Downloaded 07/08/17 to 82.167.252.134. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

Near surface changes and 4D seismic repeatability in desert environment: from days to years

Andrey Bakulin, Robert Smith, Mike Jervis, EXPEC Advanced Research Center - Saudi Aramco and Roy Burnstad, Houston Research Center - Aramco*

Summary

We describe specific challenges of onshore seismic monitoring with buried sensors and surface vibrators in a desert environment. In particular we focus on various 4D metrics applied to pre- and post-stack data. We observe clear trends suggesting that repeatability degrades with time with the best repeatability achieved between surveys separated by days, and the worst repeatability for surveys separated by years. The similarity in trends observed for stacked data and early arrivals suggests that most of these changes are likely associated with variations in the very near surface.

Introduction

Onshore seismic monitoring in a desert environment is very challenging. While shallow burial of both sources and receivers can effectively address repeatability issues elsewhere (Schissele et al., 2009), doing so in an arid environment with a complex near surface has not yet produced interpretable results (Berron et al., 2012). Using buried receivers and surface sources is the next best option that produced repeatable results in onshore 2D tests and is in progress for an actual 3D implementation (Bakulin et al., 2012). Jervis et al. (2012) made some short-term observations (minutes-weeks) specifically highlighting non-repeatability issues associated with using a surface vibroseis source. Here we analyze seismic repeatability over the wider range from days to years and speculate on underlying causes and possible ways to address them.

Field data

We examine the repeatability of 11 repeat 2D surveys acquired over the course of 19 months. The first six surveys (S1-S6) were collected within a 3-month period, then, after a 17-month break, an additional five surveys (S7-S11) were acquired over a period of a week. The survey geometry is shown on Figure 1 and further details of the permanent 2D installation can be found in Bakulin et al. (2012). A dense carpet of nine source lines (7.5 m x 7.5 m) was shot over 80 buried receivers cemented at depths of 10, 20 and 30 m. All surveys were acquired with Mertz 26 vibrators using the same sweep parameters with most shot locations repeated to better than one m accuracy. Let us first analyze repeatability of the most reliable part of pre-stack data represented by early arrivals. Then we compare this behavior with the repeatability of stacked data.

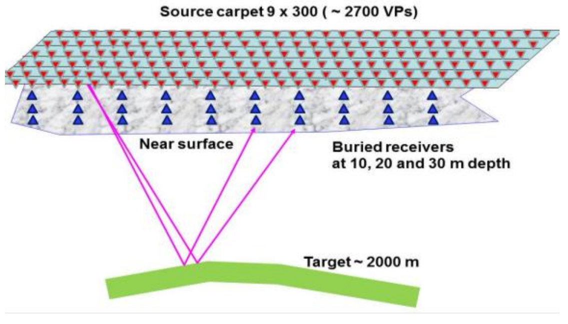

Figure 1: Sketch of the 4D test acquisition geometry.

Early arrivals

Figure 2 shows early arrivals for a small offset range around a fixed receiver buried at 30 m. It is clear that repeatability of surveys acquired with a short time interval is significantly better (Figure 2) compared to that of surveys shot with a larger time interval (Figure 3).

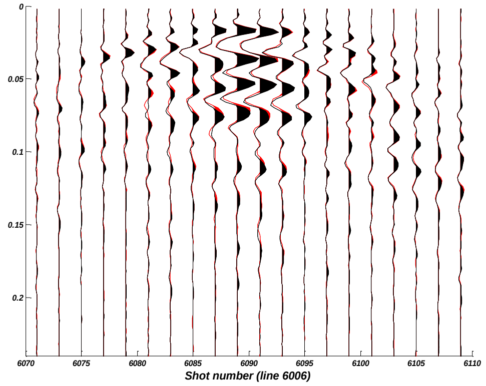

Figure 2: Overlay of common-receiver gathers for 30 m geophone from surveys S7 (black) and S11 (red) spaced by six days.

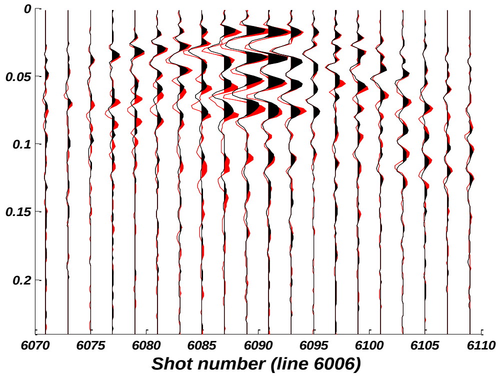

Figure 3: Overlay of common-receiver gathers for 30 m geophone from surveys S1 (black) and S7 (red) separated by 19 months.

© 2014 SEG

DOI http://dx.doi.org/10.1190/segam2014-0429.1

Downloaded 07/08/17 to 82.167.252.134. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

4D time shifts for early arrivals

To evaluate average changes over the long 17-month interval between surveys S1-S6 and S7-S11, we stack traces in each batch and then examine 4D time shifts obtained by simple cross correlation for all 80 buried receivers (Figure 4). If the 4D timeshifts are due to changes in vibrator coupling or positioning errors – then we would expect curves obtained for various offsets to be largely uncorrelated. This is clearly not the case, which suggests that the most likely cause of the observed time shifts is seasonal changes in the topmost layer of sand. This layer must be very thin as time delays at the smallest offset (propagation angle ~ 0 deg) and largest offset (propagation angle ~ 45 deg) are almost the same, even for shallower receivers (Figure 5).

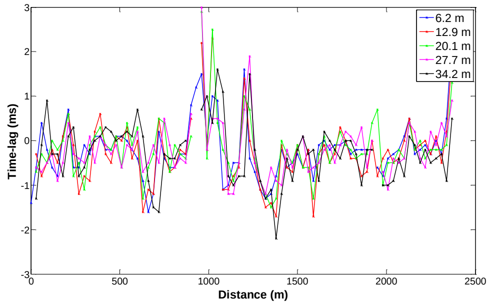

Figure 4: 4D time shifts along the seismic line between S1-S6 and S7-S11 for various near offsets obtained from 30 m deep receivers.

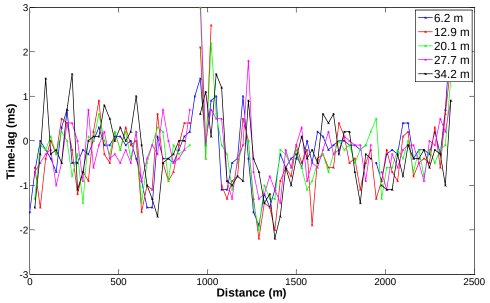

Figure 5: Same as Figure 4 but obtained from 20 m deep receivers.

Other measures of repeatability on early arrivals

It is clear from Figures 2 and 3 that early arrivals for different surveys not only change in arrival time but also in amplitude and phase. One possible measure to quantify changes beyond simple static shifts is predictability defined as

$$PRED = \frac{\sum \Phi_{ab}(\tau)\times\Phi_{ab}(\tau)}{\sum \Phi_{aa}(\tau)\times\Phi_{bb}(\tau)},$$

where Φ_{ab} denotes the cross correlation between traces a and b computed within a time window (Kragh and Christie, 2002). Predictability expressed as a percentage, varies between 0 and 100% and is not sensitive to overall static or amplitude differences between traces. If we take survey S1 as a common reference, then predictability computed for early arrivals of zero-offset traces generally exhibits a steady decline with time (Figure 6). If we examine predictability for all possible pairs of surveys S1-S6 as a function of return time (time between surveys), we observe a clear decrease in predictability indicating deteriorating repeatability with increasing return time (Figure 7). We refer to this trend as a “return time curve” for repeatability. As such we can declare that there are additional changes in the near surface beyond simple time shifts that keep accumulating with calendar time. Another measure of repeatability is normalized RMS that is sensitive to all possible changes including overall static or amplitude differences. NRMS variations along the seismic line versus return time (Figure 8), show a similar trend where values are smallest for closely spaced surveys S10-

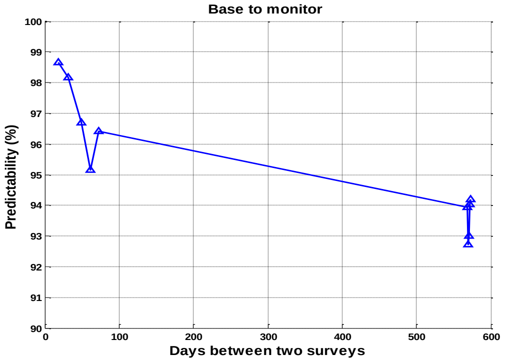

Figure 6: Average predictability computed for early arrivals (from zero-offset traces) using 11 repeated surveys with S1 as the baseline survey.

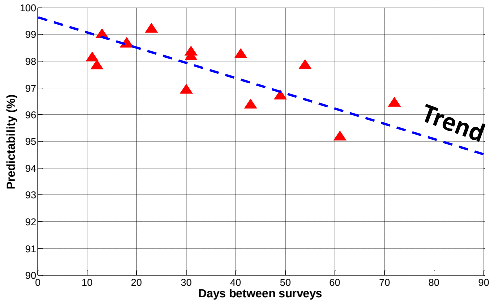

Figure 7: Average predictability computed for early arrivals (from zero-offset traces) for all 15 pairs of surveys S1-S6 as a function of survey interval and the resulting return time curve.

DOI http://dx.doi.org/10.1190/segam2014-0429.1

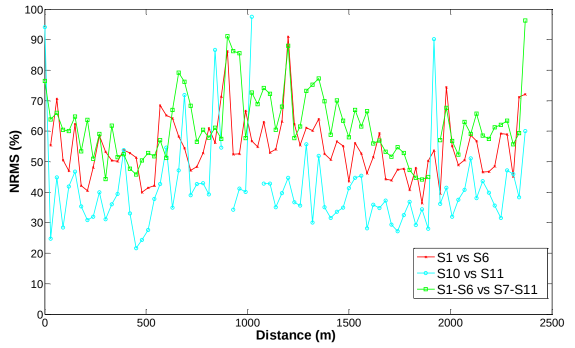

Figure 8: NRMS computed for early arrivals (from zero-offset traces) using three different survey combinations.

S11 (one day apart), whereas it is larger for S1-S6 (2.5 months apart) and highest between S1-S6 and S7-S11 separated by 17 months. We can speculate that both travel time and amplitude changes are likely related to variations in the topmost sand layer, causing different receiver ghosting. This is also evident from buried source/buried receiver data, which shows almost perfectly repeatable direct arrivals but much less repeatable later arrivals (not shown here).

Post-stack repeatability

Similar repeatability observations can be made on stacked data. After basic processing and stacking without match filtering or image warping we obtain the stack traces shown in Figure 9. Traces appear to be fairly consistent within the first (S1-S6) and second (S7-S11) batch of surveys. There is a clear mismatch between the two batches. If we quantify the repeatability using NRMS for a short window around the reservoir and use S1 as a baseline (Figure 10), then we see NRMS increasing with time and experiencing a 30 % jump in the 17 months separating S6 and S7. When we compute repeatability using the previous survey as a reference then we observe smaller NRMS values of around 15-20 % for S1-S6 and S7-S11. An important observation is that even for a shorter time period, such as three months (S1-S6), we do clearly see increasing NRMS implying deteriorating repeatability (Figure 11). Analyzing this behavior for different survey combinations, we can generally see that NRMS increases proportional to the return time between the surveys (Figure 11). It remains unclear if there is a seasonal cycle over the entire period, since our observations continuously cover only 2.5 months with no significant weather events

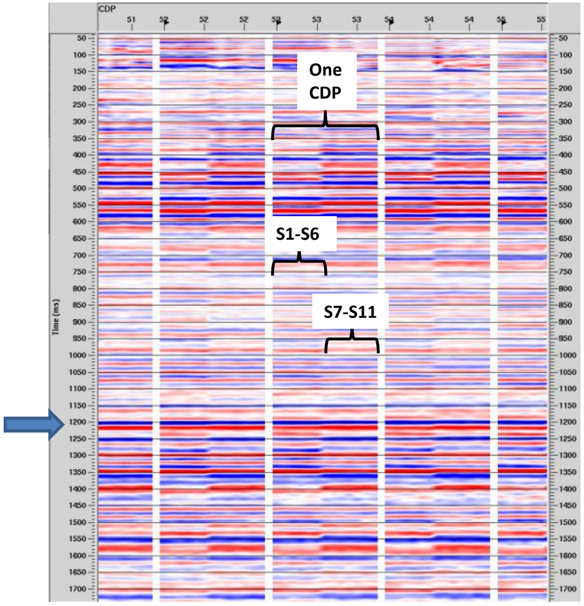

Figure 9: Stacked traces from surveys S1-S11 .

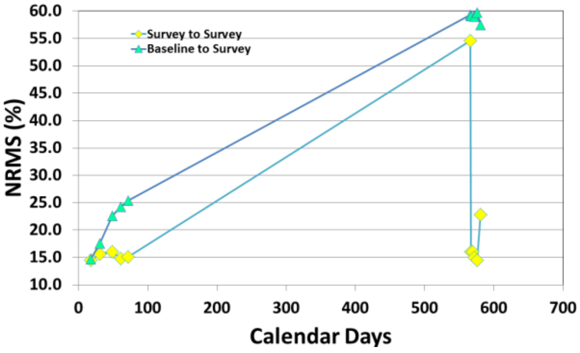

Figure 10: Stacked NRMS over reservoir window computed using two approaches: baseline survey S1 was used as a common reference (yellow); and survey-to-survey (green).

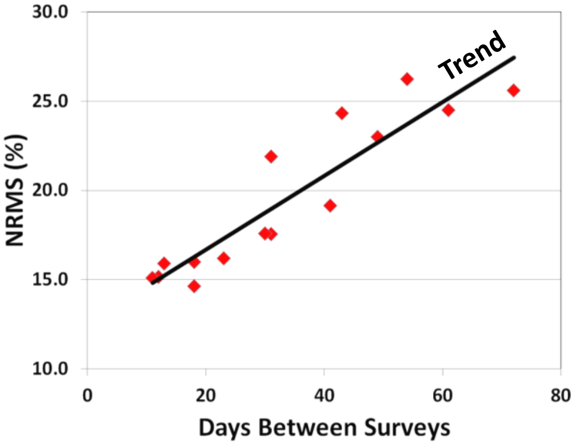

Figure 11: NRMS computed from stacked sections over the reservoir window for all 15 pairs of surveys S1-S6 as a function of survey interval and the resulting return time curve.

Downloaded 07/08/17 to 82.167.252.134. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

Downloaded 07/08/17 to 82.167.252.134. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

occuring during the two acquisition periods S1-S6 and S7-S11. With seismic monitoring during future CO_2 injection, we expect to have continuous acquisition throughout the year (one survey per month), which should provide additional insight into the nature of these variations.

Discussion

While buried receivers significantly enhance repeatability of land 4D seismic data in a desert environment (Bakulin et al., 2012), significant non-repeatability remains associated with use of a surface vibroseis source, as well as near-surface daily and seasonal variations. Our observations show that both post-stack and pre-stack data (early arrivals) exhibit similar trends with repeatability declining over time when referenced to a fixed baseline survey. At the same time, repeatability between surveys close in time appears to be better. The fact that repeatability of early arrivals for different depth receivers seems to follow a similar trend (return time curve) as for stacked data suggests that the majority of the changes are associated with extremely shallow near-surface variations, at least for larger return times. Additional tests conducted with very shallow buried receivers (0-300 cm) recording using buried sources, also seems to support the observations that only the topmost sand layer experiences daily and seasonal changes (P. Roux, personal communication). It should be noted that the water table in the area, present at a depth of around 70 m, does not show annual depth variations of more than 0.1 m. While observed effects are reported using buried receivers, there is little doubt that 4D seismic with surface receivers/sources will be likewise affected to an even larger degree. Clear examples contrasting repeatability obtained with buried and surface receivers in this environment were presented by Bakulin et al. (2012) and Jervis et al. (2012).

Conclusions and way forward

Reported observations reveal quite good repeatability over relatively short time periods using buried receiver data with a surface vibroseis source. Significant challenges remain when monitoring over longer periods due to daily and seasonal near-surface variations. These challenges are being addressed via high source density and continuous acquisition, as well as novel processing strategies. Frequent monthly surveys using a permanent 3D installation will allow us to fully and frequently sample seasonal changes as they occur as well as actual 4D signal. These changes are expected to occur on different temporal and spatial scales. The high temporal sampling should provide a better opportunity to separate 4D signal from noise by multi-survey 4D processing. Better repeatability between month-to-month surveys will also allow us to capture the fast reservoir changes expected during early CO_2 injection. In addition, we will rely on full-fold and full-azimuth 3D surveys with dense shot and buried receiver sampling that are expected to undershoot many near-surface complexities, such as karsts, and deliver better quality data that was not achievable in low-fold 2D tests. 4D binning may play a role in weighting different data to optimize repeatability (Johnston, 2013). In processing, a variety of 4D approaches exist to further reduce observed non-repeatability, including physics-based methods to ad hoc cross-equalization approaches. For example, data-driven redatuming such as the virtual source method (Bakulin and Calvert, 2004) promises to reduce the impact of seasonal changes and coupling variations (Alexandrov et al., 2012). Surface-consistent matching filters may be extended to multi-survey time-lapse processing (Almutlaq and Margrave, 2013). Novel overburden correction methods relying on frequent surveys (Burnstad et al., 2012; Burnstad, 2013) may address specific non-repeatability issues. While each of these techniques may be most effective when applied pre-stack, the biggest challenge for all of them remains the generally low signal- to-noise ratio of onshore pre-stack data in Saudi Arabia. Pre-stack noise removal techniques mix traces and leave significant residue of non-repeatable shot-generated noise. As a consequence it is likely that (pre-stack) data quality will determine the success of each of these 4D processing techniques in a complex desert environment.

Acknowledgments

We would like to thank Saudi Aramco for allowing us to publish this work and CGG-ARGAS for support in these 4D tests.

DOI http://dx.doi.org/10.1190/segam2014-0429.1

http://dx.doi.org/10.1190/segam2014-0429.1

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2014 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Alexandrov, D., A. Bakulin, R. Burnstad, and B. Kastan, 2012, Improving land seismic repeatability with virtual source redatuming: Synthetic case study: Presented at the 82nd Annual International Meeting, SEG.

Almutlaq, M., and G. Margrave, 2013, Surface-consistent matching filters for time-lapse seismic processing: Geophysics, **78**, no. 5, M29–M41, http://dx.doi.org/10.1190/geo2013-0049.1.

Bakulin, A., R. Burnstad, M. Jervis, and P. Kelamis, 2012, Evaluating permanent seismic monitoring with shallow buried sensors in a desert environment: 82nd Annual International Meeting, SEG, Expanded Abstracts, doi: 10.1190/segam2012-0951.1.

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.

Berron, C., E. Forgues, A. Bakulin, M. Jervis, and R. Burnstad, 2012, Effects of complex near surface on 4D acquisition with buried source and receiver: Presented at the 82nd Annual International Meeting, SEG.

Burnstad, R., 2013, Correcting time-lapse seismic data for overburden and recording effects: U. S. Patent Application US20130033961.

Burnstad, R., A. Bakulin, M. Jervis, and D. Alexandrov, 2012, A novel method of 4D analysis and application to land seismic data with buried receivers: 74th Annual International Conference and Exhibition, EAGE, Extended Abstracts, E012.

Jervis, M., A. Bakulin, R. Burnstad, C. Berron, and E. Forgues, 2012, Suitability of vibrators for time-lapse monitoring in the Middle East: 82nd Annual International Meeting, SEG, Expanded Abstracts, doi: 10.1190/segam2012-0948.1.

Johnston, D., 2013, Practical applications of time-lapse seismic data: DISC, SEG.

Kragh, E., and P. Christie, 2002, Seismic repeatability, normalized rms, and predictability: The Leading Edge, **21**, 640–647, http://dx.doi.org/10.1190/1.1497316.

Schisselé, E., E. Forgues, J. Echappé, J. Meunier, O. de Pellegars, and C. Hubans, 2009, Seismic repeatability — Is there a limit?: 71st Annual International Conference and Exhibition, EAGE, Extended Abstracts, V021.

Downloaded 07/08/17 to 82.167.252.134. Redistribution subject to SEG license or copyright; see Terms of Use at http://library.seg.org/

© 2014 SEG

DOI http://dx.doi.org/10.1190/segam2014-0429.1