Numerical and field experiments for virtual source tomography, Perth Basin, Western Australia

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SUMMARY

A virtual source method (VSM) field experiment was performed at the Mirrabooka Trial Aquifer Storage and Recovery Site in Perth Basin, Western Australia. The experiment used hydrophones deployed simultaneously in two adjacent vertical fibreglass-reinforced plastic monitoring wells. The objective was to provide detailed P-wave velocities between two wells using conventional vertical seismic profiling equipment. It was hoped that the recovery of detailed velocity distribution would provide insight into the distribution of sand and clay above and within a highly heterogeneous injection interval. For the purpose of validating the processing methods used and to gain insight into the radiation pattern of the virtual source, the field experiment was duplicated with finite element numerical modelling. For both numerical and field experiments the seismic energy was propagated using 150 surface source positions with 2 m source point spacing. The seismic energy was recorded simultaneously at two vertical boreholes with 23 hydrophones. The hydrophones on each string were spaced at 10 m intervals. For the numerical model, near-surface velocities were obtained from a refraction seismic survey. All other velocities were derived from acoustic wire-line logging and zero-offset VSP. The thickness of the unsaturated zone in the near-surface layer was approximately 5 m, with P-wave velocities ranging from 360 to 800 m/s. Beyond this was saturated sand/sandstone in which the P-wave velocity was close to 1600 m/s. We directly compare the velocity distributions derived from field and numerical modelling experiments and demonstrate that the virtual source method applied to dual vertical wells has considerable potential. Further analysis with numerical modelling indicates that detail in the crosswell velocity tomogram can potential be pushed to an even higher level of resolution by using dense receiver arrays.

Key words: Virtual source, vertical seismic profiling, tomography.

INTRODUCTION

The virtual source method (VSM) is a technique that can be used for re-datuming a set of surface sources below complex near surface layers to achieve better subsurface images. VSM requires a number of surface sources and receivers set into two boreholes recording the data simultaneously. To generate a virtual source, we simply cross-correlate the wavefield recorded in receiver R_A located in the first borehole to another receiver R_B in a neighbouring borehole, then sum the cross-correlated signals over the surface sources (Mehta *et al*., 2008a; Bakulin and Calvert, 2006). This procedure of generating a virtual source can be given by the following correlation algorithm (Bakulin and Calvert, 2006; Minato *et al.,* 2007):

$$D_{AB}(t) = \sum_{k=1}^{N} S_{KA}(-t) * S_{KB}(t)$$

where $S_{KB}(t)$ is the signal received from the k-th source at the surface and at R_B, S_{KA} (-t) is the time-reversed record from the k-th source at R_A, "*" donates convolution, and N is the number of surface source elements.

The virtual-source technique has been successfully used for performing crosswell seismic survey between two vertical wells. Mehta *et al*. (2008b) compared virtual and real sources in a crosswell seismic survey using field data obtained on two vertical boreholes. They found that VSM is kinematically comparable to real crosswell datasets, and it has several advantages over conventional cross-well surveys, including: (1) the flexibility of the virtual source to penetrate horizontally and vertically with desirable wavefield types (P- & S-waves); and (2) it can also be performed using only reflections or direct arrivals.

For a vertical borehole setting, the VSM is limited by the rays taking a downward direction from the virtual sources to the receivers. This is because, for a given surface source aperture that feeds the virtual source, the receivers at a depth below the virtual source location have a better opportunity to record the stationary phase response (Snieder *et al*., 2006; Mehta *et al*., 2008a). Thus, if two receivers are located at two different borehole and same depth, then there is no possible stationary source position. For direct arrival, a stationary condition is involved such that only the stationary source at the surface will be in the ray path which can join two receivers at two different depths with a surface source (Snieder *et al*., 2006). At this stationary source, the cross correlation-gather will show the maxima in arrival time. This arrival time is useful information for tomography. However, summing over the sources at other source locations will interfere distractively (Wapenaar *et al*., 2005; Snieder *et al*., 2006; Mehta *et al*., 2008a). Minato *et al*. (2007) found that for vertical borehole sitting, the up-going patterns of the virtual sources located in deepest sections were less recognized in their experiment because the original locations of the feeding sources were penetrate the energy downward from the ground surface.

The surface source aperture that feeds the virtual source is an important factor that must be considered to produce a reliable virtual source dataset. Mehta *et al*. (2008a) determined that using a small source aperture results in artefacts caused by the non-stationary phase contribution, which will remain after summing the cross-correlation gather in the form of low-amplitude blips. On the other hand, using a very large source aperture will also create artefacts caused by the edge effects which are associated with the sources at the end of source apertures. This type of far-offset artefact can be recognized from the slope of arrivals on correlation gather (Mehta *et al*., 2008a). For instance, on cross-correlation gather, the far offset sources tend to have a lower slope ($\Delta t/\Delta x$); thus, increasing the offset will produce a nearly flat response, which will maximize after stacking to create a virtual source gather.

In this research, VSM was used to provide velocity tomogram images between two vertical boreholes located at the Mirrabooka Trial Aquifer Storage and Recovery (ASR) site Perth, Western Australia (Figure 1). These boreholes penetrate the Leederville aquifer at depths of between 300 to 428 m below the surface (Rockwater Proprietary Ltd, 2009). The felid experiment data were acquired in two monitoring wells, M345_408 and M345_109, to increase the understanding of the aquifer's heterogeneity above and within the injection interval. At this site, conventional crosswell tomogram application using a downhole source seems to be formidable task, since this may cause near wellbore damage in specially designed monitoring and injection boreholes. Therefore, the flexibility of the virtual source approach can be alternatively used to create a virtual crosswell tomogram. To illustrate the effectiveness of the applied method, first the field data were synthesized using finite element modelling, and then a field experiment was conducted.

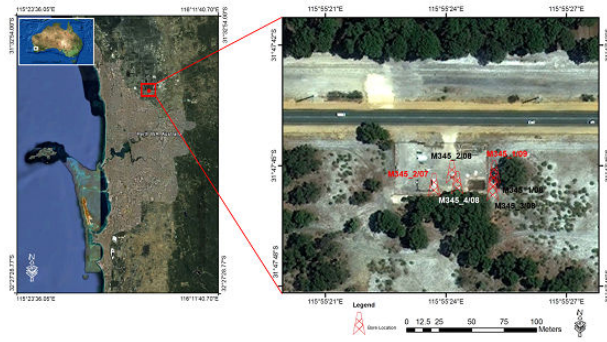

Figure 1. Map view of study site. The site consists of one injection and five monitoring boreholes (M345_207 and M345_208, _108, _109, _308, and _408, respectively). Monitoring wells M345_109 and M354_408 are used for the virtual source experiment. They are 25 m apart and both penetrate the Leederville formation from a depth 300 m to 428 m.

Synthetic virtual source

To determine the validity of the virtual source data for extracting the main features of the subsurface velocity between two vertical wells, finite element modelling with full discrete layering information had to be constructed. In this model, we simulate a similar acquisition parameter for the field experiment of walkaway vertical seismic profiling VSP acquired simultaneously in two boreholes. The acquisition geometry for the numerical model is shown in Figure 2. As can be seen, for each well, the model consists of 23 receivers spaced by 10 m. The receiver depths for well M345_109 are from 170 m to 400 m, while M345_408 is shifted with respect to M345_109 by 10 m in the Z direction. Both boreholes vertically penetrate the model layers and are separated by 25 m. A surface line of 150 shots with 2 m spacing was used to generate seismic energy.

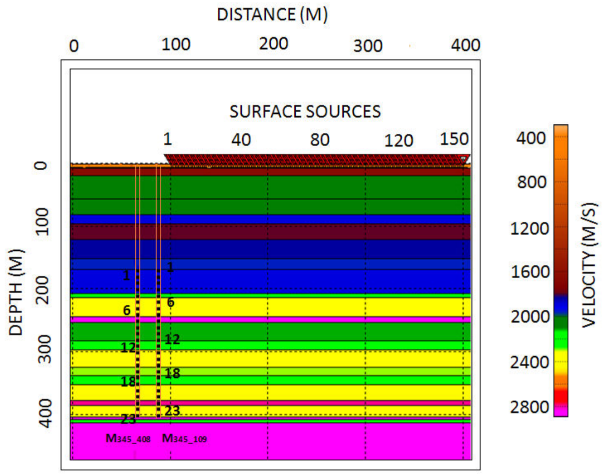

Figure 2. Numerical model used for virtual source simulation. Two vertical boreholes were used to deploy 23 receivers. Note that the receivers in borehole M345_408 are 10 m lower than those in M345_109. There are 150 surface sources with 2 m spacing. The velocity model was built by gathering the information from the refraction data, zero-offset VSP, and sonic logging.

Near-surface velocity information was included in the numerical model by using refraction data. That is, a seismic refraction line was acquired using 17 shots and 15 surface geophones. The spacing between sources and receivers was 4 m starting from borehole M345_109 and moving to the same direction of survey line that was used for the virtual source experiment. From refraction tomography, the depth of the first layer was approximately 5 m, with P-wave velocities ranging from 360 to 800 m/s; beyond this layer was a saturated sandstone layer in which the P-wave velocity was 1600 m/s (Figure 3). Up to a greatest depth of 400 m, the velocity was identified by using zero-offset vertical seismic profiling VSP and acoustic logging. Gamma rays and acoustic logs were used to find out the layers depth.

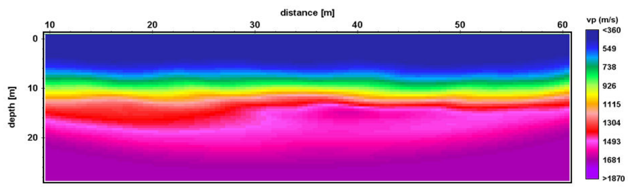

Figure 3. Near-surface velocity model obtained using a refraction survey.

Field experiment

Using a walkaway VSP dataset acquired simultaneously in two vertical boreholes, we were able to propose the VSM by projecting 150 sources into 23 hydrophones deployed at a depth of 170 m to 400 m at well M345_109. This depth interval is within the Pinjar and Wanneroo members of the Leederville formation in the Perth Basin. However, only the first 16 hydrophones were included for tomography, since the remaining hydrophones would generate unneeded up-going rays with respect to another borehole, M345-408. Borehole M345-408 contained only nine active hydrophones distributed in a depth range from 180 m to 340 m. A surface line of shots was generated at 150 source positions spaced at 2 m.

To generate virtual source data, the down-going P-wave was selected by applying a muting window around the first arrival time. This was done to remove all unneeded wavefield recorded in the original walkaway dataset and only the remaining P-wave was included for the virtual crosswell process.

METHOD AND RESULTS

In our experiment, all up-going rays gave incorrect cross-correlation time and higher velocity anomaly on the velocity tomogram. Figure 4A-C shows the cross-correlation time for three modelled virtual sources located in different positions along the borehole.

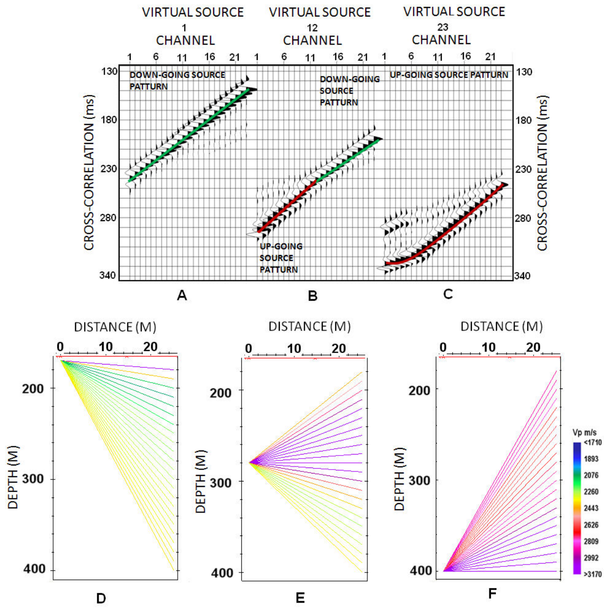

Figure 4. (A)-(C) Example of the cross-correlation time of three virtual sources located at the top, middle and bottom of the borehole. The up-going and down-going rays for each position are highlighted by red and green colour respectively. (D)-(F) Associated rays velocity for the three virtual sources are plotted.

Figure 4A and D illustrate the cross-correlation time and associated ray velocities for the upper virtual source at a depth of 170 m, where all the rays penetrate downward. These rays are given correct cross-correlation time (Δt) to measure the velocity and are fully included for tomography process. In Figure 4B and E, the cross-correlation time and associated ray velocities are presented for the virtual source located in the middle of the string where half of the rays are artificially propagating up-going (red) with high velocity. In Figure 4C and F, all of the rays are propagating upward, with only one ray close to horizontal level. All of these rays are given higher velocity values and should be removed from the final tomogram image.

Figure 5 and 6 show the velocity tomogram with associated rays obtained by the numerical and field experiment respectively. To determine the velocity tomogram, a homogenous velocity model with a single velocity value of 2000 m/s was used for both figures. As can be seen in modelled data (Figure 5), all up-going rays and low coverage areas have been removed. However, there are still higher velocity values for those rays travel near to horizontal level with smaller dipping angle, especially for virtual sources at a depth from 290 m to 340 m. Although after removing all up-going rays will result in a few numbers of rays, the remaining rays represent stable results. Indeed, the tomogram result can be improved by increasing the number of virtual sources in well M345_109 and the receivers in well M345-408.

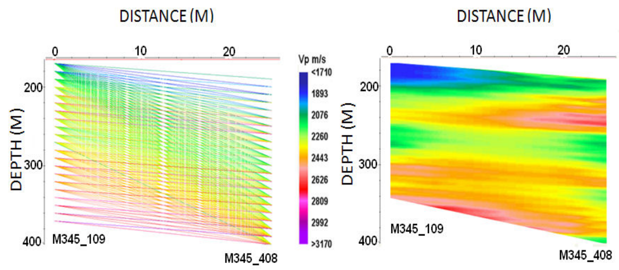

Figure 5. Velocity tomogram obtained by modelled data. On the left, the rays are plotted with colour given for velocity variation. On the right is the P-wave velocity tomogram after removing low coverage areas.

For the field experiment in Figure 6, only 80 down-going rays were used, after removing up-going rays, to obtain the tomogram image. This is because well M345_407 contains nine active hydrophones for the field experiment. As can be seen in Figure 6 (left), some areas were not covered by any ray. For instance, from a distance of 10 m to 25 m, there is a gap from a depth of 170 m to 250 m. This may cause misinterpretation of the velocity tomography. For this reason, the section at a distance of 0 to 10 m is the only part considered for interpretation proposes.

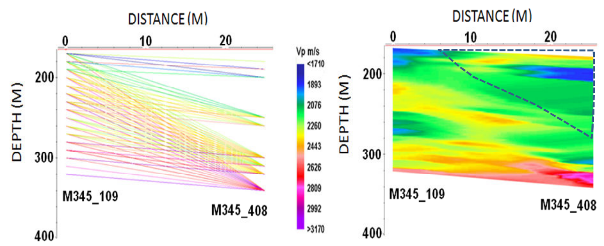

Figure 6. Velocity tomogram obtained from field data. On the left, the down-going rays are presented. On the right, the smooth version of the velocity tomogram is plotted. The highlighted dashed area on right represents the low coverage area.

To compare both field and numerical results, the areas with higher ray coverage up to 10 m distance and a depth of 320 m have been selected (Figure 7). Figure 7A and B are P-wave tomography images for field and modelled data, respectively. A homogenous single velocity layer of 2000 m/s has been used to generate both tomogram results. As can be seen, the images are quite similar, however, the field data resolution is decreasing (to the right) toward the low coverage area.

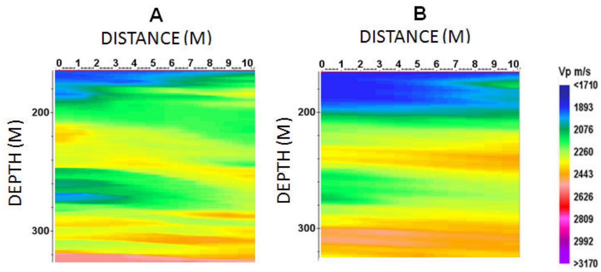

Figure7. (A) and (B) Comparison between P-wave velocity tomograms resulted from field and synthetic data respectively. The initial velocity model for the tomography computation is a homogenous layer (Vp=2000 m/s).

In Figure 8, we used the detailed velocity model which constructed by gathering the information from zero-offset VSP, acoustic logging and gamma ray (Figure 2) .The accuracy of initial velocity model between the boreholes is an important factor for tomography computation. As can be seen in Figure 8 A and B, the tomogram images are significantly improved for both field and modelled data, respectively.

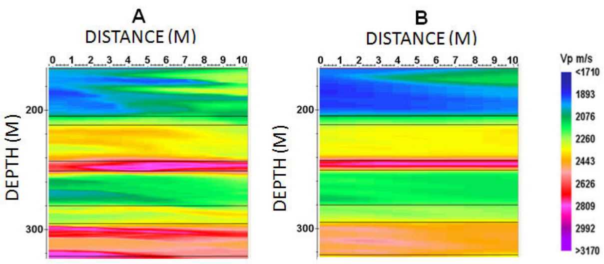

Figure 8. (A) and (B) Comparison between P-wave velocity tomograms resulted from field and synthetic data respectively. The initial velocity model used for the tomography is constructed by using zero-offset VSP, acoustic and gamma ray wire-line logging.

CONCLUSIONS

A high resolution walkaway VSP experiment was completed simultaneously in two close vertical groundwater monitoring wells. The data from this experiment were used to complete virtual crosswell tomography. Finite element modelling was used to synthesize the field data and generate a comparable virtual crosswell experiment. For synthetic data, we built a discrete velocity model using the shallow velocities derived from a refraction survey, zero-offset VSP, and wire-line logging (e.g. FWF sonic and gamma ray). The virtual source method seems highly promising for defining the heterogeneous velocity distribution in the Pinjar and Wanneroo members of the Leederville formation in the Perth Basin. There are several factors which should be taken into account to successfully perform crosswell tomography using more that one vertical borehole. These include the following: (1) only pathways from downward radiation patterns should be used, (2) the receivers should be placed in a deeper section relatively to the virtual source positions, and (3) the number of both receivers and virtual sources should be high enough to produce sufficient downward ray coverage for crosswell tomography. There are thousands of well sets (i.e. group of monitoring wells) throughout Australia and the world. All these sites are accessible to the virtual source method at minimal additional cost to a conventional walkaway VSP survey.

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