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Suitability of vibrators for time-lapse monitoring in the Middle East

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Summary

A series of land surface vibrator repeatability tests were conducted in Saudi Arabia as a part of a feasibility experiment for permanent monitoring. While post-stack repeatability of 15% to 20% was achieved, pre-stack seismic repeatability is difficult to accurately quantify. If we can understand the main controlling factors behind pre-stack vibrator repeatability, we stand a chance to improve upon these results. This study focuses on pre-stack repeatability metrics for field data acquired using a surface vibrator and a combination of surface and cemented buried geophones. A series of six 2D surveys were repeated as well as daily and hourly sweep tests. Observations suggest that the main factors affecting seismic repeatability include vibrator geometry errors (as small as 0.5 m), and how the vibrator interacts with the near surface. It was observed that the initial sweeps acquired with a vibrator show significant time and amplitude variability as measured by both the surface and deep cemented sensors, whereas data recorded from later sweeps appears more repeatable. This initial "warming up stage" followed by a more stable sweep was observed on all repeat acquisition tests, even when sweep sequences were only one hour apart. This effect may be caused by ground compaction, with some partial rebound within a short time following termination of the sweep sequence. Due to all these factors, it is clear that land seismic data acquired using a surface vibrator has some inherent non-repeatability, even when the source positioning errors are minimal.

Introduction

Desert environments represent a significant challenge for seismic imaging and 4D reservoir monitoring. Industry is addressing imaging challenges by dramatically increasing the source and receiver effort to properly illuminate the targets with a sufficient signal to noise ratio to obtain good quality data. It would be highly desirable to use surface vibrators for 4D acquisition. This requires a good understanding of the stability of the repeated vibroseis sweeps and the seismic repeatability that could be achieved over time. This study focuses on the analysis of pre-stack seismic data repeatability based on a comprehensive field experiment conducted in one of the onshore oil fields in Saudi Arabia.

Land repeatability

In marine 4D seismic, the single most important factor is repeatability of the acquisition geometry (Calvert, 2005). This is because energy sources are placed in a simplified overburden or near surface represented by the water layer. Errors in acquisition geometry cause non-repeatability in the data that is amplified by the complexity of the overburden. Repeatability is typically measured using the normalized root-mean-square amplitude (NRMS) difference between two traces. Figure 1a shows an example of pre-stack NRMS calculated for marine 3D vertical seismic profile (VSP) data using a 0 to 2 s time window of recording from a single deep geophone (Landro, 1999). In this case, source geometry errors of greater than 20 m were considered too great to include the data in time-lapse analysis.

To put land seismic into perspective, we compute analogous synthetic land NRMS using a fixed buried receiver at 30 m as in the field experiment described in Figure 1b. We used only short offset data (< 60 m) and the same time window. One can see that the slope of the land variogram is significantly steeper. Therefore, a much smaller geometry error on land causes a much larger increase in the non-repeatability or 4D noise from survey

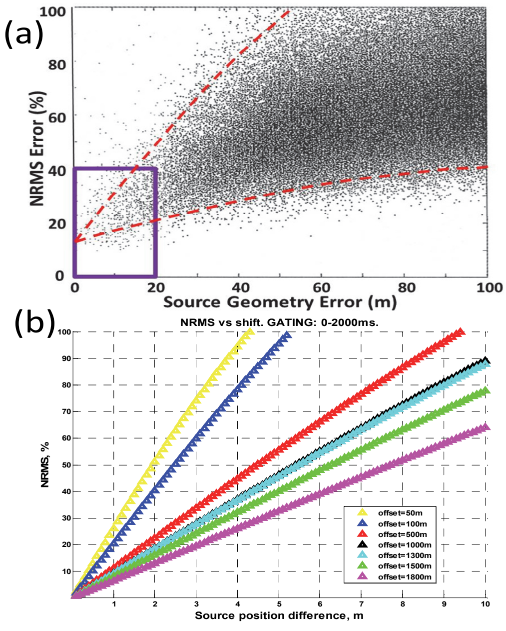

Figure 1: Comparison of 4D variograms for marine and land: (a) 3D VSP variogram from the North Sea obtained with a single deep receiver (after Landro, 1999) and (b) synthetic land variogram obtained with a single buried receiver at 30 m for the 1D realistic model shown in Figure 2d. Note that same level of NRMS is reached for much smaller geometry errors in the land case. Error bars for the 3D VSP data are similar to those for the land case in Figure 2b.

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to survey. This is confirmed by field data (Figure 2). These larger differences can be attributed to significantly more complex overburden in the onshore case. Thin near-surface layers with high-velocity contrasts, karsting, sand layers, all scatter and absorb energy very differently depending on the actual source and receiver geometry; magnifying any geometry differences during acquisition. In addition to these effects there are source and receiver coupling variations and near-surface seasonal and diurnal changes further adding to the challenge of seismic monitoring on land.

Here we present some initial observations from the field experiment in an attempt to better understand vibrator repeatability.

Field tests

To evaluate vibrator repeatability we use data from 80 receiver locations along a 2D seismic line each separated by 30 m. The sensors include 12 bunched geophones buried under 10 cm of sand and cemented geophones at a depth of 30 m. Acquisition used a single Sercel M26HD/623B surface vibrator with a 12 second sweep from 4 to 124 Hz. Two sets of data are used comprising (1) a 2D line shot with 7.5 m spacing repeated six times over period of four months, and (2) a series of hourly and daily tests with the vibrator permanently placed at one location.

The repeat surveys were used to evaluate geometry errors, whereas the stationary vibrator tests were used to study the effects of variable coupling and daily/seasonal variation in the immediate near surface. The ultimate goal was to quantify the relative contribution of each of these factors into the overall non-repeatability of 4D surveys, however, here we report initial observations on significance of each factor.

Positioning errors

A way to evaluate the effect of source geometry errors is by looking at the first arrivals for repeat seismic surveys. The results presented here are computed on the near-offset traces from the surface vibrator to 30 m buried receivers (Figure 2a) and concentrate on early arrivals, which are expected to be direct body waves mixed with some later arrivals, including surface-related ghosting, internal multiples and mode conversions. Plotting NRMS and source position errors using the real data (Figure 2b) shows a trend similar to a typical variogram (Calvert, 2005). Comparison with a synthetic ideal variogram for the same parameters reveals similar behavior albeit with larger NRMS values and increased scatter for the real data case (Figure 2c). Note that for the real data case, even when the acquisition geometry is almost perfectly repeated, the pre-stack NRMS does not reach zero, but approaches a minimum of about 20%.

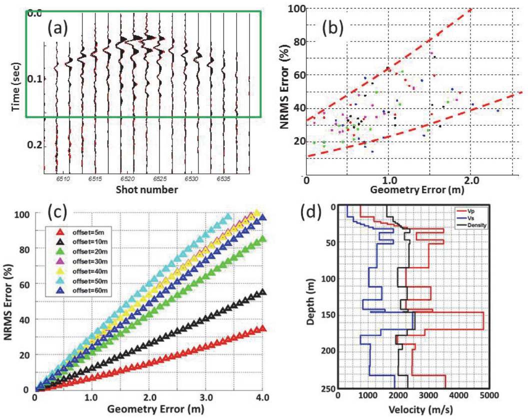

Figure 2: Results from vibroseis acquisition into a geophone cemented at a depth of 30 m showing: (a) a common-receiver gather, and (b) a composite variogram (trace-by-trace computation of NRMS vs. source position difference over six different surveys as compared to a baseline). The analysis window is shown by the green box. Traces from survey 1 are shown in red and surveys 2 through 6 are shown in black. Colored dots in the right panel represent source positioning error and the NRMS values for the different survey pairs. Synthetic variogram computed with the same parameters is shown in (c) and the corresponding 1D realistic model on (d). Note generally similar trend between real-data and synthetic variograms.

Coupling variations

In addition to positioning errors, we expect other factors to affect onshore seismic repeatability, such as daily/seasonal changes in the very near surface and variable vibrator coupling with the ground (Spitz and Faure, 2006). To minimize the influence of geometry on repeatability in this study we fixed the source location for a series of hourly and daily vibroseis source tests. Therefore, we expect this test data to be influenced mainly by variable source coupling and daily variations to seismic repeatability. During daily testing, the vibrator remained stationary for two weeks with the baseplate down. The vibrator made 20 sweeps every morning (7 a.m. local time [+3 GMT]) and every afternoon (2 p.m.). Figure 3 shows the repeatability analysis using a 40 ms time window supposedly representing useful signal outside the noise cone. To minimize the effect of the poor signal-to-noise ratio, we have analyzed not a single trace, but a stack of 20 adjacent traces from offsets 709 m to 1,338 m (yellow rectangle, Figure 3a) after NMO correction. Repeatability of the timing and amplitude of the stacked wavelet was evaluated with respect to the median value over the entire period by using simple cross-correlation analysis: time delay captures temporal variation, whereas the maximum of the crosscorrelation quantifies amplitude changes. While trends for the surface and buried geophone data appear similar, the scatter is significantly

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larger using the surface sensors. This is probably due to the fact that surface geophones are significantly noisier, not as well coupled as cemented sensors, and more susceptible to daily wind and temperature variations despite shallow burial (afternoon recordings have generally earlier traveltimes than the morning). This clearly demonstrates that surface (even permanently placed) geophones in a desert environment are not ideal for 4D monitoring. As a consequence we focus on the deeper cemented geophone data to evaluate variations caused by the source. Figure 3 shows that there appears to be a “warming up” or ground compaction stage where the first few sweeps show large timing and amplitude variations that quickly decrease and stabilize. We also observe drift and jumps in timing and amplitude between morning and afternoon tests that do not correlate well with daily temperature variation. We should note that the weather was dry and sunny throughout the entire acquisition period.

Figure 4 shows results of hourly testing of pre-stack vibrator repeatability. Figure 4a shows no clear correlation between wavelet variations and diurnal temperature, though data acquired in the afternoon shows somewhat higher amplitude with slightly larger timing differences than the morning data. Smoother variations in wavelet timing and amplitude from each hourly test to the next is visible with some discontinuities, but with generally smaller jumps than those observed on the daily test experiments.

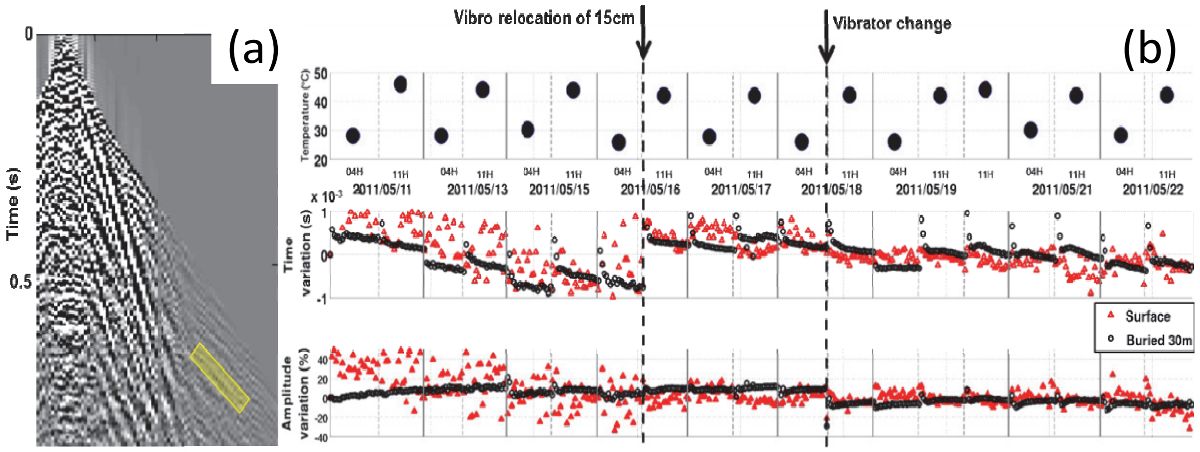

Figure 3: Daily vibrator repeatability tests: (a) a shot gather (buried receivers) with the window used for analysis overlain in yellow, and (b) daily amplitude and timing variations over a several days for both the surface and buried geophones. The vibrator remained at one location with the pad down except when moved slightly on May 16 and swapped with another vibrator for maintenance on May 18.

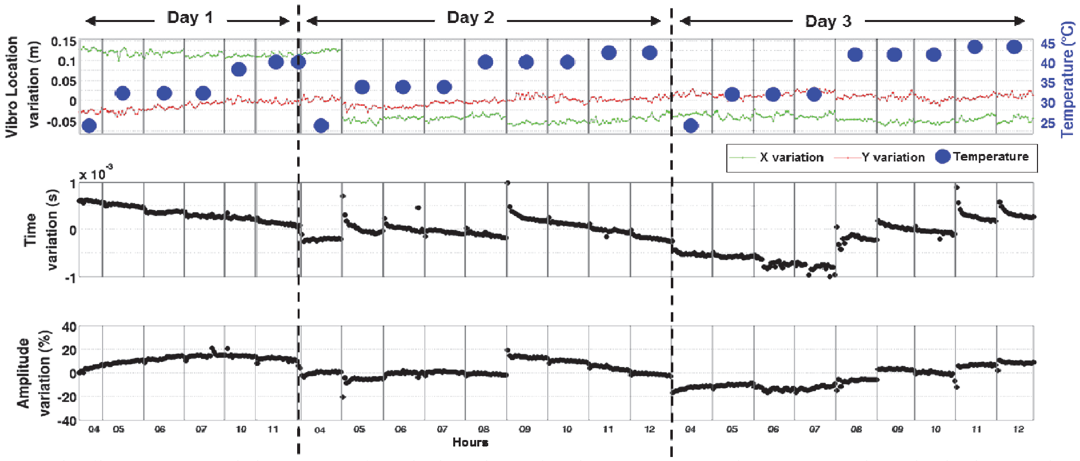

Figure 4: Hourly vibrator test recorded over approximately three days using the permanent geophones cemented at a depth of 30 m. The vibrator remained stationary throughout the test with the pad down. No obvious correlation of the hourly variations with ambient temperature is observed.

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These surface vibroseis results should be compared to similar tests with a stationary low-energy piezoelectric source bolted to a concrete plate (Berron et al., 2012). Using the same cemented geophones, the piezoelectric data show smoothly varying hourly and daily perturbations in amplitude and traveltime that correlate well with diurnal temperature changes. This clear correlation is not observable on the surface vibrator data suggesting that variations in the surface vibrator are not mainly related to ambient temperature, but to either non-repeatable vibrator excitation, or the variable baseplate coupling with the ground. The "warming up" or ground compaction stage for the surface vibroseis data is larger for the daily test data and somewhat less apparent for the hourly sweep tests suggesting that the vibrator may compact the sand, but within less than one hour the sand partially relaxes/ rebounds and there is a jump in timing and amplitude at the beginning of the next sweep test. This behavior is more apparent on the daily test experiment where there is a longer time between sweep tests (eight hours vs. one hour). These results imply that onshore 4D seismic surveys with a vibroseis source will always suffer from this intrinsic non-repeatability caused by variable interaction of the vibrators with the ground, even if the acquisition geometry is fixed.

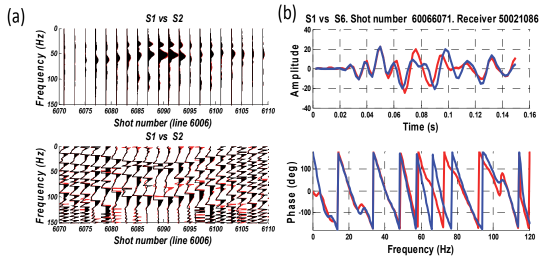

Figure 5. Variations in amplitude and phase spectra for a common-receiver gather from two different surveys: (a) spectra shown for all near-offset traces (<60 m) recorded by a buried receiver at 30 m, and (b) a single trace and associated phase spectra showing that phase spectra starts to differ significantly above 50 Hz and below 10 Hz.

During 4D onshore surveys using vibrators, the sources leave and return and can never be perfectly repositioned at the same locations. Therefore, the exact configuration of the contact area between the base plate and the ground will be different each time. According to Wei et al., (2011) this mis-positioning should lead to larger changes in generated signal at higher frequencies. This is consistent with what we observe that even for data with small source geometry errors (< 0.5 m), the phase spectra of the first arrivals are very similar between 10 Hz to 40 Hz, and then start to show significant differences above 50 Hz and below 10 Hz (Figure 5b).

Discussion and conclusions

We examined pre-stack repeatability of land data acquired with a vibroseis source in a desert using permanent buried geophones. Even with a fixed acquisition geometry (fixed vibrator and permanent receiver), pre-stack data shows significant short-term (minutes) and long-term (hours to days) variations in amplitude and traveltime. We confirmed that at least a portion of these variations should be attributed to the receiver side since these variations are larger for surface geophones as compared to geophones cemented at a depth of 30 m, however, the majority of these variations seem to be associated with the vibrator excitation itself. Data suggest that the surface vibrator has a "warming up" stage during which it probably compacts the sandy ground within the first two or three sweeps. The sand seems to partially rebound within a period of an hour or less and almost completely within a day. As a consequence, repeat onshore seismic surveys with surface vibrators will always have an irreducible non-repeatability level that cannot be eliminated even when using permanent buried receivers. We refer to these variations as "variable vibrator coupling" although it likely includes effects related to non-repeatable vibrator mechanics and hydraulics, as well as interaction of the vibrator with the ground and to a much lesser extent the daily temperature variations.

In addition to the factors above, positioning errors play an even more important role than in marine 4D seismic. Even though source locations were repeated with an accuracy of less than 4 m, data suggests that better accuracy could significantly improve pre-stack repeatability. Therefore, positioning tolerance is significantly tighter in land than marine.

For future surveys we recommend for source geometry to be repeated with accuracy of better than 0.5 m. We also speculate that the azimuth of the vibrator plate needs to be recorded during each survey and replicated as closely as possible in addition to the positioning in subsequent surveys. This may be facilitated by replicating the same vibrator path in all monitoring seismic surveys. We hope that such improvement may lead to a closer replication of the same baseplate-ground conditions and minimize NRMS differences between surveys. We expect that there are other avenues to improve vibrator repeatability. Remember that in 4D our goal is not to re-create an ideal signal, but rather re-create the same signal as was achieved in a baseline or previous survey at the same location. The former seems to be a more achievable task for the geophysical industry.

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EDITED REFERENCES

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