P103

Head-wave Excitation with Virtual Source

M. Tatanova* (Saint-Petersburg State University), A. Bakulin (Shell International E&P), B.M. Kashtan (Saint-Petersburg State University) & V. Korneev (Lawrence Berkeley National Laboratory)

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. Application of VSM to realistic 3D model with complex near surface heterogeneous components has demonstrated many similarities in real and restored wavefields. Summation over limited number of surface shots in the vicinity of stationary point for head waves has demonstrated a better restoration of virtual source wavefield.

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.

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 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

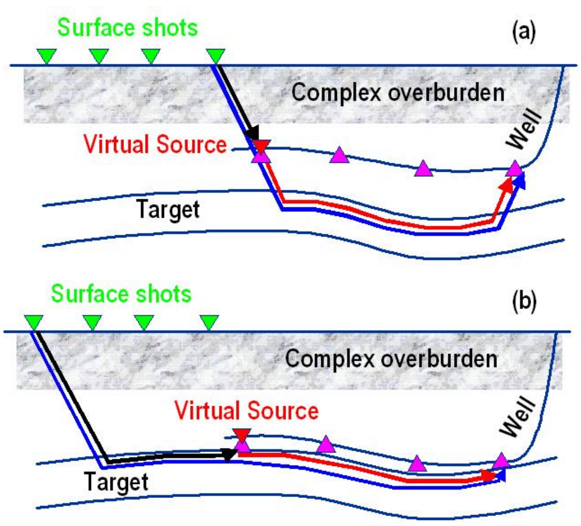

Figure 1. Scheme of virtual source method for head waves. (a)Waves emitted by a surface source (blue rays) propagate as body waves until they reach a high velocity target horizon at a critical angle and then propagate along this horizon radiating head waves. Head waves generated by a virtual source have 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.

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.

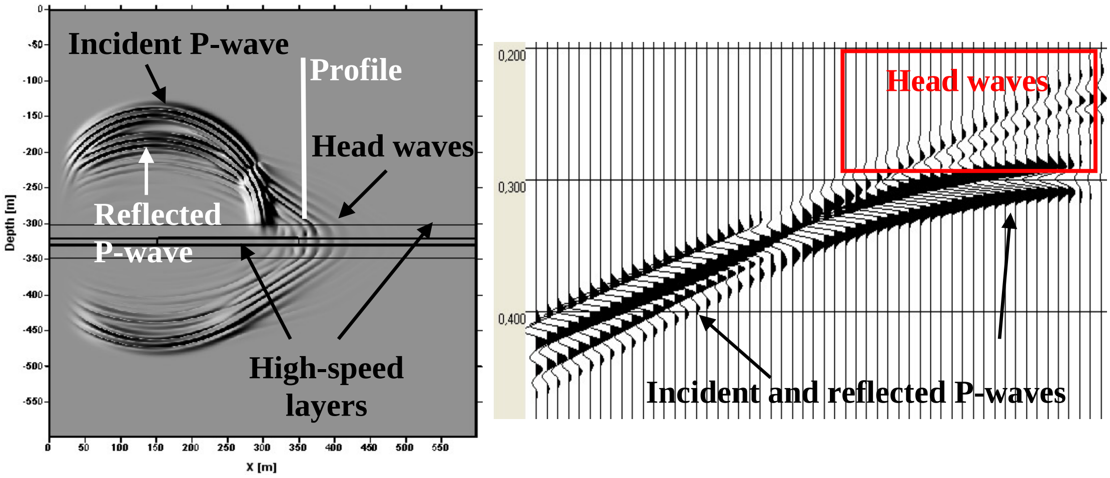

Figure 2. Wave propagation in layered media. The model is constructed of two half-spaces separated by three high-velocity layers. The acquisition geometry consists of vertical profile instrumented with 40 receivers at 5 m spacing. Head waves are coming at first arrivals as indicated on left picture. The right figure demonstrates the recorded wave field. Head waves have simple linear moveout.

- Head wave may provide significantly larger images compare to reflection surveys.

This latter statement is illustrated using Figure 3. 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.

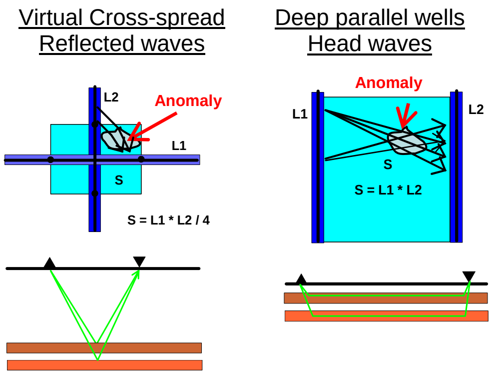

Figure 3: Plan views (upper panels) and vertical sections (lower panels) for a reflection cross-spread survey (left) and a head wave survey (right). Blue lines indicate buried at some depth horizontal wells instrumented with receivers. For the same well lengths the coverage area of the head waves is 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.
- Head waves have demonstrated a high sensitivity to the velocity and density reservoir changes and look promising for field monitoring applications.

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.

Application of VSM to realistic 3D 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 synthetic multi-layered 3D-model, which consists of a target-layer sequence dipping at 15 degrees (Figure 4) and complex near surface heterogeneous components. This is one of the typical models for Middle East (Mehta et al., 2007).

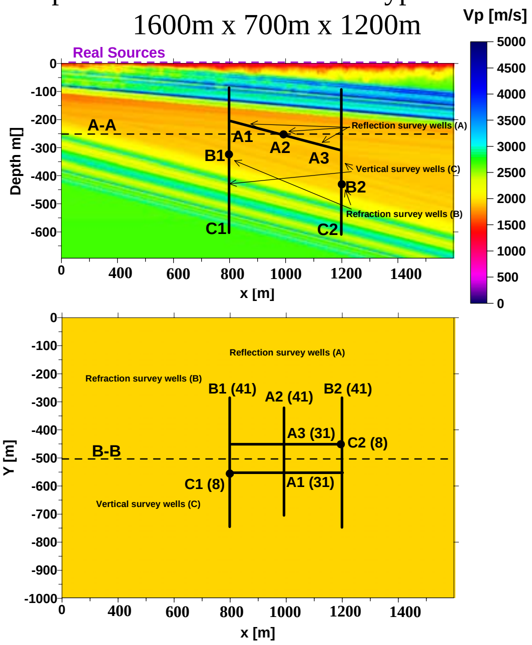

Figure 4: Realistic 3D model typical for Middle East.

The acquisition geometry consists of two horizontal wells (B1 and B2) instrumented with 82 receivers at 7.5 m spacing. The total number of real sources, located on the surface (vertical force sources) is 27354 shots, which are distanced at 7.5 m. The Virtual source method was applied to B1 and B2 wells to prove features of head waves.

If we select receiver in the well B1 as a Virtual source location and cross-correlate the recorded traces with traces recorded in B2 well then we obtain a Virtual source gather shown in Figures 5, where it is compared with ground truth response computed when the actual downhole source was placed at B1 well and receivers at well B2 have recorded the wavefield. The wavefield at first arrivals, obtained from virtual source after summation over all surface shots is looking similar to field obtained from real source (Figure 5a). However the scanning procedure has demonstrated better restoration of VS wavefield compared to ground truth response at summation over limited number of surface sources in the vicinity of stationary point (Figure 5b).

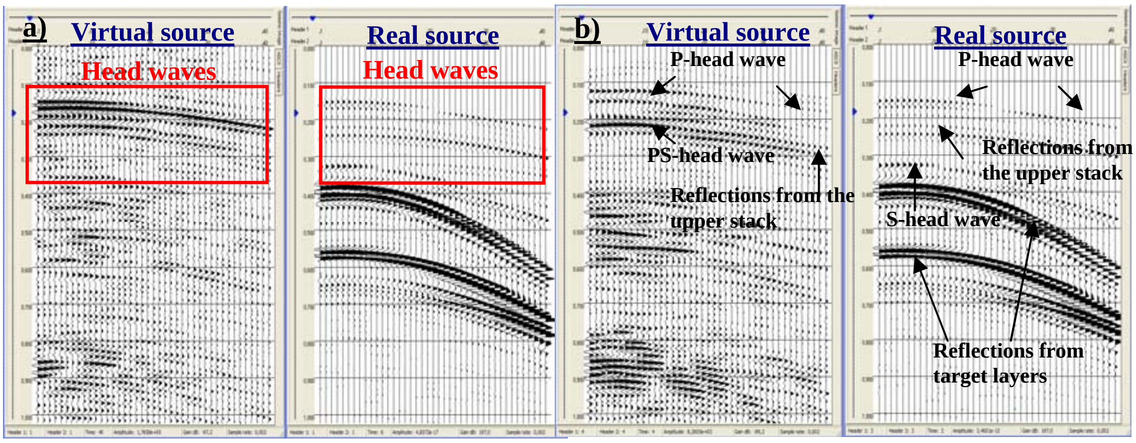

Figure 5: Comparison of virtual source field with ground truth response computed for source in B1 well and all receivers (41) of B2 well: a) when summation is performed over all source located on the surface; b) when summation is performed over limited number of surface shots located in the vicinity of stationary point. The wavefield interpretation was conducted using the finite difference code by means of simplification of 3D to 2D model.

The summation results were improved by 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. It should, however, contain all the wavelet we wish to use in cross-correlations. The wavefield interpretation was performed using the finite difference scheme after reducing the 3D model to 2D.
In some 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.

Conclusions

There is number of reasons to expect even better results when head waves are restored and used for imaging compared to reflection waves. Head waves have shown a high sensitivity to the velocity and density reservoir changes and look promising for reservoir monitoring applications. Application of VSM to realistic 3D model with complex near surface heterogeneous components has demonstrated many similarities in real and restored wavefields. Summation over limited number of surface shots in the vicinity of stationary point for head waves has demonstrated a better restoration of virtual source wavefield. We expect to get even better results by introducing an anomaly into 3D model and dealing with difference seismogram for before- and after- experiments for array of virtual sources to obtain tomographic monitoring images of introduced anomaly in the reservoir.

Acknowledgements

We thank Shell International Exploration and Production for supporting this work. The CRDF grant number RUG2 -1678-ST-07.

References

Bakulin, A., A. Mateeva, K. Mehta, P. Jorgensen, J. Ferrandis, I. Sinha Herhold, and J. Lopez, 2007a, Virtual Source Applications to Imaging and Reservoir Monitoring: The Leading Edge, **26,** N 6 (in print).

Bakulin, A., and R. Calvert, 2006, The virtual source method: Theory and case study: Geophysics **71** (4), SI139-SI150.

Bakulin, A. and R. Calvert, 2004, Virtual Source: new method for imaging and 4D below complex overburden: 74th Annual International Meeting, SEG, Expanded Abstracts, 2477-2480.

Korneev, V., and A. Bakulin, 2006, On the fundamentals of the virtual source method: Geophysics **71** (3), A13-A17

Mehta, K., A. Bakulin, J. Sheiman, R. Calvert, and R. Snieder, 2007, Removing Artifacts and Overburden Multiples from Virtual Source Data: European Association of Geoscientists and Engineers, Annual Meeting and Exhibition, Extended Abstract, E043.

Snieder, R., K. Wapenaar, K. Larner, 2006, Spurious multiples in seismic interferometry of primaries, Geophysics, 71, SI111-SI124.