Evaluating permanent seismic monitoring with shallow buried sensors in a desert environment

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Summary

We present results of a feasibility study evaluating various configurations for seismic monitoring in a desert environment. The experiment, conducted in an onshore field in Saudi Arabia, involved drilling and instrumenting 80 shallow receiver holes located along a 2D line and shooting multiple repeat surveys with a dense carpet of vibrator points. In each shallow hole colocated geophones and hydrophones were permanently cemented at 10, 20 and 30 m below surface. A small cluster of 12 surface geophones is placed next to each hole for comparison purposes. It was essential to design a processing sequence that was optimized for imaging and repeatability. The best stack image and repeatability were obtained using data from the receivers located at the deepest level. Post-stack repeatability of around ~ 15% normalized root-mean-square amplitude (NRMS) is obtained over a large portion of the 2D line. Virtual source redatuming of buried receiver data offered additional imaging improvements. Both conventional and redatumed images show significant improvement when adaptive dual-sensor summation was also utilized. Despite a very complex near surface, dense and frequent shooting to permanently cemented buried sensors delivers repeatability approaching marine data.

Introduction

Seismic monitoring on land is very challenging, particularly in Saudi Arabia in areas of complex surface and near-surface geology that can compromise the seismic data quality and repeatability (Robinson and Al-Husseini, 1982). This paper describes a comprehensive feasibility study of land seismic monitoring using various configurations of sources and receivers in a desert environment. Since the ultimate goal is to establish a workable areal solution, only configurations that are easily extendable to 3D were tested, whereas approaches like deep-well 3D vertical seismic profiling were excluded due to potential limitations of over smoothed images, limited areal extent and edge artifacts.

Field trial

The layout of the 2D feasibility experiment is shown in Figure 1. Eighty receiver holes were drilled along a slightly bent 2D line with a spacing of 30 m. Each hole is instrumented with colocated geophone and hydrophone receivers at depths of 10, 20 and 30 m below surface, with 12 bunched geophones covered with sand deployed at each surface location. The entire surface area is covered with sand varying from 2-3 m on the left side of the line to 15-17 m on the right (Figure 1e). Dense areal shooting with a surface vibrator is acquired at a 7.5 m by 7.5 m spacing over a swath of nine source lines to allow sufficient sampling for efficient noise removal as well as for use in testing redatuming approaches. The target horizon is located at a depth of around 2 km. We evaluate several different configurations of surface sources into surface and buried sensors listed in Table 1. The objective of the tests are to compare image quality, repeatability and 4D noise characteristics obtained with each configuration. Six repeat

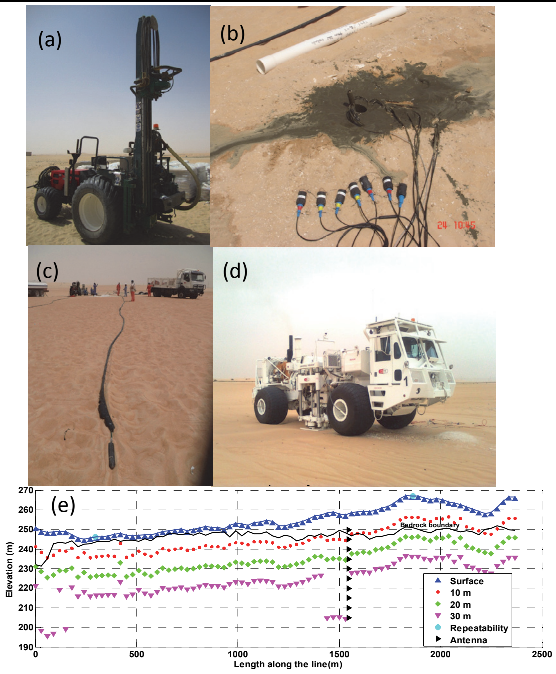

Figure 1. Equipment and layout used for the field experiment: (a) drilling machine, (b) surface connectors from cemented sensors with cables going into the shallow hole, (c) packaged receiver assembly before cementation, (d) surface vibrator, (e) schematic of actual sensor layout (photos courtesy of CGGVeritas/ARGAS).

Method	Redundancy	Image	Repeatability	4D Cost
Surface source-surface receiver	Medium	Good	Poor	Low
Surface source-buried receiver	Medium	Good	Good	Medium
Virtual Source-buried receiver	Medium	Excellent	In progress	Medium
Buried source-buried receiver	Single fold	N/A	Excellent	High

Table 1. A qualitative evaluation of the various acquisition configurations employed using the experimental 2D line.

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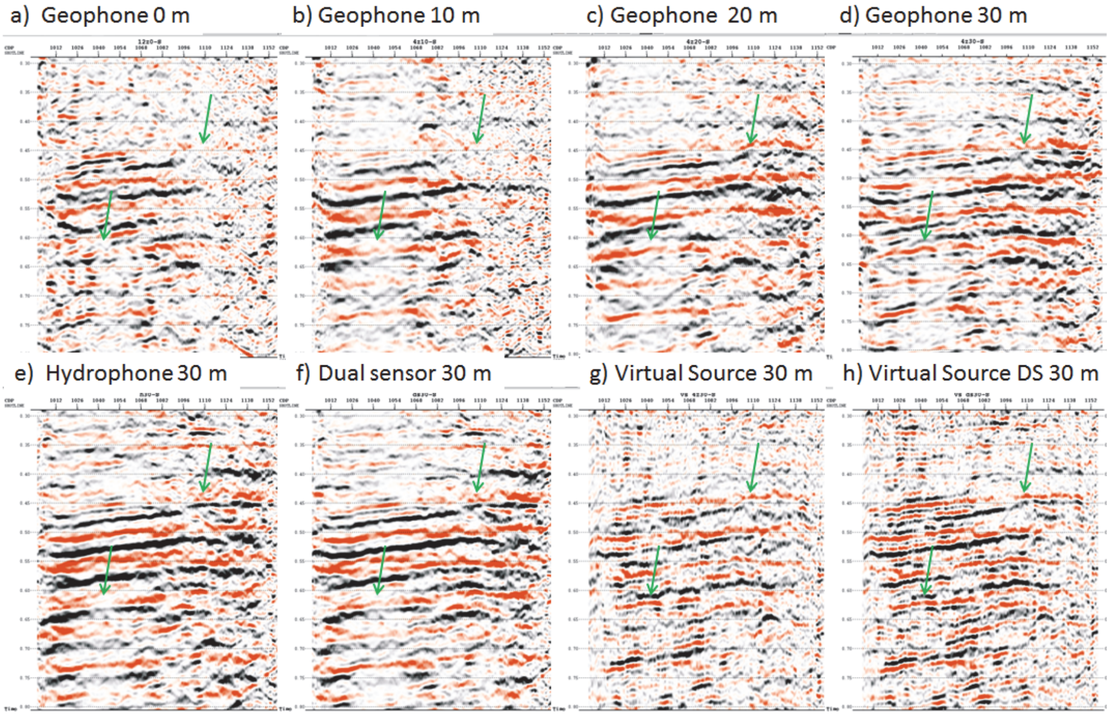

Figure 2. Stacked sections optimized for repeatability in processing showing the shallow portion. These were obtained with various source and receiver configurations including: (a) surface source and surface receiver, (b) surface source and buried geophones at 10 m, (c) surface source and buried geophones at 20 m, (d) surface source and buried geophones at 30 m, (e) surface source and buried hydrophones at 30 m, (f) surface source and buried dual sensors at 30 m (summed hydrophone and geophone), (f) virtual source and buried geophones (all at 30 m), and (h) virtual source and buried dual sensors (all at 30 m).

surveys were acquired over four months and no reservoir changes were expected during the acquisition period. Additional surface vibrator repeatability tests with hourly and daily shooting are conducted and are described in another study. Several permanent surface and buried piezoelectric vibrators are installed to evaluate the signal penetration and quality in this complex area (Berron et al., 2012). In this paper we discuss results from the first two repeat surveys using only the surface vibrators.

Stacked sections from this test were benchmarked against images from the legacy high-fold 3D seismic data that possesses high redundancy and relatively good image quality.

Imaging results

While point-source and point-receiver acquisition is becoming popular in the industry, it requires high fold, high channel counts and small receiver intervals to properly sample the signal and noise in areas of complex near-surface geology, such as over most of Saudi Arabia. In effect, the old recipe of using source and receiver arrays is still in place with perhaps a modern twist of more sophisticated digital group-forming or single-sensor processing all the way to migration. This is emphasized by the fact that most reflections cannot be seen on the single-sensor pre-stack data in a karsted near-surface desert environment (Robinson and Al-Husseini, 1982). Legacy 3D data can deliver relatively good seismic images despite near-surface complexity, mainly due to the high redundancy achieved in modern full-azimuth seismic surveys and the noise rejection capabilities of surface arrays. Using a 2D swath acquisition configuration, we acquire data with a dense surface vibrator shooting pattern in both in-line and cross-line directions. The high source density was critical for efficient pre-stack noise attenuation and increasing data redundancy, as well as providing data necessary for virtual source redatuming tests. Data is processed with a production time imaging workflow that included cross-line diversity summing, gain application, noise removal, adaptive dual-sensor summing (as applicable), normal moveout correction, application of field

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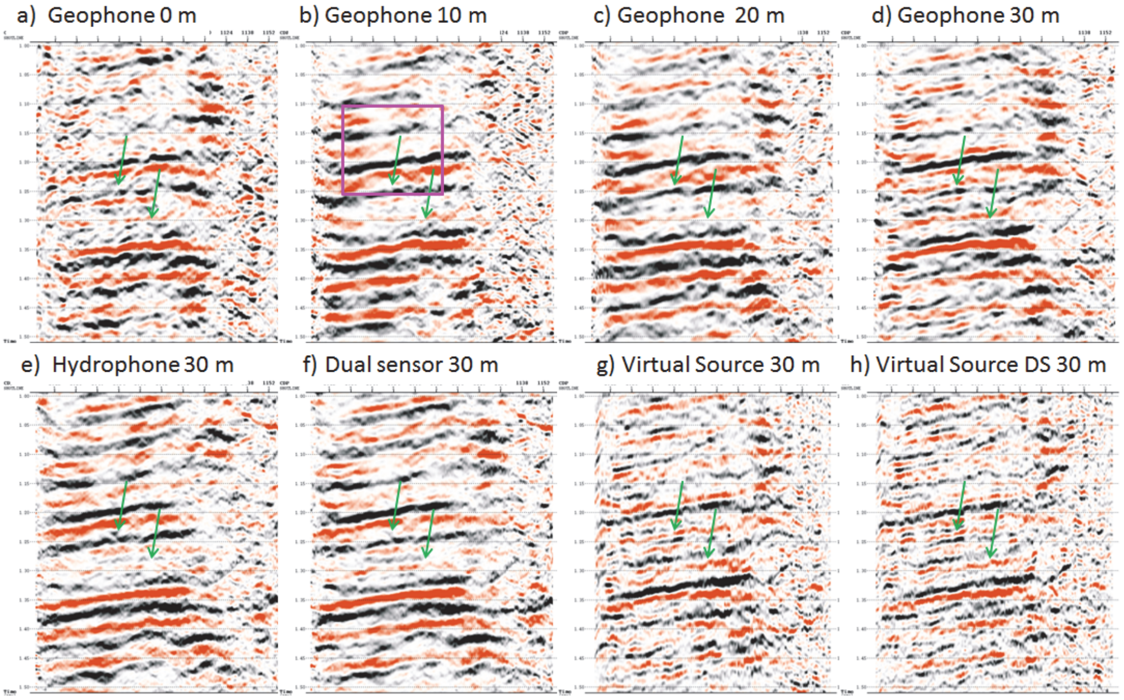

Figure 3. Same as Figure 2 but zoomed around target area. The pink rectangle in (b) outlines the window used for deriving the NRMS values shown in Table 2. The green arrows highlight differences in event continuity and resolution achieved with different configurations.

statics, time-variant scaling, and common-depth point (CDP) stacking. Figures 2a to 2d and 3a to 3d show a comparison of the images obtained using different geophones depths. Clearly, surface receivers produced the noisiest stacked section, while the buried receiver stacks produced higher-quality images with improved reflector continuity and higher bandwidth, particularly for stacks generated from receivers at 30 m. Note that during drilling of the receiver holes, more than a quarter encountered voids and lost circulation zones. One reason for the improved imaging with depth may be that that receivers are below some of the near-surface karsting present in the area. Another reason for the improved data quality by burying receivers is that they record a reduced level of surface-wave noise.

We should note that data acquired using the buried piezoelectric sources lacked the fold and signal-to-noise ratio to produce an equivalent image. It is likely that the permanent piezoelectric sources used have insufficient signal strength to illuminate the deep target zone.

Land hydrophone and dual sensor

It was our expectation that buried receiver data would be contaminated by surface ghosting and other near-surface multiples. To mitigate those effects, we cemented hydrophone sensors next to each geophone at 10, 20 and 30 m (Figure 1) to allow us to perform dual-sensor summation to remove ghosting effects. We did not have high expectations cementing hydrophones in a dry rock. Indeed while the geophones showed consistent signal strength, coupling variations among the hydrophones were significant. Nevertheless, after carefully designed processing, we obtained reasonable images from the hydrophone data (Figures 2e, 3e). Despite the variable hydrophone coupling, dual-sensor images obtained after adaptive hydrophone and geophone summation, showed significant improvements in event continuity and vertical resolution (Figures 2f, 3f). Spectral analysis confirms that dual-sensor data has higher resolution with less frequency notching due to receiver-side deghosting.

Virtual source redatuming

While conventional processing used only static corrections to overcome near-surface challenges, a more accurate approach is to redatum buried receiver data using the virtual source method (Bakulin and Calvert, 2006). While our redatumed dataset only contains 80 virtual sources from the 80 buried receivers, each pre-stack virtual trace is a product of areal summation from at least 81 surface shots,

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thereby improving signal to noise by utilizing "fold" in a manner consistent with the wave equation. The virtual source stacks obtained using the geophone data (Figures 2g, 3g), show better vertical resolution and improved event continuity compared with the conventional single-sensor processing without redatuming (Figures 2d, 3d). Applying virtual source redatuming to hydrophone and geophone and performing wavefield separation step via dual-sensor summation, we obtain an improved virtual source images (Figures 2h, 3h) that further validates the robustness of our adaptive dual-sensor summation. Comparing dual-sensor data with (Figures 2h, 3h) and without redatuming (Figures 2f, 3f), we can see that redatumed image have better vertical resolution although we may observe somewhat reduced event continuity on the right side of the line.

Repeatability

It may be easier to repeat source positions on land than marine; however, generally much more stringent geometry tolerance is required to achieve a comparable level of repeatability. While mean deviation between shotpoint locations was less than 0.8 m for the two surveys in this study, the pre-stack repeatability was quite poor. This is likely because in addition to geometry, repeatability is affected by changes in source coupling and daily/seasonal variations of the near-surface. An analysis of the pre-stack repeatability of the surface vibrator data and its controlling factors are the subject of a separate study. In this paper we quantify post-stack repeatability between the first and second surveys (Table 2). Most repeatability improvements occur when depth of burial changes from 0 to 10 m. Additional reductions in NRMS are achieved by burying sensors at 20 m, but repeatability has almost no improvement going to the 30 m sensors. In contrast, while dual-sensor summation provided superior images compared to geophone data alone, the repeatability of the results was slightly worse. This is caused by the inconsistent hydrophone coupling, and therefore, worse signal-to-noise ratio as noted above. These results show similar general trends to those observed in non-desert environments (Schissele et al., 2009).

Method	**Post-stack NRMS (%)**
Surface source – surface geophone	53
Surface source – buried geophone at 10 m	24
Surface source – buried geophone at 20 m	17
Surface source – buried geophone at 30 m	16.5
Surface source – buried hydrophone at 30 m	24
Surface source – buried dual sensor at 30 m	20

Table 2. Stack repeatability achieved with different receiver configurations for the first two surveys acquired with a surface vibrator. NRMS is estimated from a window of good data seen in Figure 3b.

Discussion and conclusions

We have conducted a comprehensive onshore seismic feasibility study in Saudi Arabia and evaluated various source/sensor configurations for permanent land seismic monitoring. In the presence of a challenging karsted near surface with a variable thickness sand cover, this study focused on evaluating shallow buried receivers from 0 to 30 m deep using a surface vibrator. Increasing receiver depth provided significant improvement in both image quality and repeatability. The best stacked section was obtained using receivers at 30 m, probably because at this depth the receivers were below the near-surface sand layer and also below areas of karsting observed during drilling and deployment.

Virtual source redatuming applied to geophones buried at 30 m resulted in improved vertical resolution on the sections and suggested that this technique can be useful for overcoming some of the near-surface complexity in this area.

Wavefield separation achieved by adaptive summation of geophone and hydrophone data provided some of the best images both for conventional as well as virtual source stacks. More consistent hydrophone coupling may further improve these results.

The best NRMS estimates resulted from the 30 m sensor data with the most dramatic improvements occurring for sensors buried below 10 m, whereas repeatability at 20 m and 30 m was almost identical. Repeatability of around 15% is achieved, which approaches that of marine seismic data using towed streamers giving us confidence in moving forward with a monitoring program. All tested geometries allow straightforward extension to 3D and both image and repeatability should improve when moving to 3D acquisition due to increased subsurface sampling.

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EDITED REFERENCES

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