Virtual Shear Source: a new method for shear-wave seismic surveys

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Summary

Shear-wave seismology holds great promise but always remains small niche activity due to a variety of operational and subsurface limitations. In this study we demonstrate that the Virtual Source method can overcome many of these limitations and revive shear-wave seismology. With an array of sources at the surface this method allows us to obtain a Virtual Shear Source at the location of each downhole geophone in a well. Firstly, in certain cases it allows us to generate pure shear-wave energy without P-wave contamination using conventional P-wave sources even in a marine environment. Secondly, we can construct SS images of the subsurface even through a complex near-surface for which the velocity model is unknown. Thirdly, we can control the polarization. All this is at a price of placing geophones in the subsurface and making downhole recordings. This price tag is expected to decrease with greater use of permanent downhole monitoring, cheap wells and instrumented oilfields.

We will show examples of SS images obtained through a complex near-surface and show shear-wave checkshots generated with the help of P-wave sources even in a marine environment. This development may lead to a renaissance of shear-wave seismology especially for permanent seismic monitoring.

Introduction

Shear-wave seismology would be a more attractive proposition if we could overcome two major problems:

- reliable controlled excitation of shear waves is costly on land and not yet developed in the marine environment;
- shear velocities are extremely low, anisotropic and variable in the near-surface (both on land and on the sea bed). Thus near-surface problems are worse for shear-wave seismology.

The advent of ocean-bottom receivers has allowed the recording of PS data, but does not give a control on polarization of excited shear waves, suffers from seabed shear statics and requires different processing jointly with PP data.

Advent of 4D seismic monitoring has changed the economics of seismic acquisition: it is recognized that repeated seismic surveys are necessary throughout the field life in order to optimize production. Such necessity makes it possible to spread the cost of preferably permanent installation of receivers and possibly sources over the life of the field and thus make it cheaper for each individual survey. 4D seismic is also giving renewed interest in shear-wave monitoring as a promising way to track changes associated with production.

In our view dowhnole geophone arrays are an even more direct route getting value from shear shear-wave seismic. This technology is often referred as “smart”, “intelligent” or “instrumented” wells. It offers unparalleled capabilities of multi-channel multicomponent *in-situ* on-demand recording along the producing or dedicated observation wellbores.

It is the objective of this paper to demonstrate that seismic monitoring objectives combined with the “smart” well capabilities may offer a unique combination that overcomes the mentioned drawbacks and leads to easier and better shear-wave seismology. To achieve this objective we need to add third missing ingredient called “Virtual Source” (VS) method (Bakulin and Calvert, 2004). The VS method offers a way to overcome severe overburden problems without knowledge of the overburden velocities. In addition the VS method brings significant advantages with respect to seismic monitoring. In our previous study it has been applied to conventional P-wave seismic. Here we extend it to multicomponent acquisition and illustrate the additional unique capabilities of the VS method that may revive shear-wave seismology.

Virtual Shear Source

The Virtual Source principle is depicted on Figure 1 and described in detail by Bakulin and Calvert (2004). The

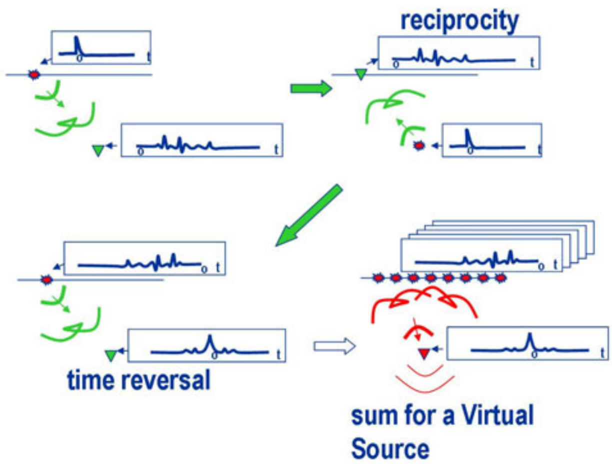

Fig. 1: Virtual Source principle.

essence of the method is to obtain a Virtual Source at the location of each geophone by utilizing energy from an array of surface sources. The acquisition is as for conventional VSP with surface shots and downhole geophones. The output is a new dataset with both downhole sources

Virtual Shear Source

and receivers at the same locations. Downgoing signals recorded by downhole geophones are time-reversed and re-sent back from each shot. Linearity and reciprocity are assumed in order to simulate a time reverse experiment numerically on the computer rather than doing it physically as described by Fink and Prada (2001). Since no velocity model is required to perform the generation of Virtual Source data, we can image through extremely complex realistic overburdens (Bakulin and Calvert, 2004).

Since our objective in this paper is to generate shear-wave Virtual Source data, we modify the VS process as follows:

- We use inline horizontal vibrator (SV) for excitation;
- We use horizontal component for recording;
- We mute first (P-wave) arrivals on time-reversed portions.

In laboratory experiments at a solid-fluid interface Draeger et al. (1998) demonstrated that selective time-reversal of converted modes can result in a tighter focal spot for reconverted S-waves due to their smaller wavelength. We employ similar idea but for a different objective: we want to focus back only the "desired" shear wavefront and eliminate unwanted longitudinal wavefronts, so that after focusing the Virtual Source emits only transverse energy.

To illustrate the concept let us utilize the same synthetic model described by Bakulin and Calvert (2004). The target is at 560-590 m and the challenge is to image through extremely heterogeneous near-surface part of upper 240 m. Shot line is at the surface and recording is done in a horizontal well at a depth of 430 m.

Figure 2 illustrates a typical common-receiver gather. The top blue line outlines the direct arrival time with P-wave velocity. Despite recording the horizontal component the mode-converted energy is abundant there due to the use of SV (inline) vibrator and due to strong ubiquitous mode conversion and scattering.

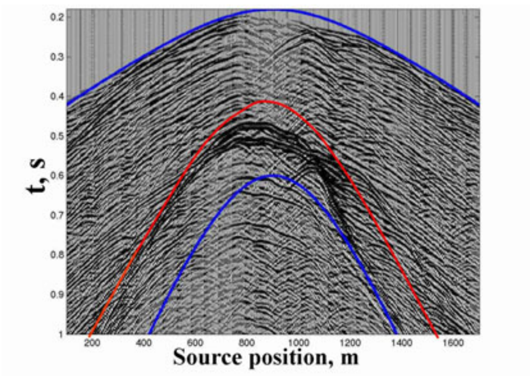

Fig. 2: Common-receiver gather on the input VSP data. Lines separate gates used for time reversal.

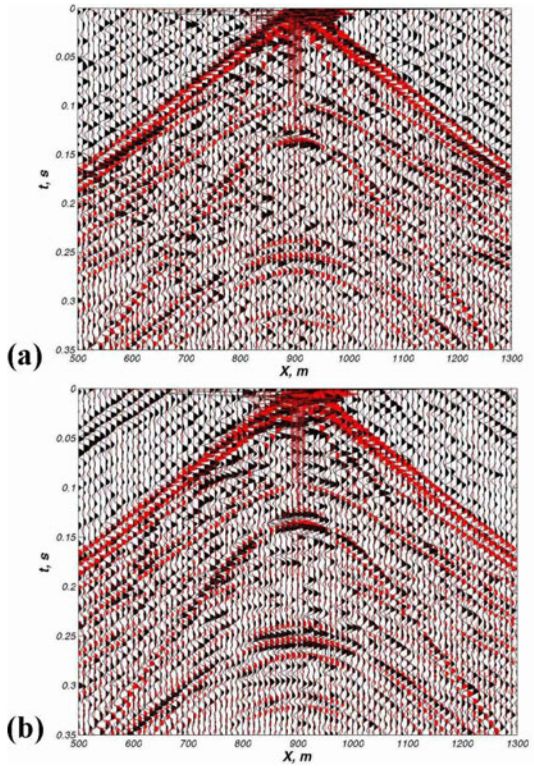

Fig. 3: Virtual Source gather (black) at $X = 900$ m with gate including (a) and excluding (b) first P-wave arrivals. Seismograms for real downhole horizontal vibrator (red) are shown for comparison.

The pre-stack VS gather generated by the Virtual Source algorithm (Bakulin and Calvert, 2004) is depicted on Figure 3b. The red background waveforms on this and other figures is a synthetic computed for a physical source at the VS location. The gate for time reversal was centered around "direct" shear arrivals (between middle red and bottom blue lines on Figure 2). The output is not sensitive to exact gate as long as we exclude the first arrivals. When a large gate (between top and bottom blue lines on Figure 2) is used for time reversal then resulting SS reflections become weaker and the VS gather looks noisier (Figure 3a). By muting first arrivals we cut the $S-P-..$ scattered energy and shape the Virtual Source to have advantageous radiation pattern not achievable with real horizontal vibrators: we cut the P-wave lobes of the radiation pattern while preserving the SV-wave lobe. This is similar to Draeger et al. (1998) who cut the first-arriving $P-P$ and preserve $S-P$ wavefront to focus only S-mode back into the focal spot.

For this model the VS data can be easily imaged with a 1D velocity model below the receiver string (Figure 4a). In fact the VS image has less artifacts and noise than an image obtained using surface data and *an exact velocity model including overburden* (Figure 4b)! Remarkably the Virtual Source SS image is of similar or better quality than the Virtual Source PP image obtained in the same model (Figure 5, Bakulin and Calvert, 2004). Use of cross-line SH vibrator should produce better images since P- and SV-waves are neither excited at the source nor converted in a 2D model.

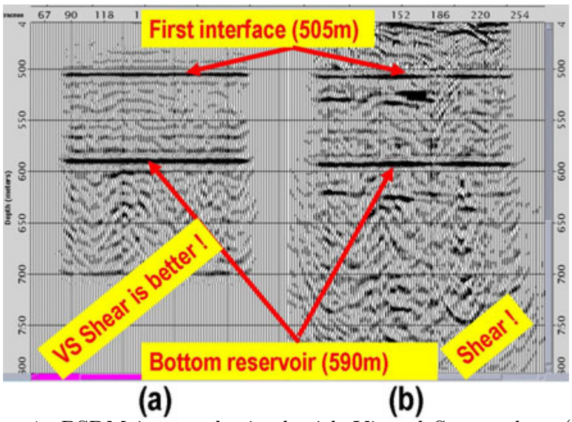

Fig. 4: PSDM image obtained with Virtual Source data (a) and original surface-to-downhole data (b). To obtain former image exact overburden velocity was used.

Buy one get one free?

To obtain Virtual Source SS image of comparable quality to PP image we used a horizontal SV vibrator. If we want to obtain both PP and SS images simultaneously, we would need to perform acquisitions with two different excitations for P- and S-waves. Can we obtain both PP and SS images utilizing single source type and 3C recording?

Although it may be possible in some instances data quality of one or the other is usually compromised. Let us examine the possibility of constructing an SS image using an explosive source and a vertical vibrator. Figure 5a illustrates that a vertical vibrator for this model leads to pre-stack VS SS data that are inferior in quality to the horizontal vibrator (Figure 3b). It also suffers from a polarity reversal caused by S-wave radiation pattern. As expected an explosive source produces even poorer SS data (Figure 5b).

Tables 1 and 2 represent summary of quality of VS data generated by various sources and recorded on various components. Based on this model we conclude that *we could not obtain good quality data for both PP- and SS-waves from only one type of source.* This is consistent with conclusions drawn from conventional seismic applications aimed at PP and SS data. In a real earth with more sharply 3-D heterogenous overburden results may be different.

Rec/Source	Explos.	Vert. force	Horiz. force
Hydrophone	Good	Good	Poor
Vertical	Good	Good	Poor
Horiz. (inline)	Poor	Poor	Poor

Table 1. Quality of P-wave VS data generated by different sources recorded at various components.

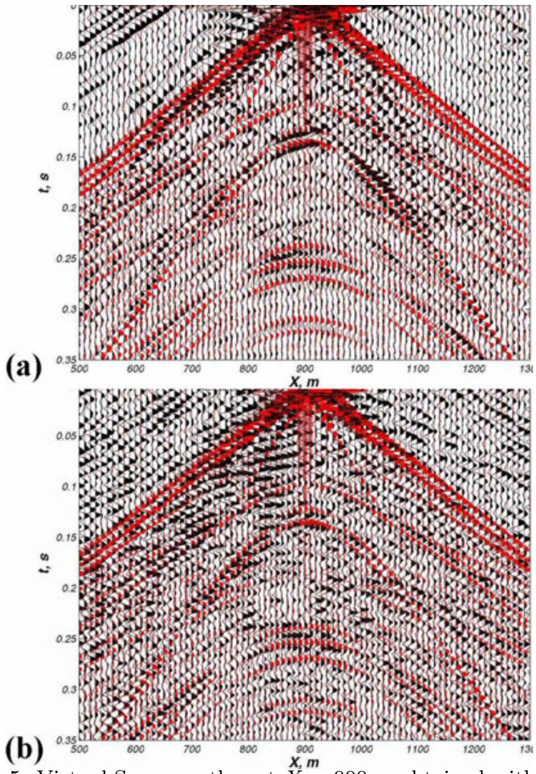

Fig. 5: Virtual Source gather at $X = 900$ m obtained with the vertical vibrator (a) and explosive source (b). Seismograms for real downhole horizontal vibrator (red) are shown for comparison.

Rec/Sour	Explos.	Vert. force	Horiz. force
Hydroph.	Poor	Poor	Poor
Vert.	Poor	Poor	Poor/medium
Horiz. (inline)	Poor	Poor/medium	Good

Table 2. Quality of S-wave (SV-wave) VS data generated by different sources recorded at various components.

Shear-wave checkshot with airguns

In certain cases a Virtual Source may allow the generation of shear waves utilizing a P-wave source only. Let us attempt to create a Virtual Shear source at the top geophone during vertical VSP in a marine environment. We use a real 1D velocity from Tommeliten field in North Sea (Allnor et al. 1997) depicted on Figure 6. A buried horizontal geophone at 200 m depth records the following wavefield from an airgun array at sea (Figure 7). Due to reciprocity the same wavefield would be generated by a buried horizontal force and recorded by hydrophones in the water. Due to fine layering it is difficult to separate the individual waves. First arrivals clearly represent $P-P$ scattered energy while later energy consists of mixture of $P-S-..$ and other reverberations. The radiation pattern of the horizontal force consists of a P-wave lobe and two S-wave lobes. Since we only want to reconstruct the shear energy we cut the first P-wave arrivals in the time-reversed portion and only backpropagate data inside the rectangular gate outlined on Figure 7.

Checkshot from a Virtual Source at 200 m recorded by deeper geophones in the vertical well (Figure 6) reveals clear direct arrival propagating with shear velocity. This is easily seen comparing it with a second set of waveforms that represent the firing of a real downhole source placed at 200 m depth and recorded on a horizontal geophone. We observe not only a direct S-wave arrival, but also an upgoing reflection from a 400 m interface visible on both data (Figure 6) which is consistent with the downward radiation pattern of the Virtual Source.

The obtained results are somewhat surprising if we recall that a horizontal force does not excite any shear waves in a strictly vertical direction and also that $P-S$ conversion is zero at a fluid-solid interface. Nevertheless the VS constructively combines all the mode-converted scattered energy at non-zero offsets and still generates reasonable shear waves on a vertical incidence of VS records.

Of course in real life velocities are rarely 1D and any deviation from homogeneous plane-layered model will create more mode-converted energy enhancing the Virtual Source at vertical incidence as well as other angles.

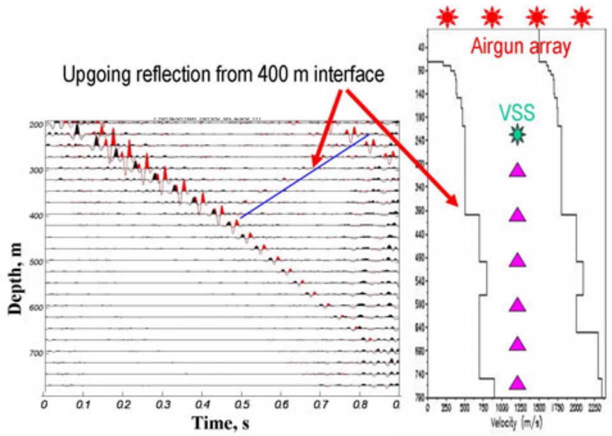

Fig. 6: Virtual Source checkshot (left) and corresponding velocity model (right). Virtual Source data is in black and seismograms from real downhole physical source are in red.

Conclusions

We extended the Virtual Source method to multicomponent data and showed how to create a downhole shear source at the location of a horizontal geophone. This procedure allows us to transform conventional VSP recordings into a new Virtual Source dataset with downhole (virtual) sources and receivers that predominantly contains SS reflections from below. Since the Virtual Source method is based on a time-reversal logic it does not require any velocity model and therefore is it is an attractive way of overcoming the severe near surface problems. In fact the VS approach benefits from the mode conversions caused by the near-surface heterogeneities.

As a consequence we have demonstrated possibility of obtaining pre-stack SS data and images below severely scattering overburden. In favorable cases of scattering overburden both SS and PP images can be obtained simultaneously utilizing single type of source and 3C downhole recording.

We also can choose and control the polarization of the the Virtual Shear Source. By selecting proper shots and components from surface patch we can obtain orthogonally polarized shear sources.

Selective gating of the time-reversed wavefield allows us designing Virtual Sources that excite only downgoing S-waves without P- and vice versa. This is impossible to achieve with real downhole sources.

In favorable circumstances we may also generate Virtual Shear Source utilizing only P-wave sources like airguns in case of marine environment.

Acknowledgements

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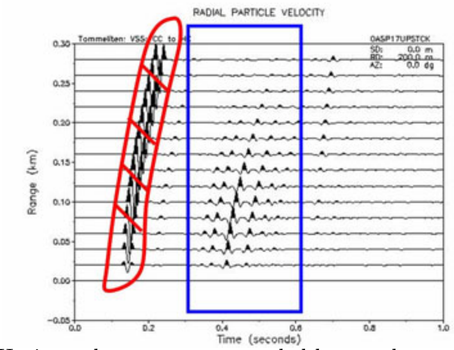

Fig. 7: Horizontal component recorded by geophone at 200 m depth inside the sediment from an airgun array at sea. Square box outlines data used for time-reversal. First arrivals of $P-P-...$ nature have been muted.

EDITED REFERENCES

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