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A Novel Method of 4D Analysis and its Application to Land Seismic Data

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SUMMARY

An alternative to traditional 4D seismic repeatability metrics is proposed. The new metric is based on surface consistent, iterative least-squares analysis of pre-stack seismic data in common source and receiver domains. It is simultaneously estimated across multiple time-lapse seismic surveys. Two sets of scalars are produced, one that is common to all surveys, and one that changes with each survey. The second set of scalars contains information on 4D repeatability. The new repeatability analysis method is applied to data acquired for a seismic monitoring experiment in a carbonate oil field in Saudi Arabia. The results indicate that buried hydrophones are less repeatable than the colocated geophones. These conclusions and the new metric are confirmed using post-stack normalised root mean square (NRMS) repeatability analysis on data recorded using high source density 2D swath line acquisition into the same permanent receivers.

Introduction

Time-lapse seismic monitoring requires acquisition and processing systems that are repeatable, and are capable of minimizing stationary and time-dependent noise. Ideally, seismic events recorded using the same acquisition equipment and parameters over the same area at different times, change only according to acoustic or elastic property changes in the zone of interest. If the expected changes are small, such as fluid changes in low porosity carbonate reservoirs, then time-lapse surveys may need to be repeated more frequently than several times per year to improve the 4D signal to noise ratio. Perfect repeatability is difficult, if not impossible, to achieve with conventional seismic acquisition equipment and methods. Time-lapse acquisition surveys are evolving into permanently installed source and receiver systems where seismic acquisition can be continuous, and problems in non-repeatability due to positioning errors and near-surface effects can be minimized (Meunier et al., 2001). In permanent monitoring systems, sensors are typically cemented into shallow boreholes, while sources may or may not be fixed permanently. Once installed, the seismic monitoring systems must be quantitatively evaluated for repeatability before reservoir changes can be reliably measured.

There are several seismic attributes commonly used for measuring seismic survey repeatability. One of the first metrics established in the industry is based on the normalised root mean square (NRMS) amplitude difference between results from two seismic surveys. Using NRMS as a metric has its own drawbacks given its sensitivity to the signal-to-noise ratio (SNR) of the input data (Pevzner et al., 2010). Typically, pre-stack NRMS estimates are too high and unstable to relate to expected reservoir changes, especially in areas that require high-fold, wide-azimuth stacking to image the target. Comparing source and receiver configurations using stacks has its own drawbacks given surface signatures are combined and processing choices can add variation to SNR levels.

In this paper we propose a new repeatability measurement that does not require stacking of the seismic data. The analysis is derived from pre-stack least-squares analysis of residual 4D amplitude scalars computed across multiple time-lapse surveys. The main advantage of the new technique over conventional NRMS analysis is it robustly estimates repeatability on low signal-to-noise ratio pre-stack data. The new method uses computed source and receiver scalars to provide a direct indication of repeatability for individual acquisition components. This new analysis is demonstrated on seismic monitoring field experiments conducted over a carbonate reservoir in Saudi Arabia. Results comparing buried hydrophones and geophones indicate the least-squares repeatability metric could complement, or replace, the standard NRMS analysis.

Method

The proposed workflow consists of pre-processing of the pre-stack seismic data followed by computation of surface-consistent coupling scalars. First, all shot records from each time-lapse survey are pre-conditioned by applying noise removal and normal moveout corrections. A time window near the target is then selected to calculate the average absolute amplitude for each trace. A surface consistent algorithm (Cambois and Stoffa, 1992) then reduces these measurements into common-source and common-receiver terms in a least-squares sense. The source and receiver terms have two components: one is an average for all surveys and the other is common to each individual survey. The scalars with components common to each survey represent a residual 4D amplitude level which is related to survey repeatability. That is, if the acquisition system is perfectly repeatable, each survey's residual 4D amplitude would be 1. Since this is not the case, the standard deviation of the residual 4D amplitudes is computed to use as the repeatability metric. A unique feature of this solution is that surface-consistent coupling corrections and repeatability metrics are estimated simultaneously for all the surveys. The 4D residual amplitude values can be plotted in section, map or histogram form. The histogram plot is a convenient way to compare different land acquisition options, such as hydrophones versus geophones or sensors buried at different depths.

Field Study

This new 4D repeatability analysis method is demonstrated using data from a reservoir monitoring feasibility study conducted over a carbonate reservoir in Saudi Arabia. One of several tests conducted in this study was repeat cross-spread surveys recorded using two permanent sensor types. The acquisition layout consists of a surface vibrator source line shooting perpendicular to a receiver line consisting of both buried hydrophones and geophones. Eighty receiver stations are spaced at 30 m and cemented with multiple sensors at different depth levels up to 30 m deep. The "dry" hydrophone is encased in a fluid-filled vessel, while the geophone stations are configured with four bunched sensors wired in series. The cross line component consists of 266 single vibrator positions spaced at 7.5 m which crosses the receiver spread near the center of the spread. The seismic line was acquired six different times with an average time interval between surveys of 20 days.

Preconditioning of the field data includes 4:1 source summation (from a 7.5 m to 30 m group interval), 3D linear noise attenuation (Figure 1) and normal moveout correction. A window above the target reservoir is used to measure average absolute amplitudes and these measurements are input to an iterative least squares analysis that processes all six surveys simultaneously. Receiver coupling scalars computed for both geophones and hydrophones are compared at each station (Figure 2). Histograms of residual 4D amplitude (Figure 3) highlight the repeatability differences between the colocated receiver types. Standard deviation analysis of residual 4D amplitudes (annotated in Figure 3) is used to compare the survey's repeatability.

To validate this pre-stack least-squares repeatability measurement, additional data were acquired along the line of receivers using a dense source pattern to produce a reasonable quality stack image for conventional post-stack NRMS analysis. Approximately 3000 vibrator positions were acquired during each survey to provide the benchmark data. NRMS measurements between consecutive surveys were made on the hydrophone and geophone stacks. Post-stack mean NRMS values for each survey are compared to the pre-stack least-squares repeatability metric (Table 1). Both metrics clearly indicate the hydrophone has more 4D noise (is less repeatable) when compared to the geophone. A second comparison of the pre-stack repeatability metric to NRMS versus geophone depth is provided (Table 2). Both metrics show a major improvement in observed repeatability when the receiver burial depth is increased from 10 to 20 m.

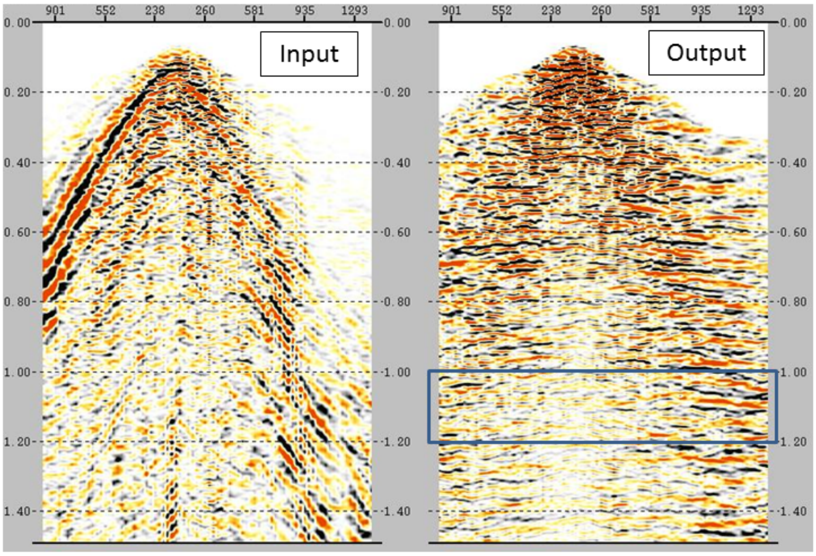

Figure 1 *An example of 3D FK filtering applied to a geophone source record for noise attenuation. Preconditioning steps such as 4:1 shot summation, receiver elevation correction, normal moveout correction and display gain are applied on both sections. Pre-stack trace amplitudes extracted above the target level (black rectangle) are input to the surface-consistent least-squares analysis.*

Summary

A novel repeatability metric has been demonstrated that does not require stacked data. The metric is based on surface-consistent pre-stack least-squares analysis of trace amplitudes across multiple time-lapse surveys. The standard deviation of the surface consistent scalars provides information on the repeatability of both sources and receivers. The new method has advantages over NRMS by robustly estimating surface-consistent coupling and repeatability on low signal-to-noise ratio, single fold, pre-stack data. Independent acquisition and NRMS analysis using the same receiver spread confirms the validity and improved sensitivity of the new repeatability metric.

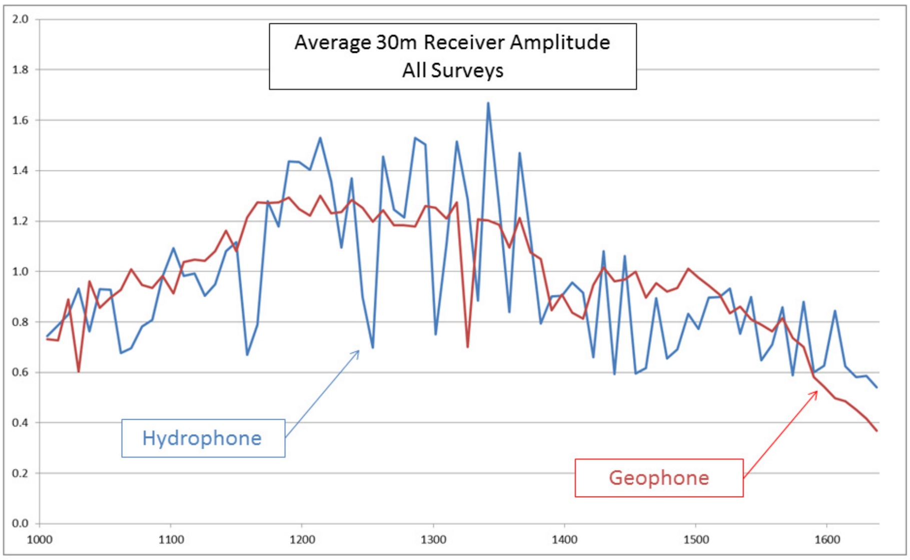

Figure 2 *A plot of average receiver coupling amplitudes based on iterative least-squares analysis of multiple time-lapse surveys. The horizontal axis is the station number along the line. Values for buried hydrophones (blue line) indicate wide variations in coupling as compared to the colocated geophones (red line). Visual analysis of field records confirms these results.*

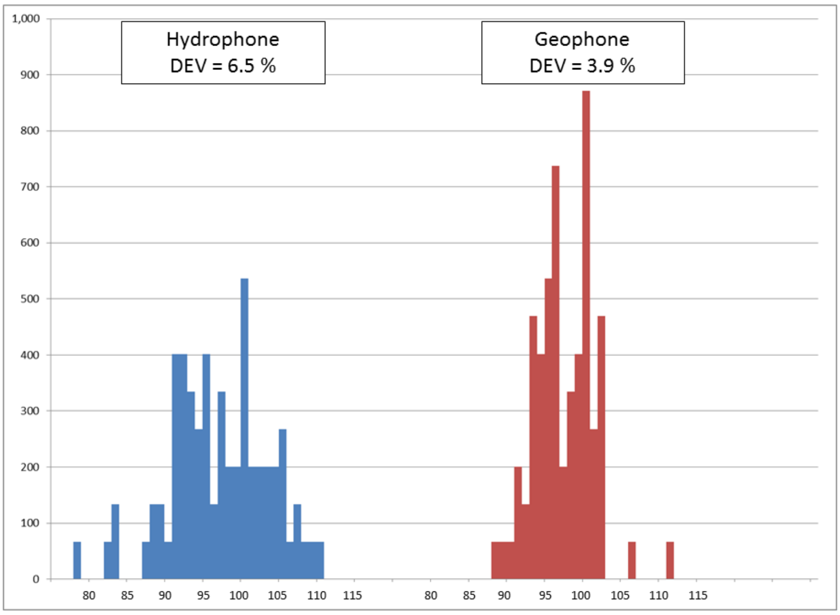

Figure 3 *Common-receiver residual 4D amplitude histograms based on iterative least-squares analysis of multiple time-lapse surveys. These histograms for the sixth survey compare hydrophones*

and geophones buried at 30 m. Standard deviation analysis indicates the hydrophones, in general, will generate higher levels of 4D noise as compared to the colocated geophones.

Survey	GEO 4D AMP DEV %	HYD 4D AMP DEV %	GEO NRMS%	HYD NRMS %	
1	3.5	9.8			
2	4.1	6.0	22.8	28.9	(s2 v s1)
3	(9.4	37.4)	23.1	31.7	(s3 v s2)
4	4.3	5.7	25.9	40.0	(s4 v s3)
5	3.4	5.3	25.2	39.7	(s5 v s4)
6	3.9	6.5	26.4	39.7	(s6 v s5)
Average	3.8	6.6	24.7	36	

Table 1 *Standard deviations of residual 4D amplitudes for geophones and hydrophones based on iterative least-squares analysis (columns labelled 4D AMP DEV %) are compared to post-stack NRMS estimates from an independent high-fold survey that used the same receivers. Average values of standard deviation do not include survey 3 due to numerous source skips in that survey. An apparent decrease in repeatability for hydrophones is shown by both repeatability metrics.*

GEOPHONE DEPTH	PRE-STACK 4D AMP DEV (%)	POST-STACK NRMS (%)
10m	12.7	29.0
20m	4.7	23.0
30m	4.4	23.0

Table 2 *A second comparison of standard deviations of residual 4D amplitudes for three different geophone depths based on iterative least-squares analysis run simultaneously on five surveys. For comparison, mean post-stack NRMS estimates from an independent high-fold survey, that used the same receivers, are listed in the right-hand column. The decrease in 4D repeatability for shallower geophone depths is observed in both repeatability metrics.*

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