Head-wave monitoring with Virtual Sources

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Summary

The original applications of the Virtual Source Method (VSM) concentrated on reflected waves and demonstrated that imaging and monitoring through complex and changing overburdens can be accomplished at the expense of using downhole geophones in horizontal wells. There is number of reasons to expect even better results when head waves are restored and used for reservoir imaging and monitoring purposes. Being compared with a reflection survey, the head waves have less strict requirements for surface sources placements providing data for high resolution tomographic image for substantially larger areas. Head waves show high sensitivity to changes in the reservoir and look promising for monitoring applications. The drawback of this VSM application is in requirement of receiver lines placement close to reservoir depths.

Introduction

The Virtual Source Method (VSM) has been proposed by Bakulin and Calvert (2004, 2006) as a practical approach to reduce distortions of seismic images caused by complex overburdens. The method is based on using the surface shots and downhole receivers placed below the most complex part of the heterogeneous overburden. The time reversal technique, combined with downhole recording, allows to eliminate the transmission effects of the near surface and to obtain reflections from deeper targets, which are free from distortions caused by complex overburden. No knowledge of the velocity model between surface shots and receivers is required. Korneev and Bakulin (2006) showed that the VSM can be derived directly from the Kirchhoff-Helmhotz integral (KHI) using the reciprocity principle. Application of the KHI for seismic data processing and imaging represents back propagation of the recorded (time-reversed) wavefields to image underground structures. Although the presence of a full aperture for applying the KHI is never attainable in practice, under certain conditions it is possible to restore a field phases and amplitudes by summation over a limited number of surface sources. The body wave's total field can be well restored as the integral over the Fresnel zone around the stationary points (Snieder et al, 2006), which give the best locations for surface shot placement. Up to date, the VSM has demonstrated effectiveness in seismic applications based on reflected P- and S- waves. We consider an application of VSM for head waves propagating along an underground reservoir and in order to assess its feasibility for reservoir monitoring.

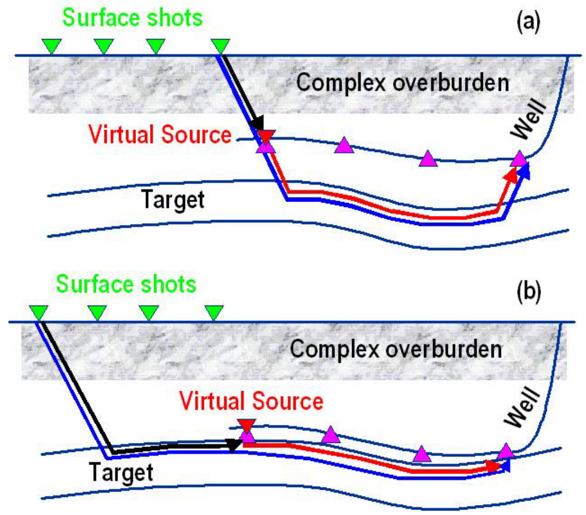

Figure 1. Scheme of virtual source method for head waves. (a)Waves emitted by a surface source (red rays) propagate as body waves until they reach a high velocity target horizon at a critical angle and then propagate along this horizon radiating head waves. Head waves generated by a virtual source have a common travel path (red) with those generated by the surface shot (blue) at stationary point. (b) Far offset sources also belong to stationary points for virtual sources located close to the target layer.

Background

Gas and oil reservoirs usually can be found in sedimentary rocks, which generally represent a set of high- and low-velocity contacting layers. In addition to traditionally used reflected waves such structures are capable of forming head waves starting from large enough offsets when incident waves reach angles exceeding the critical ones. After critical angles the refracted waves propagate along the layers with fast velocities and radiate energy back into an upper structure by forming head (conical) waves. An application of head waves in surface exploration seismic is relatively rare because it uses larger depths and correspondently requires quite large offsets for sensor placements. However, if horizontal wells are used for observations then critical angles can be reached at much smaller offsets providing favorable conditions for head wave registration and use. One might expect several potential advantages of the head waves for reservoir monitoring purposes if compared with schemes relying on the reflected waves registration:

- Head waves typically arrive ahead of other waves that makes them free from distortions caused by interference, which is especially important for monitoring applications when signal to noise ratios define sensitivity to changes

- Head waves propagate horizontally for substantial distance along the layers. This property allows application of high resolution tomographic methods for data inversion and imaging as opposed to migration of reflected data with their lower resolution and higher dependence on information about velocity models. Long propagation paths within reservoir zones also generate favorable conditions for better vertical resolution within the reservoir, assuming existence of head wave-generating high velocity layers at different depths
- Head waves have simple linear moveout which is an advantageous for wave extraction, picking, and filtering
- Head wave may provide significantly larger images compare to reflection surveys.

This latter statement is illustrated using Figure 2. If two orthogonal wells are used for Virtual Source reflection imaging or monitoring (so called Virtual Cross-Spread, Bakulin et al., 2007) then area L1*L2/4 can be illuminated, where L1 and L2 are length of the horizontal boreholes. With head waves and two identical but parallel horizontal wells, one can monitor area L1*L2 which is four times larger.

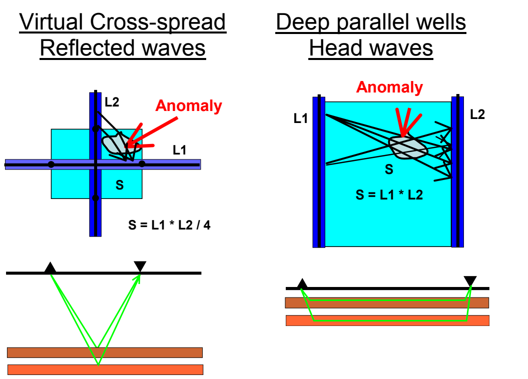

Figure 2. Plan views (upper panels) and vertical sections (lower panels) for a reflection cross-spread survey (left) and a head wave survey (right). Blue lines indicate buried at some depth horizontal wells instrumented with receivers. For the same well lengths the coverage area of the head waves is about four times larger than corresponding area for a reflection survey.

- Generally, the VSM applications assume extensive summation over the surface shots in the vicinity of the stationary points. However, for the head waves excitation, it is expected, that requirements for surface shots placement will be less strict as long as critical incident angles take place outside of the coverage area. This feature can be especially important for mature fields with many surface facilities that prevent from surface shooting right above the target area.
- At large offsets the head waves amplitudes are larger then reflected-refracted waves because of smaller geometrical spreading.

Disadvantage of head wave use for VSM is in need of horizontal wells for data acquisition which are deeper (closer to the reservoir) then those used in the Virtual Source Cross-Spread with reflected waves.

Two half-spaces model

To better understand the main properties of VSM application for head waves we consider a simple model with two half-spaces. The goal of the present section is to compare head waves obtained with Virtual Source and real downhole sources. The velocities of the upper half-space are smaller than velocities in the lower half-space. The acquisition geometry consists of two vertical profiles (b1 and b2) instrumented with 58 receivers at 10 m spacing. In Virtual Source experiment wavefield is excited by a remote source A* (Figure 3). Intensive P- and S-head waves traverse receivers in well b1 and then well b2.

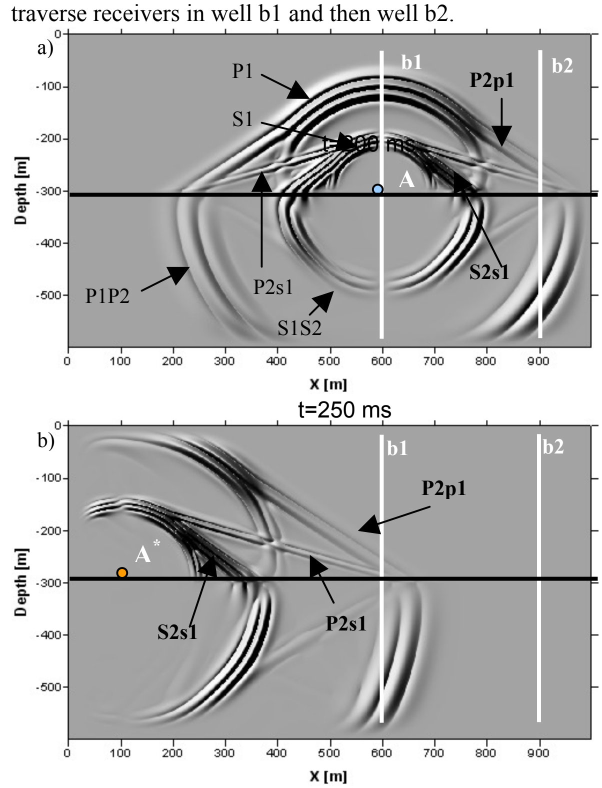

Figure 3. Wave propagation in two experiments: a) real source at A (600 m, 300 m); b) remote source at A* (100 m, 300 m) that is used to excite Virtual Source at A. Upper half-space velocities V_P = 2000 m/s, V_S = 650 m/s; lower half-space velocities V_P = 3700 m/s, V_S = 1850 m/s.

If we select receiver A in the well b1 as a Virtual Source location and cross-correlate recorded traces at Virtual

Source with traces recorded in the well b2, then we obtain Virtual Source gather shown on Figure 4 where it is compared with a ground truth response computed when the actual downhole source was placed at point A and receivers at well b2 have recorded the wavefield. The head-wave is correctly reconstructed on the Virtual Source data.

In real situations the required acquisition geometry might not be reachable. If the receiver is located above the interface, and the critical angle is reached before it was hit by the direct wave the surface shots are not sitting on the stationary points (Figure 1b). However, the head wave information can still be retrieved from such shots since refracted overcritical waves will arrive at receivers with same time differences providing condition for constructive summation.

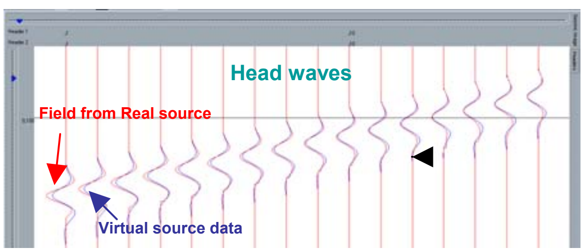

Figure 4. Comparison of common-shot gathers for Virtual Source (blue) and real downhole source at point A (red). Receivers are located along the well b2. Wavefront of the head wave is accurately restored.

The summation results can be further improved after applying "gating" or time windowing (Bakulin and Calvert, 2004, 2006) of traces recorded at virtual source position. Elimination of the unwanted phase can also be achieved by separation of the first arrivals after muting the later parts of recorded traces. We used only a small time window taken from each trace centered around the first arrivals and muted the other wave field. The mute position does not appear very critical. It should, however, contain all the wavelet we wish to use in cross-correlations.

If the real source (A-point) is located above the interface between low- and high- velocity layers, the virtual source data compared to wave field from the real source for head waves will be time delayed. It can be shown that the time delay value is proportional to A-point distance from the interface and does not depend on position of the illuminating source. For this rather simple model the head waves can be accurately restored using just one illuminating shot. In the presence of strong shallow heterogeneities an extensive summation over many such shots might be needed. The requirements for such summations will be formulated after correspondent analytical and numerical studies which are currently under way.

Multi-layered model

Real gas and oil reservoirs could be contained in layered media, which represents a set of high- and low-velocity contacting layers. In present section we compared a wave field stimulated by virtual source with field from the real source for head waves in such structure.

We have considered a multi layered model, which consists of a layer sequence dipping at 15 degrees (Figure 6). This model is a simplification of a real model from Fahud field in Oman (Mehta et al., 2007) where all shallow heterogeneous components were removed at this stage. The goal of this exercise is to determine if the head waves can be recovered by an illumination source placed on the surface with 600m offset from the well b1. The acquisition profiles have 68 receivers each with 10 m spacing sitting in both of two vertical receiver lines, named as b1 and b2. The first modeling is performed for surface point-pressure source. It is evident from the snapshot on figure 7, the incident field excites head waves, which are coming to both b1- and b2- profiles at first arrivals.

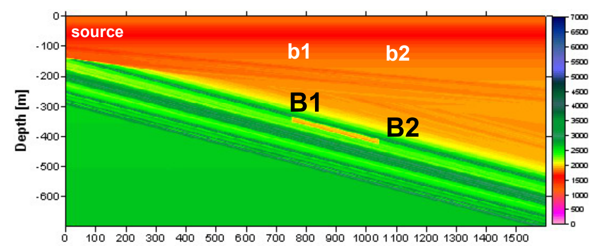

Figure 6. P-wave velocity model. White vertical lines indicate receiver lines. Red line between points B1 and B2 indicates anomaly location and amplitude in the head wave sensitivity test.

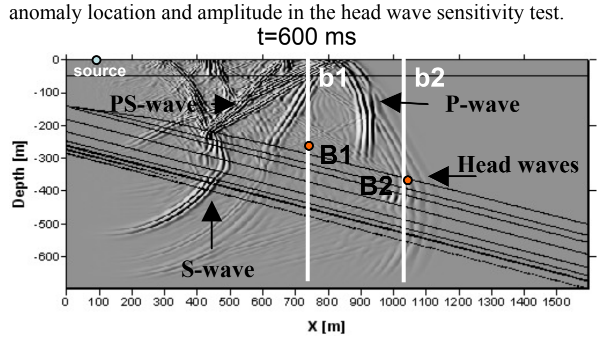

Figure 7. Snap-shot Wave propagation from surface point-pressure source in a multi layered Fahud model. The surface source excites head waves, which are coming to both b1- and b2-receiver lines at first arrivals.

To build the virtual source data, we apply similar procedures, which are described for a case of two-half space model in previous section. Since we are unable to separate the wave field properly because of its complexity, we can apply muting to later waves to remove distortions of cross-correlated results. The result of muting is shown in Figure 8 for wave field measured by receivers of b2-profile from the surface shot.

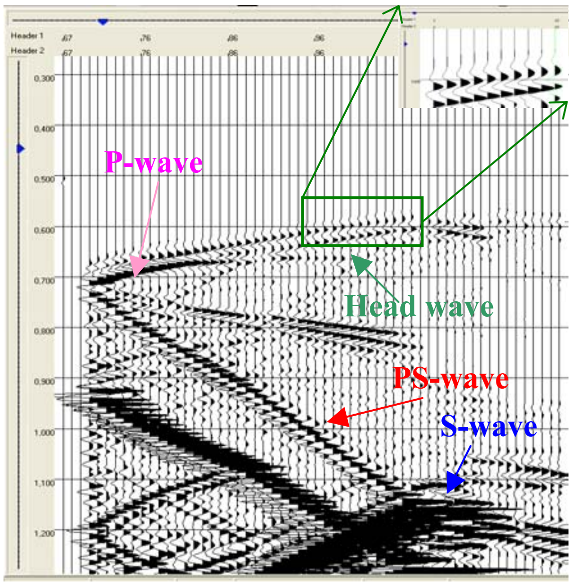

Figure 8. The response recorded by receivers of b2 receiver line for the vertical component of displacement from surface point-pressure source.

The comparison of obtained virtual source data for head wave's field with real wave field is shown in Figure 9. This single shot result does not restore true wave field amplitudes, but it correctly recovers the phase responses.

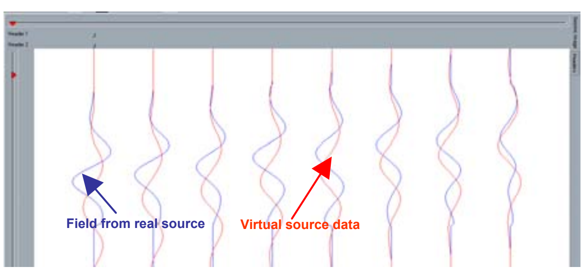

Figure 9. Comparison of restored wave field for b2-profile from the virtual source (red curve) and real source (blue curve).

The next important question is weather or not changes in the reservoir are noticeable in the head waves. We introduce a 20% lower velocity zone in one of the reservoir layers as it is shown in Figure 6 and compared the data with a background check shot. The results of comparison are shown in Figure 10. While the direct wave fields stayed the same, both P- and especially, S- head waves reveal remarkable changes in traveltimes (up to the dominant period) and amplitudes (up to 50 %) (Figure 11).

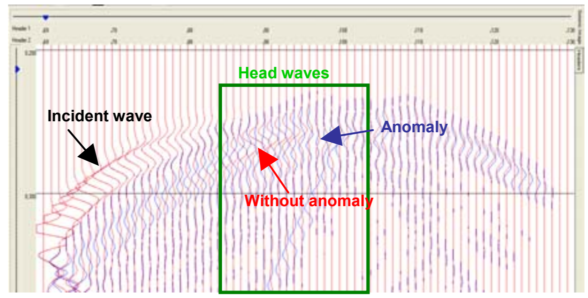

Figure 10. Influence of anomaly on the wave field excited by the point-pressure source located in the B1-point.

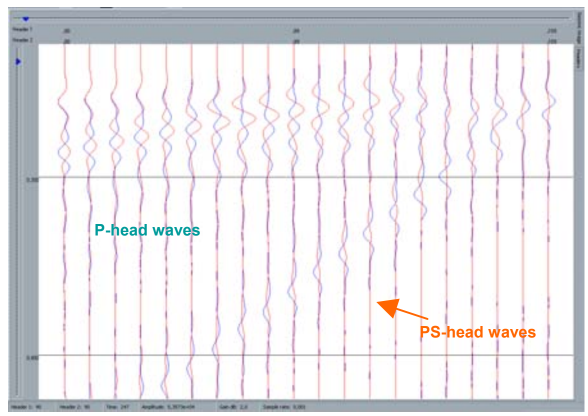

Figure 11. Blow-up of the green rectangle from Figure 10. Red curve displays the wave field without anomaly, blue curve - with anomaly.

Conclusions

Application of VSM at large offsets allows restoration of the head waves. Head waves are quite sensitive to reservoir changes for a real reservoir model and look promising for field monitoring applications. We plan to apply the method for a model containing strong shallow heterogeneity to evaluate its real abilities and properties. A 3D data set will be computed and processed aiming to obtain tomographic monitoring images of introduced anomaly in the reservoir. In present examples, we have considered a single illuminating source only. It is expected that after summation over an array of surface sources the quality of restored virtual source data will be improved.

Acknowledgments

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