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Numerical Testing of Virtual Source Method

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SUMMARY

Cross-well profiling is an important technique that produces a high resolution image between wells and provides a better delineation of rock properties. Yet, using a real downhole source is considered a major obstacle in a well logging operation. Thus, the Virtual Source Method (VSM) was introduced as an emerging technique that can virtually place a downhole source without damaging the well. This allowed us to passively use different source types on the surface with no velocity correction required for the medium between sources and downhole receivers.

Using a numerical model, we produced our synthetics and created the Virtual Source gathers. A comparison was then made between the real downhole shot gathers and the VS gathers, and we found that the direct arrivals and the reflections are matching in time. A tomogram section was then produced using the direct P-wave arrivals. Our study demonstrated that cross-well tomography can be used with the Virtual Source Method, as the inversion model that was produced showed a velocity distribution matching with the geological model.

Introduction

Cross-well seismic tomography is a technique to measure the transmitted signal between two adjacent wells to obtain a higher resolution image of the acoustic velocity or other properties (e.g. Velocities of P- and S-waves, Qp and Qs) of the area between the wells. It is often used in field development, such as time-lapse evaluation of reservoir pressure or saturation.

There are many problems which arise when using cross-well surveys. Most of these problems are associated with downhole sources. Sources must be carefully planned in order to avoid damaging the casing and the cement bond which can cause interruption in production. Using downhole sources is always determined by the condition of the well; i.e., the well temperature, pressure, and the diameter. Also, when using the cross-well technique for reservoir monitoring in time-lapse, real cross-well data requires at least one dedicated well for downhole sources. These sources cannot be physically sited in the well, and hence time-lapse survey may not be very repeatable.

The Virtual Source Method (VSM) (Bakulin and Calvert 2006, Korneev and Bakulin 2006) was introduced as an emerging technique to extract the wave field response between any two down-hole receivers using surface sources only. The VSM in cross-well tomography would circumvent difficulties of down-hole source operation by allowing simulation of the source in the well without damaging the well. This approach allows a passive use of any source type.

The objective of the research is to investigate applicability of the VSM for cross-well tomography using numerical modelling. In order to do this we computed synthetic seismograms for both 'real' downhole source and virtual downhole source (created from surface sources and receivers located in both boreholes) acquisition techniques and compared the results. We have inverted the virtual shot records to produce tomographic image and found good correspondence with the modelled geology. The effect of the number and spacing of the real surface sources was also investigated.

The Experiment

The geological model consists of a scattering layer followed by three layers at 30° dip. Two wells are perpendicular to the layers, 300m apart as illustrated in figure 1. This model represents typical situation for hard rock exploration in Australia then ore deposits are located in areas with steeply dipping layers and boreholes are drilled orthogonal to them. From that model, we produced synthetic data to create the virtual source (VS) gather. Unlike the conventional cross-well survey, the virtual cross-well method will require receivers in both wells and surface shooting to allow wave propagation between the downhole receivers in both wells. To generate synthetic seismograms we used acoustic 2D finite-difference modelling performed in Tesseral software.

Figure 2 shows the setting required to create the VS data. The method is based on using source (S_k) on the surface with downhole receivers in both wells, then cross-correlating the total wave field that travel from the surface to one downhole receiver on well A (R_{w1}) as a reference receiver with the wave field recoded at receiver on well B ($R_{w2.}$). By doing that, the field response between these two receivers $VS_{w1w2}(t)$ can be extracted as a virtual downhole source using the following formula.

$$VS_{w1w2}(t) = \sum_{k=1}^{N} S_{kw1}(t) \otimes S_{kw2}(t)$$

As one notices, this process of redatuming the source from surface to downhole does not require any velocity information above the VS. Thus, producing an image that is unaffected by the scattered near-surface.

After creating the VS data from every receiver placed in well A, a comparison was made between the real downhole and VS datasets in order to evaluate the quality of our VS data. Figure 3 (a) shows a shot gather generated by a real downhole source placed at receiver position 10 in well A, and (b) shows a virtual source gather created from cross-correlating the total wave field of the virtual source (receiver 10 in well A) with the total wave field of the receivers in well B. It can be seen that the direct arrival times match and can easily be identified in the entire record as well as the reflections. In our synthetic data, the free surface multiple was eliminated to suppress the unwanted reflections. The VS data produced spurious events observed before the first arrival. These spurious events are produced from the physical sources that feed the VS from different directions with down-going and up-going wave field. Such unwanted energy can be suppressed by gating the data to contain only the direct wave arrivals before correlation (Bakulin and Calvert 2006).
In figure 3 (a), the real downhole source radiates in all directions producing an image with reflection from above and below the reflector. However, in the VS gather, figure 3 (b), we suppress the unwanted reflections from the surface (up-going wave) due to the downward radiation pattern of the VS's (Bakulin and Calvert, 2006) because the actual sources are above the receivers and the energy feeding the VS is downward energy. This feature of the VS radiation pattern eliminated the unwanted arrivals and enhanced the reflections.

First breaks were manually picked on the direct arrivals for 29 VS location on well A, from receiver station 5 to receiver station 145 at every 5th station. In the deep VS locations, it was difficult to determine the first breaks, as the data produced more artefacts. For the deep VS's, limited first arrivals can be picked where only receivers below the VS can be considered. A set of 3114 traveltimes created from the first breaks arrivals corresponded to various source-receiver positions. For these traveltimes, the path between sources and receivers is approximated as a straight raypath. We then determined the slowness field (reciprocal of wave velocity) between all source-receiver by integrating the slowness along the known raypath that passes through certain cells.

The unknown slowness values are then estimated by solving traveltime equations to reconstruct the velocity model. Figure 4 (a) shows the inversion model created from the traveltimes dataset, representing P-wave velocity distribution. As expected, the velocity model is consistent with the original geological model, figure 4 (b), where the velocity boundaries are accurately represented in the tomography section.

VS Geometry Requirement

The geometry used on the surface can influence the quality of the VS data so surface source spacing is important. In our numerical model, we produced different synthetics with different physical source spacing, one with 15m spacing and another with 25m spacing. The VS data with 25m surface source spacing has more spurious multiples before the first arrivals and produced events in the form of ringing caused by spatial aliasing, similar that during migration, if there is insufficient sampling along the space axis (Mehta et al. 2008).

The number of surface sources summed over the correlation gathers also influences the quality of the VS image. For the same receiver position, the VS was stacked over 10 surface sources (shot 21 to 30) and then stacked over 31 surface sources. The one stacked over 31 surface shots showed clearer and sharper first arrivals. The limited source aperture can also produce artefacts. This indicates that by using wide source spacing the VS contributes more to the stationary phase and suppresses the artefacts as the VS receives energy from different directions (Snieder et al. 2006). Furthermore, in order to understand the contribution of different surface sources to the VS data, we divided the surface sources into 3 groups with different source apertures. Group 1 with shots from 1 to 10, group 2 with shots from 11 to 20, and group 3 with shots from 21 to 30. The VS gather stacked over group 3 looks similar to the VS gathers stacked with the full source aperture. However, some artefacts occur in the receivers at the shallow depth. In groups 1 and 2, the VS data had many artefacts and did not contribute to the VS data, since the wave travelling from those sources did not contain energy that could be extracted to approximate the response between the two wells. Therefore, the arrivals at other source locations contributed destructively.

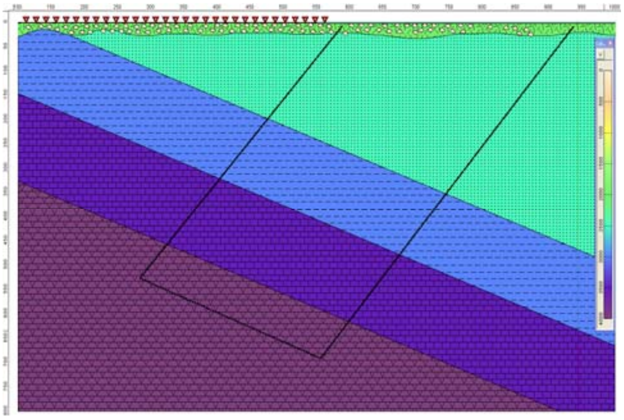

Figure 1 *This is the model designed for the experiment showing the geological structure and velocity distribution of the dipping layers.*

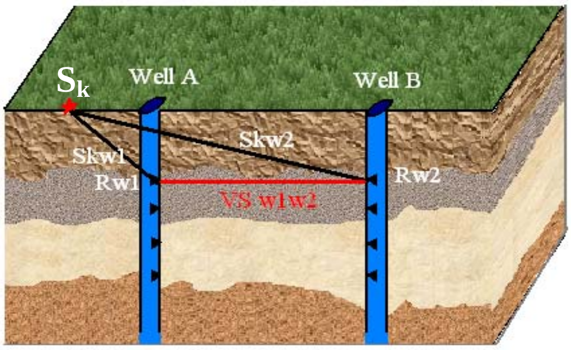

Figure 2 *A simple diagram shows the acquisition setting required to create the virtual cross-well source. Rw1 is the reference receiver (virtual source) and Rw2 is the second receiver on the adjacent well and VSw*$_1$*w*$_2$ *is the seismic response between them.*

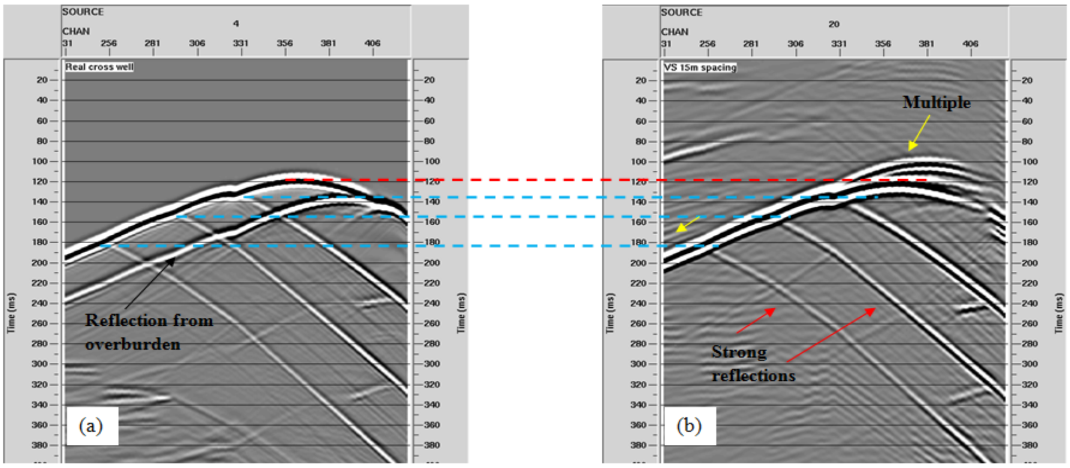

Figure 3*(a) shows real downhole source at receiver position 20 in well A, and (b) shows the virtual source gather at the same receiver location, note that the direct arrivals (red line) and reflections (blue lines) match. The yellow arrows points to a multiple and spurious events on the VS data. The reflection from overburden on (a) has been suppressed in VS image (b).*

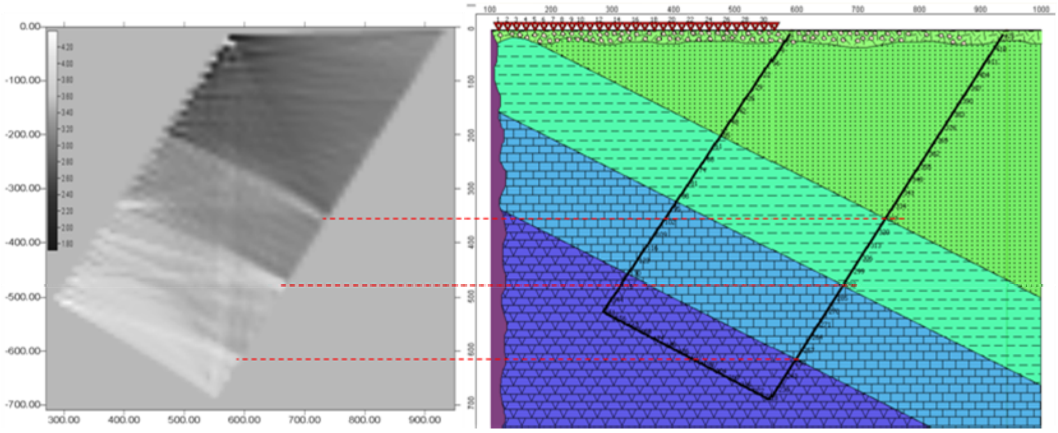

***Figure* 4** *Comparison between the velocity model constructed from the virtual source traveltime tomography and the numerical section. The broken red lines show that the layer boundaries match in depth.*

Conclusions

We demonstrated that VS can accurately reproduce the reflections and the transmission response of the wave field between downhole receivers. Using a numerical model, we were able to place a virtual downhole source in any receiver location in the well. We showed that the number of surface source and spacing used are crucial when creating virtual source gather. An inversion model was constructed from the virtual source tomography. Both the numerical and the inversion models matched, with layer boundaries agreeing in depth.
Virtual source approach has several advantages over standard cross-hole techniques:

- It could be applied in boreholes with small diameter;
- Virtual sources could be located on any depth;
- To generate virtual source various surface sources could be used, including high energy sources such as vibroseis or explosives;
- Could be used with continuous sources for extra precision;
- No additional survey time (no mechanical component required).

One limitation noted was that virtual cross-well data had lower frequency content than the real cross-well. Apart from that, it is robust and has potential applications. It also eliminates non-repeatability related to any changes occurring above the receivers. Consequently, this study indicates that we could implement the VS cross-well profiling on real data, taking into account the geometry setup required to produce accurate VS data.

References

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