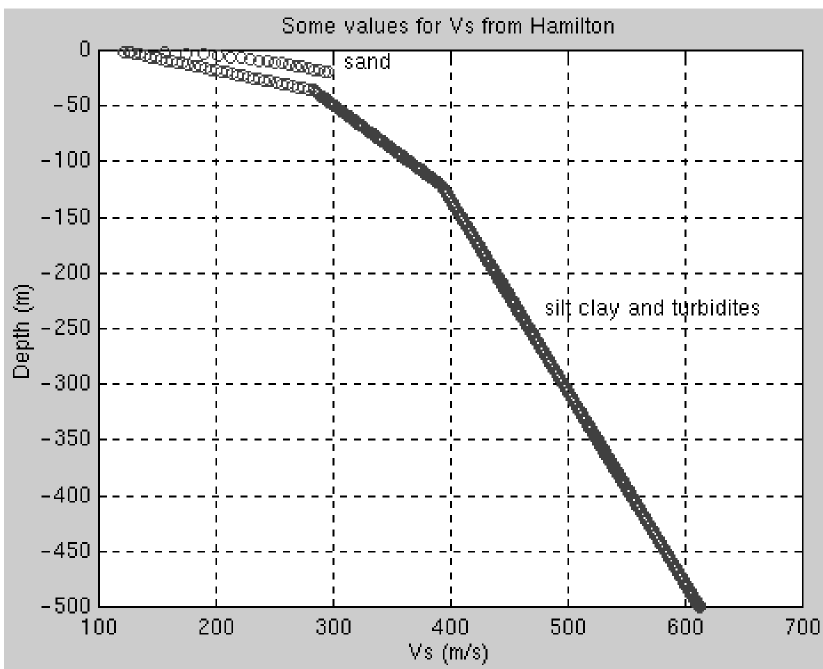

Figure 1 – Top: V_P values for marine sediments from Hamilton (1976, 1979). Observe distinct curves for siliciclastic (terrigenous) and sand lithologies. Bottom: V_S values for marine sediments from Hamilton (1976, 1979). There are similar curves for sand and silt clay and turbidities lithologies.

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). Most of the floor of Barents Sea continental slope is covered by sandy clays, marls and oozes.

The sediments have unexpected overconsolidation in the upper meter. V_S varies between 9 m/s and 47 m/s.

Richardson et al. (1991), analyzing the upper 2 m of sediments in shallow water, conclude that the shear modulus is controlled by consolidation for sands, but for fine-grained sediments, other process are important. According to the authors, values predicted by Hamilton (1976), and Bryan and Stoll (1988) near the sea bottom are often higher than measured values.

Duennebier and Sutton (1995) consider a value of 20 m/s appropriate for high porosity shallow marine sediments in ocean bottom seismometers (OBS) coupling problem analysis. They relate values varying between 10 and 40 m/s from the literature.

P-S mode conversion at the sea bottom may be important for hard bottoms (Tatham and McCormack, 1991), as the critical angle for the P-wave can be relatively small, generating downgoing energy only as S-waves. If the sea bottom is not hard, though, most energy will be transmitted as compressional, and shear wave conversion will be present mainly at sediment interfaces. Tatham and Stoffa (1976) present some examples of conversion at the sea bottom, for shallow sediments with P-wave velocities over 2000 m/s. According to Amundsen et al. (1999), the most important elastic parameter for the PSSP mode (P converting to downgoing S, reflecting as upcoming S and converting back to P at the sea bottom) is the S velocity just below sea bottom. As an example, the authors say that if a Vp/Vs ratio equal or lower than 3.0 occurs in these sediments, PSSP amplitudes are comparable to PP reflection amplitudes. However, to our knowledge almost all measurements presented in the literature (e.g. Hovem *et al.* 1991), at different locations and water depths around the world, show that Vp/Vs is usually over 5.0.

From above, the indication is that most shear wave energy recorded on the sea bottom is related to upcoming P-S conversions from deeper sediment interfaces, not downgoing conversions at the sea bottom. The results of this report support this indication. Thus, in the absence of efficient and economic ocean-bottom shear sources, we are called upon to analyze P-S reflection data.

GEOTECHNICAL DATA

The values used in this section to obtain elastic parameter came from geothecnical data obtained offshore Brazil. This data were acquired to support analysis of drilling and production platforms and (secondarily) pipelines on the sea bottom.

The shear moduli are obtained in the laboratory with the original fluids in the sediment. We consider the 'geotechnical' shear modulus as the same elastic parameter (with density) that defines the S-wave velocity in rocks.

Esteves (1996) analyzed several physical properties, such as grain size and density, of shallow (near-surface) marine sediments offshore Brazil. She found that: 1) sand percentage decreases with deeper water; 2) after 1,200 m water depth, all sediments are composed of foraminiphera and nanofossils oozes, 3) density increases with water depth, with a 1.72 g/cc average for deep water (with less sand) and 1.65 g/cc average for shallow water (more sand), and 4) sediment water saturation decreases with sediment depth, the highest values found above 5m sub-seabottom.

Kubena and Post (1992) made several measurements on physical properties for shallow (less than 100 m) marine sediments from offshore Brazil.

Figure 2 shows the average value for these measurements.

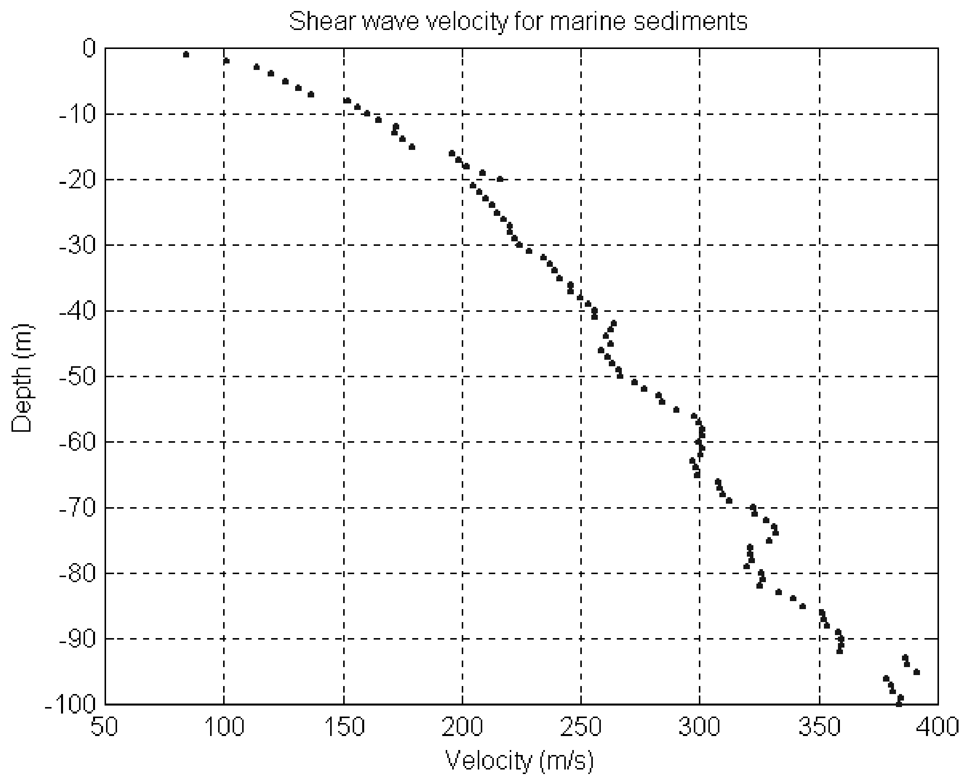

Figure 2 – Average of shear-wave velocity values obtained from geothecnical data offshore Brazil. Observe good correlation with Hamilton (1976,1979) results (Figure 1).

MODE CONVERSION

Most reports on the processing of OBC data conclude that S-wave energy recorded at sea bottom is generated from P-to-S conversion at layer interfaces rather than at the sea bottom. In general, this conclusion came from moveout velocity analysis (the velocities are much higher than expected from pure S-S mode) and/or poor imaging when conventional CMP processing is applied to horizontal components. For these reasons, converted-wave algorithms – S-wave receiver statics, P-S velocity analysis, P-S imaging, etc. have to be used.

Using the Zoeppritz equations, we analyzed and compared mode conversion at the sea bottom and at typical top of Tertiary reservoir interface. For near-surface sediments, we obtained elastic parameters by averaging much of the data referenced above. For the top reservoir interface, we use reasonable values for unconsolidated turbidite sandstones of Tertiary age, listed in Appendix I. We should point that for these reservoirs the P-wave velocity contrast can be much higher than S-wave. Generally, the density contrast is very high and cannot be neglected in modeling studies.

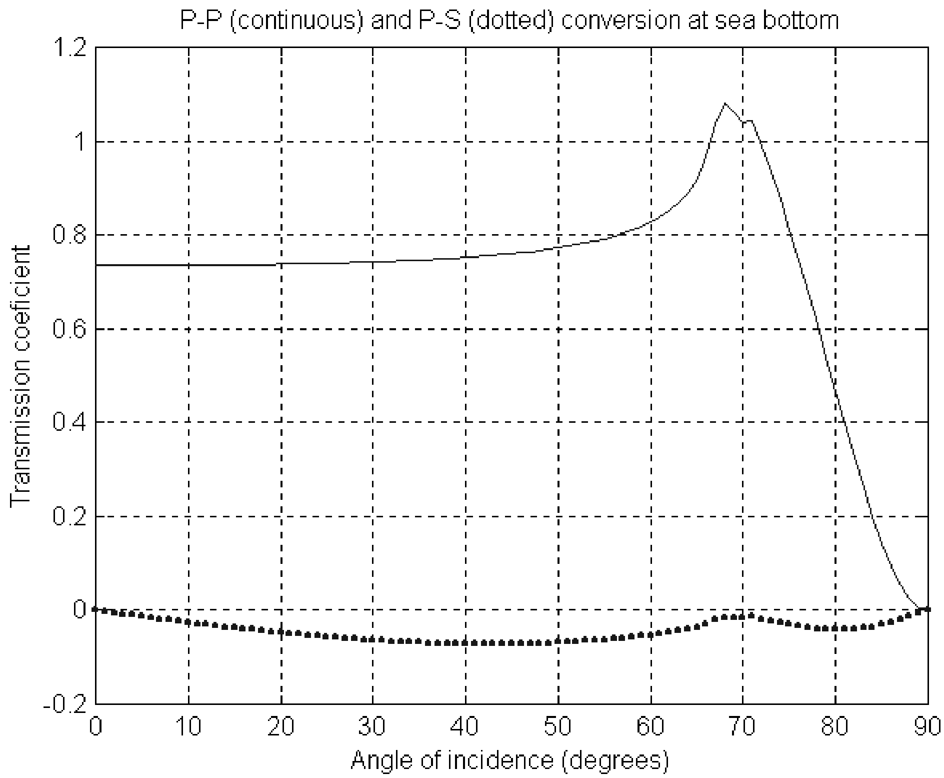

Figure 3 – Mode conversion (transmission) at sea bottom for incident down going P-wave, for P-P (continuous line) and P-S (dotted line). Observe that most energy is transmitted down as P-wave.

For a downgoing compressional wave, Figure 3 shows us that, for most incidence angles commonly present on seismic acquisition, P-P energy is more than 100 times higher than P-S (one should take the square of the amplitude transmission coefficient to analyze energy). This is a strong indication that conversion from P- to S- wave at sea bottom can be expected to be very poor in many marine environments.

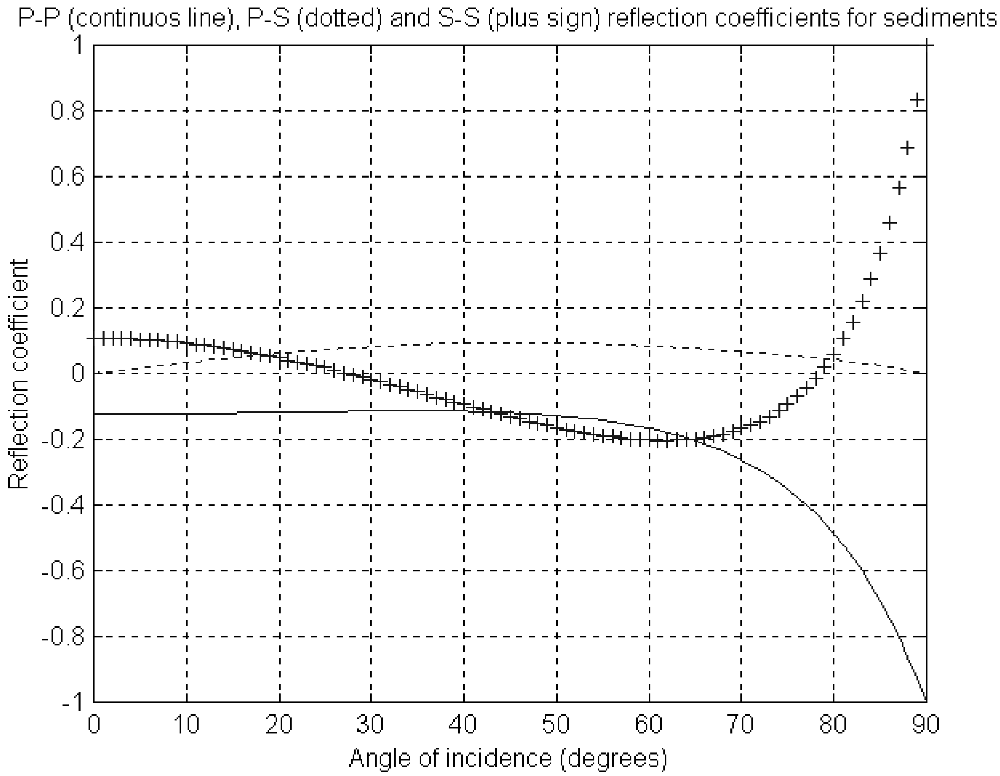

Figure 4 – Mode conversion (reflection) at top of turbidite reservoir for incident down going P- and S-wave. P-P (continuos line), P-S (dotted) and S-S (plus sign) modes. Observe that, below 70^0, modes have (relatively) close reflection coefficient values.

The behavior at top of a turbidite reservoir is presented on Figure 4. We see that P-P, P-S, and S-S modes are of similar maximum values over moderate angles of incidence. The P-P downgoing energy is, in general, many times higher than the transmitted P-S, so we conclude that most shear wave energy traveling upward should be created by the PP-S mode instead of PS-S mode. This is shown in Figure 5.

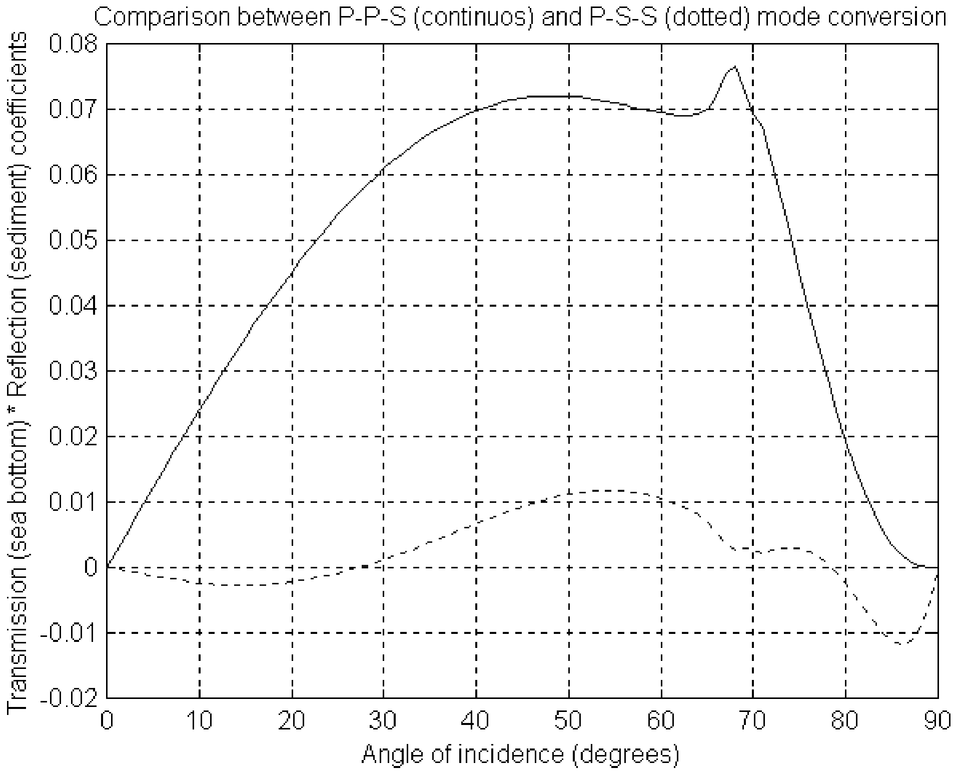

Figure 5 – Amplitude coefficients for P-S conversion at sea bottom and S-S reflection at reservoir top (dotted line) and for P-P transmission at sea bottom and P-S conversion at reservoir top (continuous line).

CONCLUSIONS

Transmission and reflection coefficients for P- and S-wave mode conversion are obtained for sea bottom and Tertiary sediments. Elastic parameters for near-surface marine sediments are calculated using literature data (Hamilton equations) and geotechnical data from offshore Brazil. The geotechnical data showed good agreement with Hamilton's results.

We conclude, from previous published data and our results, that most S-wave data recorded in OBC are related to upcoming conversions at deeper interfaces (PP-S) and not to downgoing conversions at the ocean bottom (PS-S).

ACKNOWLEDGEMENTS

We would like to thank Paulo Roberto Maldonado, from PETROBRAS, for his help on releasing the geotechnical information from offshore Brazil for this report.

REFERENCES

Amundsen, L., Arntsen, B., Kristensend, A., Rogno, H. and Sollid, A, 1999, Multicomponent seabed seismic data: a tool for improved imaging and lithology fluid prediction, *Offshore Technology Conference 1999*, paper OTC 10939.

Ayres A. and Theilen F., 1999, Relationship between P- and S-wave velocities and geological properties of near-surface sediments of the continental slope of the Barents Sea, *Geophysical Prospecting* **47**,431-441.

Bryan G.M. and Stoll R.D., 1988, The dynamic shear modulus of marine sediments, *J. Acoust. Soc. Am.* **83**, 2159-2164.

Duennebier, F.K. and Sutton, G.H., 1995, Fidelity of ocean bottom seismic observations, *Marine Geophysical Researches* **17**:535-555.

Esteves, M.G.P., 1996, Movimentos de massa: um estudo de integracao de dados geologicos, geofisicos, geotecnicos e oceanograficos. M.Sc. thesis, Universidade Federal Fluminense (*in portuguese*).

Hamilton, E.L. 1976, Shear wave velocity versus depth in marine sediments: a review. Geophysics 68:985-996.

___ 1979, Vp/Vs and Poisson's ratio in marine sediments and rocks. J. Acoust. Soc. Am., 66(4):1093-1101.

Hovem, J.M., Richardson, M.D. and Stoll, R.D., 1991, Shear Waves in Marine Sediments, editors, Kluwer Academic Press.

Kubena, M.E. e Post, M.L., 1992, Factual data report on soil investigation, offshore Brazil. PETROBRAS / Fugro-McClelland Engineers B.V. Reports N-2850-701, N-2850-702, N-2850-703, N-2850-801 and N-2850-802.

Richardson M.D., Muzi E., Miaschi B. and Turgutcan F. 1991. Shear wave velocity gradients in near-surface marine sediments. In: *Shear Waves in Marine Sediments* (eds J.M. Hovem *et al.*), pp. 295-304. Kluwer Academic Press.

Tatham, R.H. and Stoffa, P.L., 1976, V_P/V_S – A potential hydrocarbon indicator. *Geophysics*, **41**:837-849.

Tatham, R.H. and McCormack, M.D., 1991, Multicomponent seismology in petroleum exploration, Investigation in Geophysics Series vol. 6, SEG.

Appendix I

Elastic parameters for reservoir (turbidite) and overburden Tertiary rocks.

LAYER	V_P (M/S)	V_S (M/S)	DENSITY (GM/CM^3)
Overburden	2800	1165	2.4
Turbidite	2530	1070	2.1