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## Observations of Surface Vibrator Repeatability in a Desert Environment

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### SUMMARY

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A series of field tests were conducted to quantify repeatability of land seismic data acquired with a surface vibrator in a desert environment. Tests conducted included six repeated 2D seismic surveys as well as daily and hourly sweep tests using buried surface geophones and buried, cemented geophones. The results indicate that in contrast to marine seismic data, even small source geometry changes (<2 m) may seriously degrade survey repeatability. In addition, even for a fixed geometry, there is significant non-repeatability caused by the interaction of the vibrator with the ground (variable coupling). Events recorded from the deeper cemented sensors exhibit significantly better repeatability compared to those from geophones buried at the surface. Unlike permanent surface piezoelectric source data, variations in travel times and amplitudes of the signals from a surface vibrator do not seem to correlate with diurnal temperature variations.

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 becomes more repeatable. 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.

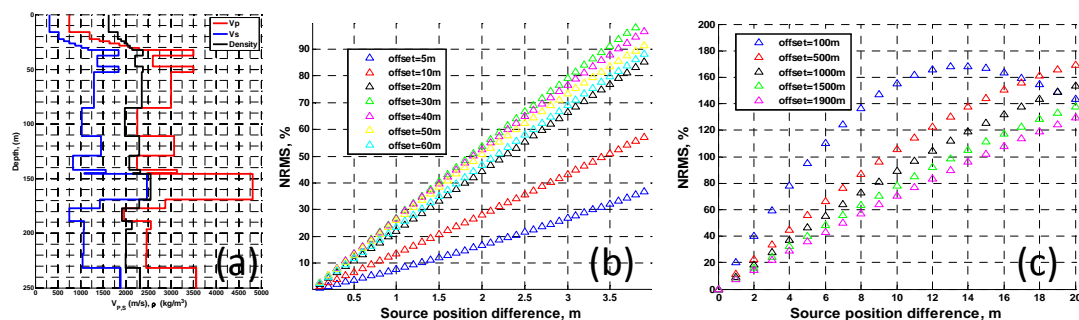
## Introduction

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.

## Setting the stage

Seismic monitoring, or 4D seismic, has made significant progress in the past few decades. A significant role in this evolution was played by understanding marine data repeatability and the factors that affect it (Calvert, 2005). It is generally accepted that the repeatability of acquisition geometry is the largest single factor affecting repeatability of marine seismic data, whereas the stability of the airgun wavelet is rarely considered significant due to the consistent coupling in water. To understand the limitations and prospects of land 4D seismic, in this study we concentrate on the pre-stack repeatability achieved with a standard surface vibrator in a desert environment.

A 1D elastic model was constructed from log and shallow first break data (Figure 1a). Variograms were computed from the model data which show commonly used 4D metric called NRMS (normalised root-mean-square amplitude difference between two traces) versus acquisition geometry errors for each offset (Figure 1b and 1c) similar to those shown by Calvert (2005). It is clear that NRMS increases dramatically for relatively small shifts in source position. For example, using buried sensor data and a 150 ms time window around the first breaks and buried sensors at 30 m (an actual field test configuration), the NRMS reaches 100% for a 3 m shift in source position between successive “surveys”. This happens because the near-surface used in the model has a number of thin layers with high velocity contrasts that scatter energy very differently depending on the actual source and receiver geometry. Unlike the marine case with a simple overburden, these very small positioning errors can have potentially very large effects on repeatability, even without considering more complex near-surface heterogeneity, and seasonal and diurnal changes.



**Figure 1** Near-surface modelling results showing (a) the input 1D model derived from log and shallow uphole data, and synthetic 4D variograms obtained with a surface source and 30 m buried receiver via full-waveform elastic modelling computed using (b) a 150 ms window around the first breaks and (c) using the full trace as the analysis window.

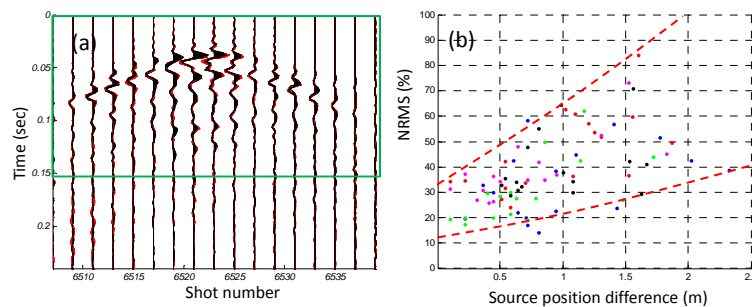
## Real world complexities

Repeatability of the surface vibrator data is affected by source geometry or location errors (amplified by near-surface 3D heterogeneity), daily/seasonal variation in the immediate near-surface and vibrator interaction with the ground (coupling). The ultimate goal of any onshore repeatability study should be to quantify the relative contribution of each of these factors into the overall non-repeatability of 4D surveys. This should give an insight into which factors are dominant and how they can be mitigated. In this study, observations are presented from an onshore feasibility monitoring experiment in Saudi

Arabia. This test data provides some initial hints on what factors are significant, and how they are affecting the data. The source used is a Sercel M26HD/623B surface vibrator, shooting into fixed, shallow buried geophones at the surface and cemented geophones at 30 m depth.

### Geometry errors

A way to evaluate the effect of source geometry errors is by looking at the first arrivals for repeat seismic surveys. Results presented below are computed on the near-offset traces from the surface vibrator to 30 m buried receivers (Figure 2a) and concentrate on early arrivals that 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 similar trend as in the synthetic data case (Figure 1b); larger geometry errors produce less repeatable data. For this real data case, even when the acquisition geometry is almost perfectly repeated, the NRMS does not reach zero, but approaches a minimum of about 20%.

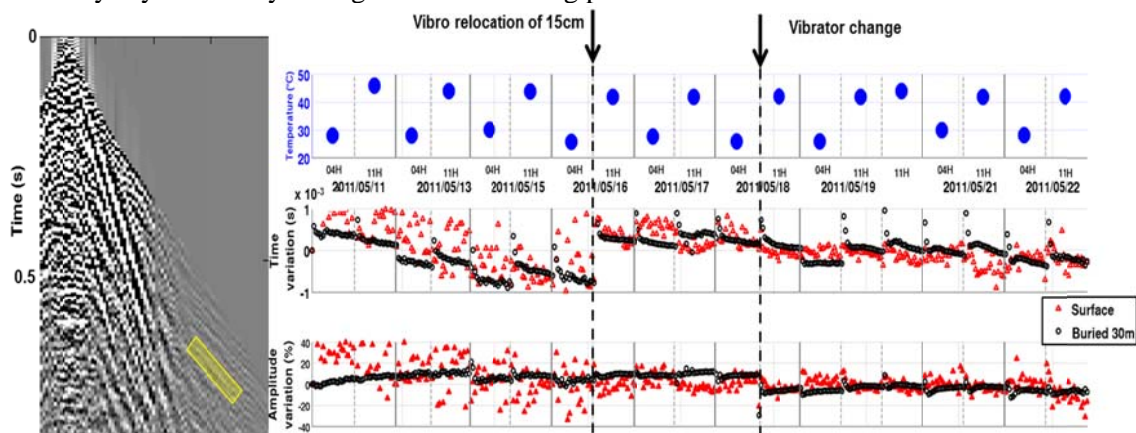


**Figure 2** Results from vibroseis acquisition into a geophone cemented at 30m depth showing (a) a common-receiver gather and (b) a trace-by-trace computation of NRMS versus source position difference over six different surveys. The analysis window is shown by the green box. Traces from survey one are shown in red and surveys two through six are shown in black. Colored dots in the right panel represent source positioning error and the NRMS values for the different survey pairs.

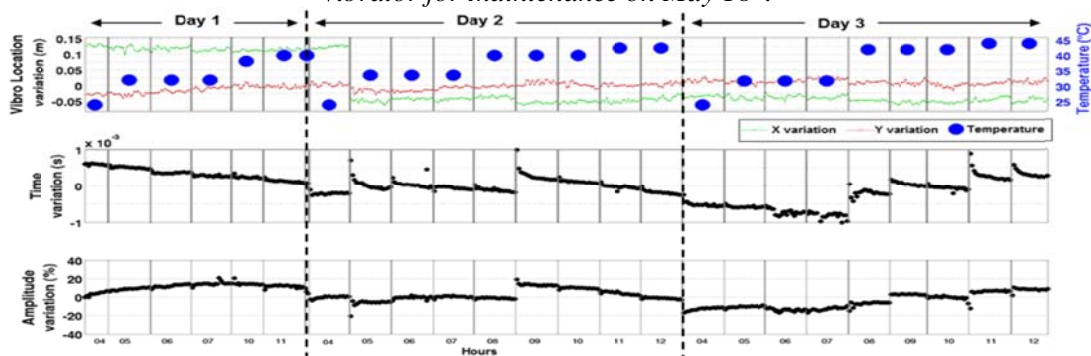
### Why geometry is only part of the answer on land? (Daily and hourly tests)

Other factors that affect onshore seismic repeatability, apart from positioning errors, include daily/seasonal changes in the very near surface and variable vibrator interaction with the ground (inconsistent coupling) (Spitz and Faure, 2006). It has been shown by Schissele et al (2009), for non-desert environments, that daily variations are clearly observable with buried receivers and a permanent piezoelectric source at the surface. It remains to be seen if such daily changes can be observed using surface vibroseis acquisition into buried and cemented receivers. In this study we fixed the source location for a series of hourly and daily vibroseis source tests to minimize the influence of geometry on repeatability. It was hoped that this test data could be used to evaluate the contribution of variable source coupling and daily variations to seismic repeatability. In these tests, the vibrator remained stationary for 14 days with the baseplate down. During the daily tests, the vibrator made 20 sweeps every morning (7 AM local time [+3 GMT]) and every afternoon (2 PM). Figure 3 shows the stability analysis of a 40 ms wavelet obtained by stacking 20 adjacent traces from offsets 709 m to 1338 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 cross-correlation analysis; time delay quantifies temporal variation, whereas the maximum of the cross-correlation describes amplitude changes. Even though trends for the surface and buried geophone data may be similar, the scatter is clearly much larger using the surface sensors. This implies that permanent surface geophones are significantly noisier, less well coupled, and more susceptible to daily variations (afternoon recordings have generally earlier wavelet times than the morning), therefore, they are less repeatable than geophones buried at deeper depths. This means that data from the deeper cemented geophones is thus more likely to show variations caused by the source. Examining the data recorded with cemented geophones, there appears to be a “warming up” or ground compacting stage where the first two or three sweeps show large timing and amplitude variations

whereas subsequent sweeps appear to stabilize and display much smaller differences. We do observe drift and jumps in wavelet timing and amplitude between morning and afternoon tests that do not seem to correlate with pronounced daily temperature variation in the desert. Note that the weather was consistently dry and sunny throughout entire testing period.



**Figure 3** Daily vibrator repeatability tests using buried and surface receivers showing (a) a shot gather with the window used for wavelet stability analysis overlain in yellow and (b) daily amplitude and timing variations over a nine day period for both the surface and buried geophones. The vibrator was stationary with the pad down except when moved slightly on May 16<sup>th</sup> and swapped with another vibrator for maintenance on May 18<sup>th</sup>.



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

Figure 4 shows results of an hourly vibrator test conducted after the daily testing. The same time and offset window is used for this analysis, as in Figure 3a, to derive wavelet arrival time and amplitude variations. Hourly tests show no clear correlation between wavelet variations and diurnal temperature, though data acquired in the afternoon shows generally higher amplitude with slightly larger timing differences than the morning data. Wavelet timing and amplitudes show smooth variations over periods of several hours with the initial sweeps in any single 20 sweep sequence showing more variation than subsequent ones. This results in discontinuities in wavelet timing and amplitude from each hourly test to the next, but with much smaller jumps than those observed on the daily test experiment.

These surface vibroseis results were compared to those for a permanent low-energy piezoelectric source bolted to a concrete plate (results not shown here). Using the same cemented geophones, the piezoelectric data show smoothly varying hourly and daily perturbations in amplitude and travelttime that correlate well with diurnal temperature changes. This clear correlation is not seen on the surface vibrator data suggesting that variations in the surface vibrator are not related to ambient temperature, but to either the inherent repeatability of the vibrator itself, or the baseplate coupling with the ground. The “warming up” or ground compacting stage for the surface vibroseis data is greater for the daily tests data and somewhat less apparent for the hourly sweep tests suggesting that the vibrator compacts

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 hysteresis-like behaviour is most apparent on the daily test experiment where there is a longer time between sweep tests (eight hours vs. one hour). As a consequence, it is expected that in onshore 4D vibroseis seismic surveys there will always have an intrinsic non-repeatability factor caused by interaction of the vibrators with the ground, even if the geometry is fixed and repeat records are acquired at exactly the same time of the day to minimize daily temperature effects.

Clearly, vibrator coupling changes even if the vibrator remains stationary. Our 1D elastic modelling (Figure 1) shows that even larger changes in wavelet timing and amplitude will occur when the vibrators leave and return during 4D repeat surveys since they can never be perfectly repositioned at the same source locations. In addition, vibrator coupling is known to strongly depend on the exact configuration of the contact area between the base plate and the ground. Wei et al. (2011) demonstrate that this problem becomes more acute at higher frequencies. Consistent with these findings, it was observed that even for data with small differences between measured source locations (< 0.5 m), the phase spectra of the first arrivals are more or less stable between 10 to 40 Hz, and then it starts to deviate more significantly above 50 Hz and below 7 Hz.

## Discussion and conclusions

The pre-stack repeatability of land vibroseis data in a desert environment was examined in detail by repeating the same 2D seismic survey six times over a period of four months, as well as conducting other daily and hourly source repeatability tests. We have verified that even with perfectly repeatable geometry of stationary vibrator and permanently trenched surface geophones in sand, pre-stack data exhibits significant short-term (over minutes) and long-term (hourly to daily) variations in amplitude (up to 30%) and traveltime (up to 1 ms). Data from stationary vibrator to a buried 30 m geophones is significantly more stable (up to 20% amplitude and 0.5 ms travel time variation), yet still shows large variations or jumps over the longer time periods. Data suggest that the surface vibrator has a “warming up” stage during which it likely changes (compacts) the sandy ground in this test area within the first two or three sweeps. This compaction at least partially rebounds within a period of less than one hour. Therefore, it is expected that repeat onshore seismic surveys using non-stationary surface vibrators will always have some kind of irreducible non-repeatability that cannot be eliminated even when the source geometry is perfectly repeated and buried cemented sensors are used. No recognizable effects from daily temperature variations were observed on these data suggesting that compaction and mechanical coupling effects dominate the non-repeatable errors.

It was observed on both synthetic and field data that even small (by marine standards) mispositioning of source locations between surveys, on the order of 0.5 to 3 meters, can cause large increases in non-repeatability as measured on the pre-stack data. While deep reflections may be much more repeatable, poorly-repeatable interfering noise (surface waves, refractions, shear waves etc) will invariably contaminate the desired 4D reservoir response on land. This type of error places much more stringent requirements on geometry repeatability for onshore vibroseis seismic acquisition.

## Acknowledgements

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## References

- Calvert, R. [2005] Insights and Methods for 4D Reservoir Monitoring and Characterization, SEG/EAGE Distinguished Instructor Short Course, SEG.
- Schissele, E., Forgues, E., Echappé, J., Meunier, J., de Pellegars, O, and Hubans, C [2009] Seismic Repeatability – Is There a Limit?, *71st EAGE Conference & Exhibition*, Extended Abstracts, V021.
- Spitz, S., and Faure, P [2006] Onshore 4D seismic repeatability at the gas storage geophysical laboratory, *76th SEG Annual International Meeting*, Expanded Abstracts, 3175-3179.
- Wei, Z., Hall, M. A. and Phillips, T. F. [2011] Geophysical benefits from an improved seismic vibrator, *Geophysical Prospecting*, DOI: 10.1111/j.1365-2478.2011.00994.x.