# Making seismic monitoring work in a desert environment with complex near surface

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**Summary**

We describe a seismic monitoring system designed for a desert environment with complex near surface. The goal is to map $CO_2$ injection using permanent buried sensors at shallow depths of 50-70 m. This is the first large-scale permanent seismic installation in Saudi Arabia deployed at such depth and we face a number of geophysical and operational challenges. These challenges were overcome through a series of focused collaborations with service providers and speedy field trials aimed to validate each new element of the installation. We highlight key achievements related to sensor design and deployment, drilling and 4D source effort. All components are validated using pre-stack data repeatability metrics on field pilot tests.

## Introduction

Seismic monitoring in a desert environment is very challenging. Bakulin et al. (2012) have shown that for areas with a complex near surface, 4D seismic acquisition with shallow buried receivers and surface vibroseis sources, may produce improved data quality and repeatability. To make this acquisition configuration work for 3D requires a number of geophysical and operational challenges to be addressed. This paper describes a series of field trials whose goal is to resolve a series of related challenges and pave the way for permanent installation of 1,000 4C sensors over a $CO_2$ injection site.

## Survey design

Figure 1a shows a schematic survey design proposed for the permanent installation. Such a design is similar to an ocean-bottom node configuration since to deploy receivers is costlier than the source effort. The central area is covered with a 50 m by 50 m receiver grid consisting of 1,000 shallow holes. A dense array of source points on a 10 m by 10 m grid is necessary to achieve good azimuthal and offset coverage inside the area of interest (Figure 1a, black rectangle). Such broad azimuth acquisition is a must in the presence of a complex near surface with extremely variable seismic data quality as it achieves very high fold at the target horizon.

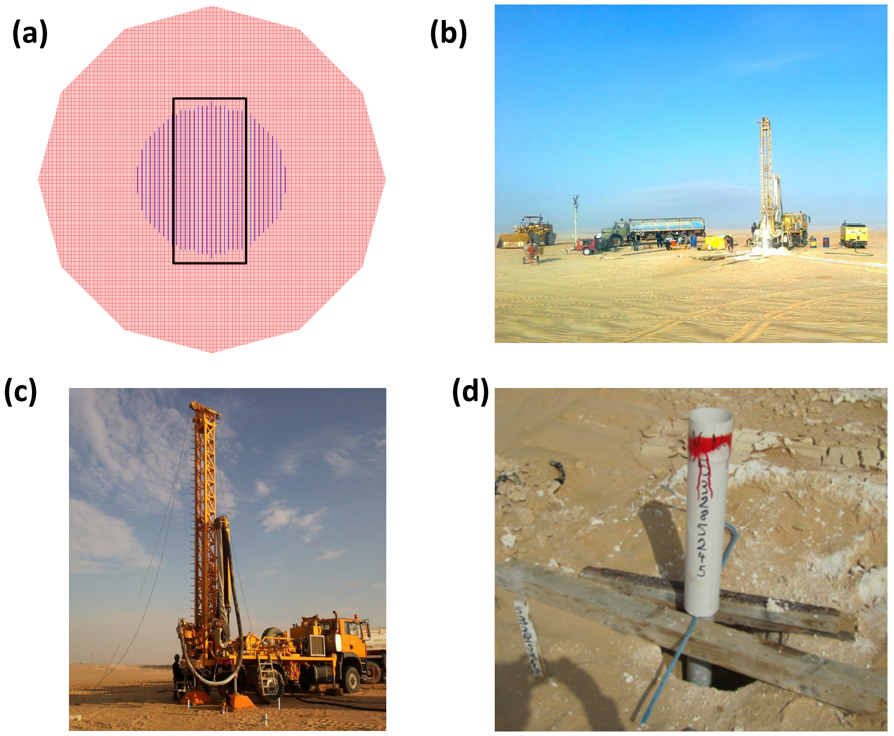


Figure 1. A schematic survey design (a) where blue lines indicate receivers and red lines indicate source coverage. The black rectangle outlines the area of interest. The drilling layout at one of the locations (b) and a portable drilling machine (c) along with a drilled location (d) ready for sensor installation.



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**Sensor depth**

An important consideration for permanent land seismic installations is the burial depth of the sensors. Bakulin et al. (2012) tested sensor depths between 0 m and 50 m. They concluded that while repeatability improvement was greatest when burying receivers from 0 m to 10 m, the best images were obtained with the deepest sensors possibly due to karsted zones at shallow depths. In addition it has been shown that substantial improvement in images resulted from performing dual sensor summation on land (combining hydrophone and geophone responses). However, hydrophones in the early feasibility study were cemented above the water table and they clearly suffered from inconsistent coupling and reduced repeatability (Burnstad et al., 2012). It was decided to test sensors just below the water table, which in this area is about 50 m to 75 m below the surface. This is expected to improve both imaging and repeatability (due to more consistent hydrophone coupling) at a slightly higher cost.

Deploying sensors just below the water table also places them in the same geological horizon at approximately the same flat datum. This simplifies drilling and deployment operations in the field as well as minimizing static variations and simplifying dual-sensor summation in processing.

**Drilling**

Areal deployment of a large number of sensors in the shallow subsurface is a long-standing challenge. Bakulin et al. (2007) discussed horizontal directional drilling and U-shaped wells, but so far these technologies are not cost effective for mass deployment. As such we found a fit-for-purpose solution using vertical holes. Vertical holes provide a simple flexible design easily adaptable to a crowded oilfield environment with plenty of surface and underground obstructions. Sensor holes can be drilled with little footprint using highly automated mobile drilling rigs shown in Figures 1b and 1c. This area contains sand at the surface overlying limestone consisting of soft and hard layers, including karsted and water zones. Variable drilling conditions make accurate and safe installation of sensors quite challenging. Conventional drilling methods would not work without the use of casing and cementing, which defeats the purpose of good coupling and would add considerably to the costs. Air drilling with foam injection is preferred over using water and drilling mud, because the foam collects the cuttings and lines the wall of the borehole and also fills in any lost circulation zones, unlike circulating water, which generally washes out areas of lost circulation thereby making the condition of the borehole worse. The foam is generally used in shallow near-surface boreholes and not deep holes. In this area with the problems of soft zones and karsting, foam is really the fastest and best method for guaranteeing a successful completion. Foam does not contaminate the subsurface, and allows for faster drilling with less water usage.

**Sensor deployment**

While any deployment environment may be suitable for buried geophones, hydrophone deployment on land is more problematic. Previous experience involved cementing hydrophones in shallow holes above the water table (Bakulin et al., 2012) and required the hydrophone to be pre-packaged inside a fluid-filled vessel. By choosing to install below the water table we decided to use hydrophone sensors as is without special packaging. Two coupling options were tested using different hydrophones: cemented and gravel packed. Generally, hydrophones with higher sensitivity showed better performance in sand, whereas lower sensitivity, stiffer hydrophones performed better in cement. Figure 2 shows representative common-receiver gathers for the two best sensors in the most optimal environment. Hydrophone deployment below the water table resulted in significantly better responses over those deployed above the water table in terms of data quality and repeatability.

**Sensor selection**

It has been previously observed that at depths of 30 m or more, higher sensitivity geophones and hydrophones would be beneficial (Berron et al., 2012). Higher sensitivity hydrophones were designed and tested first in backyard tests and later in actual field conditions. Figure 2 shows representative common-receiver gathers for collocated geophone and hydrophone sensors of two different types all deployed in closely spaced shallow holes at depths of 50 m to 70 m. Both types of hydrophones show opposite polarity to geophones on first arrivals as predicted by modeling. Figure 2 shows surprisingly similar arrivals recorded by hydrophones and geophones despite one being in sand and another being in cement. In many ocean-bottom seismic deployments there are cases when different noise types show up on hydrophones and geophones. This could be caused by variable coupling and in such instances the data requires very careful pre-conditioning before hydrophone-geophone summation. We do not observe any sign of this on sensors deployed in shallow boreholes. Simple modeling suggests that many of the high-angle and low-frequency events represent S-waves. From a theoretical perspective we expect that hydrophones should record less of these events. However, the data suggests otherwise. Such observations are also consistent with cross-well experiences where hydrophones also record shear waves, which are probably converted to P-wave energy at the borehole wall. This is not necessarily a problem if shear energy can be consistently removed from geophones and hydrophones in processing. In fact, similar noise events on hydrophones and geophones may lead to data more amenable to dual sensor summation. In addition, the higher sensitivity


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hydrophones record higher signal-to-noise ratio data, particularly at larger offsets (Figure 2f), whereas lower sensitivity hydrophones or those deployed in cement start to approach the noise floor at similar offset ranges (Figure 2g).

**Repeatability**

While signal-to-noise and data quality are important, the repeatability of the reflection data from the target depth is also critical. Novel approaches to measuring pre-stack repeatability (Burnstad et al., 2012b) were applied to assess various sensors and deployment configurations in the field and the results will be reported in another study. Most importantly we have validated that repeatability of a hydrophone below the water table can be equal to or better than that of a geophone. As such, it addresses the issue of inferior hydrophone repeatability observed for shallow hydrophones cemented above the water table (Burnstad et al., 2012b).

**4D source effort**

Our goal is to acquire multiple seismic surveys per year, possibly as often as once per month. This should help reduce the effect of 4D noise and allow robust mapping of the $CO_2$ injection front in the presence of a complex near surface. To acquire more than one survey per month, about 4,000 vibrator points (VPs) need to be acquired per day. While this task is easily obtainable for exploration surveys with flip-flop vibrator acquisition, we needed to verify that this productivity was possible in a confined area with

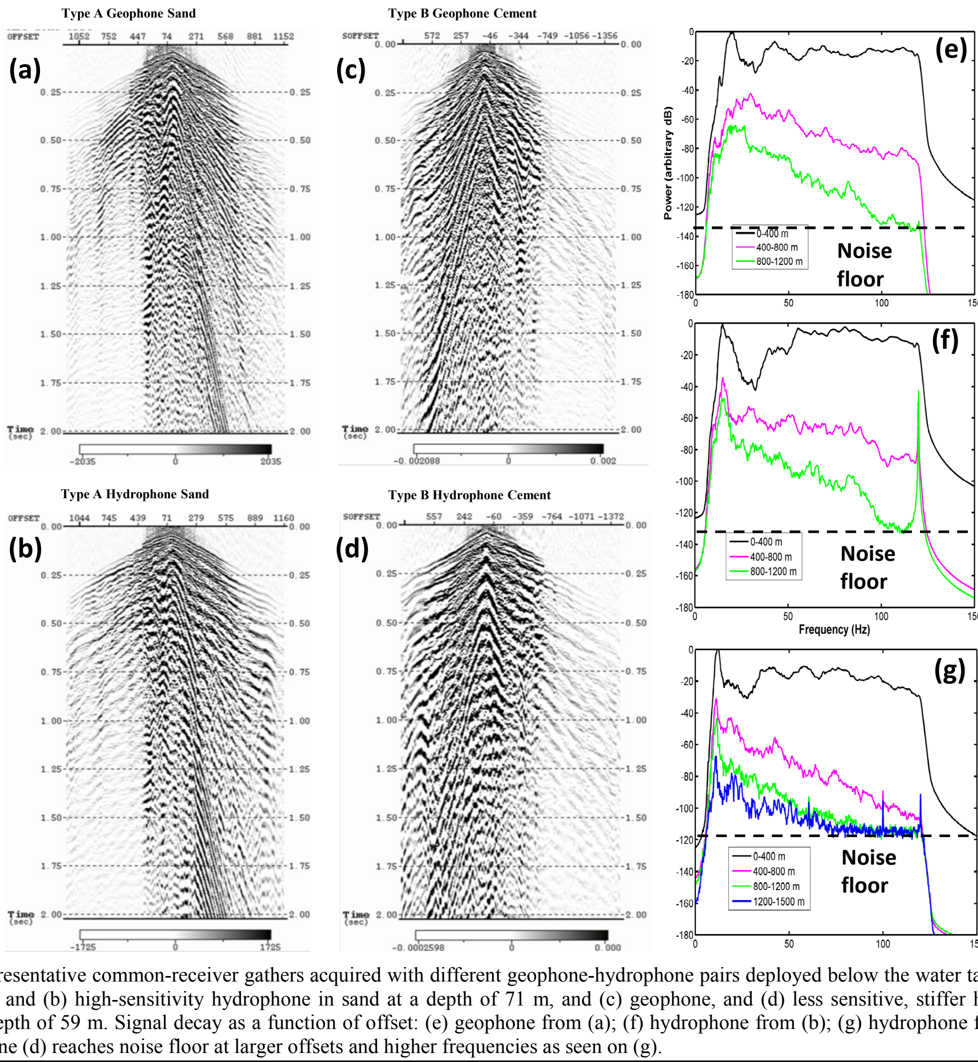


Figure 2. Representative common-receiver gathers acquired with different geophone-hydrophone pairs deployed below the water table, including (a) geophone, and (b) high-sensitivity hydrophone in sand at a depth of 71 m, and (c) geophone, and (d) less sensitive, stiffer hydrophone in cement at a depth of 59 m. Signal decay as a function of offset: (e) geophone from (a); (f) hydrophone from (b); (g) hydrophone from (d). Note that hydrophone (d) reaches noise floor at larger offsets and higher frequencies as seen on (g).


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multiple surface obstructions while maintaining stringent 4D positioning requirements. We conducted a multi-day test with 24/7 shooting and verified that flip-flop acquisition with two vibrators can deliver between 4,000 and 5,000 vibrator points per day with a re-positioning accuracy of 0.75 m for about 80% of the acquired VPs (Figure 3). We also set another 4D objective of re-positioning of the vibrator baseplate (Jervis et al., 2012) at the same orientation and were able to achieve it with 5° accuracy for 90% of the VPs during limited tests.

## Discussion

There are certainly many ways to improve permanent installations of this kind in the future. It is clear that deploying multiple sensors or antenna in each shallow hole should increase the fold and allow additional signal processing using vertical arrays. This should improve data quality and repeatability; however costs for conventional sensors even at shallow depths remain too high to make it a reality. Emerging technologies such as fiber-optic sensors may allow more complete and affordable instrumentation of shallow holes.

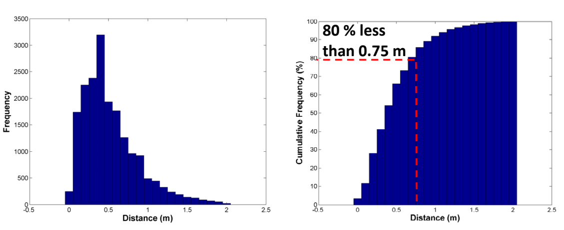


Figure 3. Histogram of positioning repeatability for three thousand VPs reshot six times during the test.

Permanent sensors generally require power that may be from batteries, a central location via trenched cables or solar panels. In addition, data collection requires telemetry for recording via cables or wireless antennas. Each of these options is far from ideal for installations in a producing oilfield in the desert. Solar panels require protection and regular cleaning. Replacing batteries every month on a thousand permanent sensors is not very practical. Trenching needs to deal with multiple surface and underground obstructions.

The ideal solution for permanent monitoring would entail a sensor with self-recharging buried battery that can draw energy from the temperature differential, wind, vibrations or be wirelessly recharged from a device attached to the vibrator truck that regularly visits all the receiver locations. While wireless data collection from land seismic nodes has been demonstrated, wireless power for permanent sensors remains a challenge. For permanent installations, it is highly desirable that the power supply and telemetry hardware for the sensor be buried as much as possible with little exposure at the surface for protection and safety. While this may sound intractable at this moment in time, we remain optimistic that solutions to some of these problems will be found in the near future.

## Conclusions

We have conducted a series of field trials aimed at evaluating various geophysical and operational components for a permanent installation with 1,000 4C receivers buried below a complex near surface. The best P-wave images are obtained using dual sensor summation, i.e., after summation of hydrophone and vertical geophone. We deployed sensors at 50 m to 70 m depth just below the water table for two main reasons: to obtain better hydrophone coupling and repeatability and to minimize the effect of shallow karsted zones to improve image quality. We evaluated several sensor designs and found that increased sensitivity beyond typical limits for surface instruments is beneficial when the sensors are buried. Cemented and gravel packed deployment methods in shallow vertical holes have generally produced good results in terms of hydrophone and geophone coupling and repeatability below the water table. Selection of the particular deployment method for hydrophones seems to be more related to the sensor design and sensitivity. For instance, more sensitive hydrophones perform best in sand, while less sensitive hydrophones perform better in cement. Drilling through a complex karsted near surface with lost circulation zones remains a challenge that is overcome using fit-for-purpose geotechnical rigs and using drilling with air and foam. The final survey design comprises a circular buried receiver patch about 2 km across with a larger shot area around it. A dense shot pattern is emphasized because of near surface complexity, high 4D noise and low expected 4D signal. For the same reasons we set more stringent but achievable repeatability requirements for shot acquisition geometry. In particular we strive to repeat shot positioning within 0.75 m and baseplate azimuth within 5° for more than 90% of the source points. After evaluation of the sensors, deployment methods and source navigation with a series of field trials, the installation of the permanent 3D sensor network is now underway. Frequent reservoir snapshots obtained with buried sensors are expected to deliver reliable tracking of the $CO_2$ front and the ability to perform 4D permeability inversion inside the flooded area.

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**EDITED REFERENCES**

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