Acquiring shear-wave information in shallow-water environment from field data near Ghent, Belgium

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Summary

A multi-component seismic experiment was conducted by deploying a 4-C ocean-bottom cable in a shallow water canal. The aim of the experiment was to investigate the feasibility of acquiring shear-wave information in shallow marine environment. In the recorded data, we observe air-gun generated shear-wave reflections. This observation is validated by a model study. The presence of shear-wave reflection is caused by the low frequency of the source in relation to the water depth. Furthermore, converted waves have also been identified based on two "attributes" namely the particle polarization and the normal moveout velocity. Comparison with synthetic data suggests the presence of waves converted at a reflector as well as at the water bottom.

Introduction

Shear-wave information is often necessary for the characterization of the shallow subsurface and for the retrieval of geotechnical parameters. During the last three decades, it has been shown by many that the S-wave velocity is much more sensitive to changes in lithology and mechanical properties than the P-wave velocity. In marine setting, the S-wave information can be obtained from seismic measurements. Different methods exist towards this end. Gerhmann *et al.* (1984) developed a system which directly generates and records horizontally polarised S-waves in shallow water areas. The system consists of a modified airgun capable of generating horizontal shear stress and a 3-component geophone system placed at the water bottom. The authors showed an example of marine shear-wave refraction profiling in the Baltic Sea. Although this system proved to be useful, it is has not been much used.

For structural mapping P-waves are still the most successful in marine environment. Therefore people have been inverting for the S-wave velocity from PP-reflections. However, Riedel *et al.* (2001) showed that large uncertainties are involved in the estimation of the S-wave velocity. These uncertainties are attributed to the insensitivity of the P-wave reflection amplitude to this parameter in shallow marine sediments.

Another approach to obtain S-wave information has been proposed by Caiti *et al.* (1994) and it involves recording surface waves using a receiver array laid down on the water bottom sediments. The recorded surface waves are analysed and inverted to obtain S-wave profiles (Caiti *et al.* 1994 and Park *et al.*, 2000). However, the depth of these profiles is limited and the accuracy and resolution are depth-dependent.

The S-wave velocity can also be retrieved from converted waves i.e., waves converted from compressional to shear mode. In hydrocarbon exploration, these waves have been applied successfully for many years. For shallow marine environment, modeling studies showed that there are two angles where maximum S-wave conversion can be expected (el Allouche *et al.* 2008), one at moderate angles (between 40 and 50 degrees) and one at post-critical angels. An appropriate way to detect converted waves is to use an ocean-bottom cable configuration.

In this abstract, we show the results of a multi-component seismic experiment conducted by deploying a 4-C ocean-bottom cable in a shallow water canal. An analysis of the components suggests the presence of source generated shear-waves as well as converted waves in the data. Furthermore, modeling is used to validate the observation that a low frequency P-wave source located close to the water bottom can directly generate shear waves.

Field data

Data acquisition

In collaboration with the University of Ghent, a small testing survey was conducted in a 2 m deep water canal. This experiment is part of a study aimed at acquiring shear-wave information in shallow marine environment. The principal objective of this survey was to test the response of the ocean-bottom cable and to assess whether with this configuration, successful in hydrocarbon exploration, shear or converted energy can be detected from shallow targets.

The tool consists of 12 combined 3-C geophones and hydrophones with 5 m spacing and was laid on the bottom of the canal. Various types of sources with different frequency bandwidths were tested during the measurement. The sources included an airgun, a watergun, a sparker and a boomer. However, in this abstract, we discuss only the

airgun data since they show most of the shear-wave information.

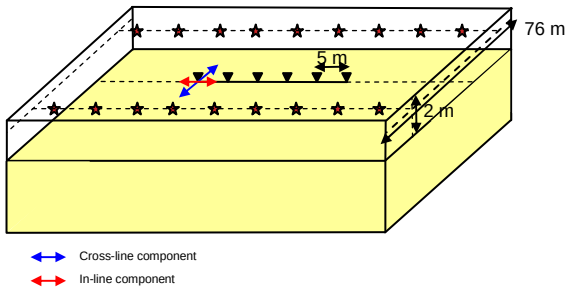

Figure 1: Sketch of the survey area showing the approximate locations of the shot lines with respect to the cable.

Data processing

The dataset includes two lines with approximately 200 shot positions. Due to the limited number of receivers, the processing and the analysis of the field data is performed in the common-receiver domain. Assuming lateral variations to be small, we combine two gathers of adjacent receivers into one super-gather with a shot spacing equal to half the actual one. As shown in figure 1, the seismic shot lines were not in-line with the receiver cable, therefore the offset is not regular especially at near offsets. Since this can impede processing operations which require regular spatial sampling, the data is linearly interpolated. A bandpass filter and automatic gain control are subsequently applied to the gathers in order to enhance the coherency of the events. The processed dataset is used to obtain a velocity model of the subsurface.

3-component analysis

The absence of sonic logs and multi-component VSP data impede conclusive interpretation of the different types of seismic events. However, based on fundamental differences in P- and S-wave seismic properties, we attempt to identify converted waves. The two "attributes" we consider in this analysis are the particle motion and the difference in propagation velocity.

S-waves are polarized in the direction perpendicular to the propagation and are thus expected to be dominant in different geophone components than the P-waves. Furthermore, in marine shallow sediments, in situ-measurement can easily reveal a Vp/Vs ratio exceeding 10 (Hamilton, 1979). This is expected to have a significant effect on the moveout velocity of the converted events. In this analysis, these two aspects are explored in order to identify the converted waves.

Figure 2 shows the receiver gathers recorded with 3-C geophones and hydrophones. In general, several remarks can be made on the presented gathers. As expected, the pressure measurement has a higher frequency content compared to the other components: especially at early times they show the high-frequency reflectivity as it is commonly observed. The dispersive events, strongly present in all components, are surface waves propagating along the water-sediment boundary. In addition to these arrivals, three other series of events draw our attention. These are included in three frames with different colors (figure 2) and are analyzed in the following paragraphs.

In contrast with P-waves, waves arriving at the receivers in a shear mode are polarized in a direction perpendicular to the propagation direction. In shallow unconsolidated sediment, the particle motion associated with converted waves is expected to be horizontally polarized due to the large Vp/Vs ratio (the reflection raypath being nearly vertical). The hodograms displayed in figure 3 represent the particle motion of the events included in the three frames. The choice of the polarization planes for the analysis is based on the amount of energy present in the components. The particle motion of the different events in figure 3a and 3c is mainly oriented in the ZY plane corresponding to the vertical and the cross-line components.

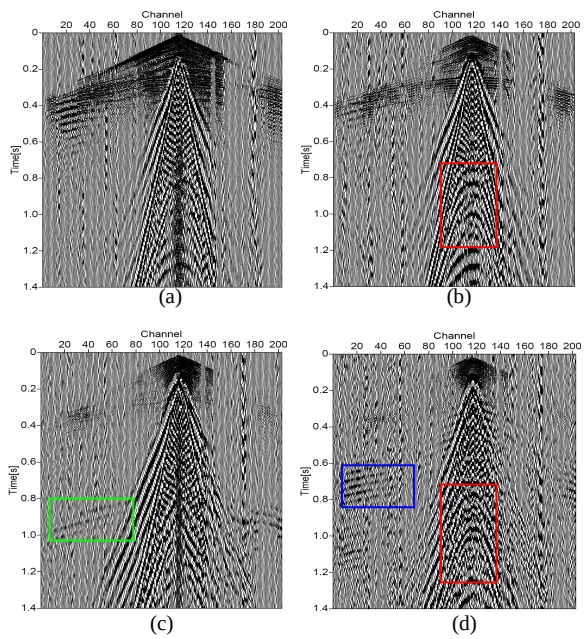

Figure 2: Common-receiver gathers recorded at: a) hydrophone, b) vertical component, c) in-line component and d) cross-line component.

The events enclosed in the red frame are relatively low frequent and have a low moveout velocity. The value 145 m/s found for one of these events is in the range of the velocities expected for the surface waves. However, the observed hyperbolic shape and the particle motion suggest that these waves are shear-wave reflections.

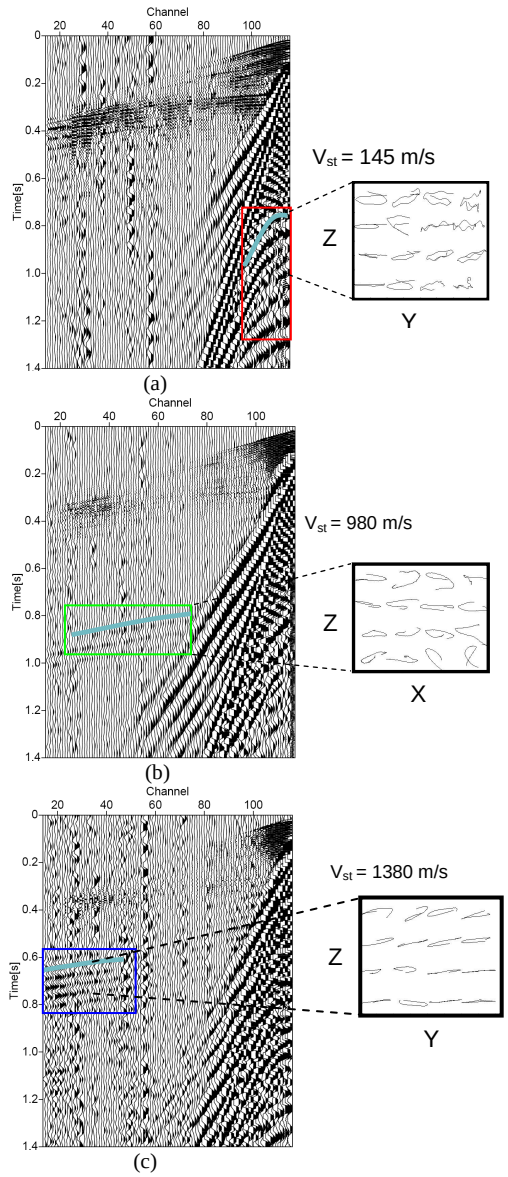

Figure 3: Common-receiver gathers recorded at a) vertical component, b) in-line component and c) cross-line component. The hodograms represent the particle motion computed for a time window of 0.2 s. The moveout velocity of the indicated event (blue) is also given.

The green and the blue frames include events polarized in the horizontal direction. The moveout velocities of these reflections are considerably lower than the P-waves registered at earlier times. This indicates that these reflections may be converted. The late arrival time and the relatively lower moveout velocity of the arrivals in the green frame suggest that these are converted at the water bottom and thus traveled the rest of their path as SV-waves. The faster converted waves in the blue frame are possibly converted at a reflector.

Modeling

To better understand the nature of the events present in the dataset and to address the question whether shear-waves were excited or not, we tried to capture it in a model. Figure 4 shows a three-layered model parameterized with values obtained from the velocity analysis of the field data. For the density we assume no variation as a function of depth. Since we do not have any constraints on the S-wave velocity we also assume a Vp/Vs ratio of 10 which is typical for shallow unconsolidated sediments. The same acquisition parameters are used for the modeling as in the field survey. The dominant frequency of the source wavelet is 100 Hz and is estimated from the direct wave in the field data. The seismograms are computed using a time-domain finite-difference algorithm.

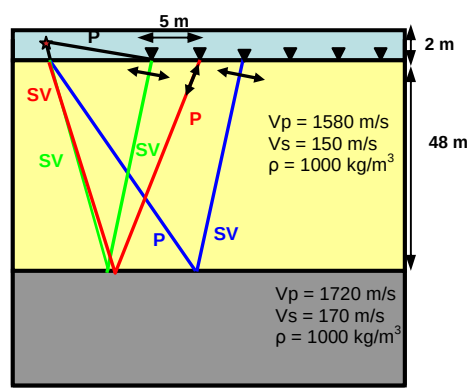

Figure 4: Sketch of the used model. The expected converted waves with their corresponding particle motion are also plotted.

Discussion

The synthetic seismograms in figure 5 show similarities with the field data. Specifically, the low-frequent hyperbolic event arriving at 0.7 s which has the travel time of an SS-reflection can be correlated with the reflection as marked by the red arrow in the real data (figure 5b). The longer travel time suggests a lower average S-wave velocity in reality than the assumed 150 m/s. Note the clear difference between this reflection and the P-SS converted

mode in figure 5a. At near-offset, they have the same travel time but they diverge as the distance between source and receiver increases. The moveout of the P-SS is dominated by the P-wave velocity in water. The excitation of the shear-wave is due to the low dominant frequency of the source in relation to the water depth. Increasing the frequency from 100 Hz to 200 Hz results in the disappearance of the SS-reflection and the converted modes as shown in figure 6. This observation indicates the necessity of using low frequency sources to acquire shear-wave information.

Moreover, the synthetic data shows that the modes of conversions present are primaries, i.e. only one mode conversion occurred, and that they contain enough energy for being observed. The converted primaries identified in the synthetic seismograms suggest that the reflection marked with a green arrow is a P-wave converted at a reflector. This event is one of the reflections captured in the green frame in figure 2 and is recorded in the cross-line component.

The P-wave, converted at the water bottom, is also detected in the synthetic seismogram. This event is characterized by its longer travel time and low moveout velocity. The identified reflection can be correlated with the event indicated in figure 5 by the blue arrow. This implies that the reflections included in the blue frame in figure 2 are waves converted at the water/sediment interface. These reflections are only observed in the in-line component and as in the synthetic case, at near-offset they have the same travel time as the source generated shear-wave reflection.

Conclusions

By comparing real data with modeling results, we have shown that shear-wave reflection in shallow marine environment can be excited from a P-wave source. This observation can be due to the interaction of the generated wave with the water bottom. However, further research is needed to understand this interaction. Furthermore, we have been able to interpret converted waves in field data by considering their particle polarization and moveout velocity. Two types of mode conversions are identified on the synthetic data. These are waves converted at the water bottom and at a reflector. The visibility of the converted waves seems to be frequency dependent. The physical mechanism relating source frequency to conversion of wave modes is currently under research.

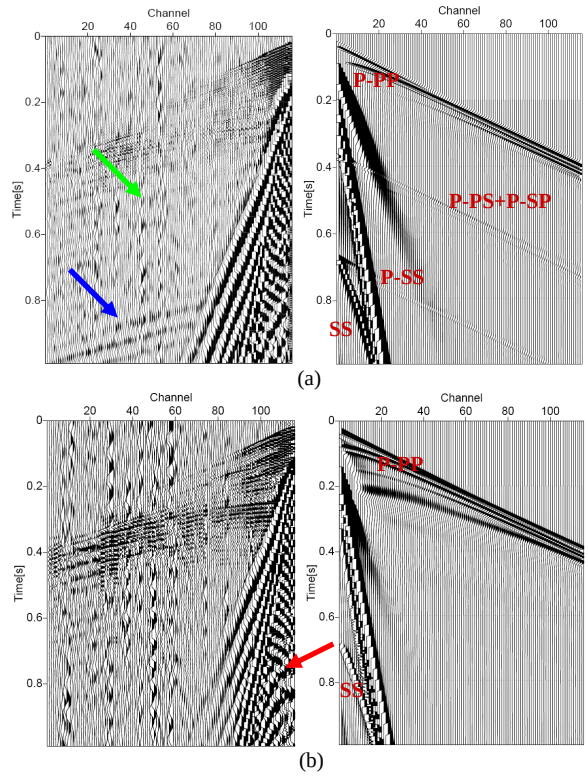

Figure 5: Comparison between field data and synthetic data. a) In-line component and b) vertical component. Converted waves including P-PS, P-SP and P-SS are marked on the horizontal component of the synthetic data.

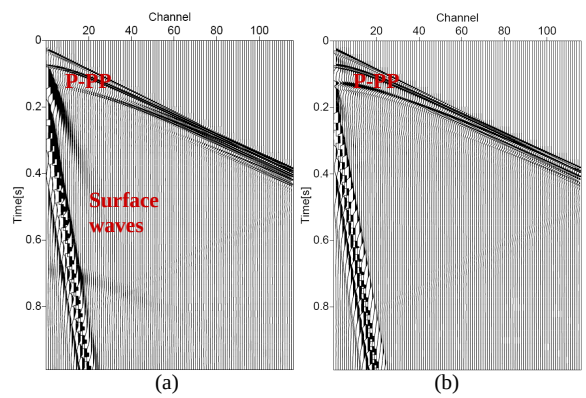

Figure 6: Synthetic data computed for a dominant frequency of 200 Hz. a) In-line component and b) vertical component.

EDITED REFERENCES

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