Smart DAS upholes for near surface model building and imaging with buried vertical arrays

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Summary

We propose smart DAS uphole with permanently placed cheap fiber as seismic sensor. Uphole survey can be acquired any time with a single shot since all depth levels are simulatenosuly recorded. Dense grids of on-demand smart DAS upholes provide perfect characterization of long-wavelength statics at the prospect level. Connecting multiple upholes with a single fiber enables seismic survey with buried vertical arrays that can provide robust subsurface images similar to surface seismic but with much improved accuracy due to eliminated near-surface uncertainty. System consisting of carpet of surface shots and dense grid of smart DAS upholes provides complete dataset for near-surface characterization as well as imaging of low-relief structures. We successfully validate this concept using 2D field experiment in Saudi Arabia.

Introduction

Modern exploration challenges require ability to accurately delineate low-relief structures with vertical closure of less than 60 meters or 30 milliseconds. To achieve this goal, near-surface velocity models and long-wavelength static corrections have to be estimated with an accuracy that should be only a small fraction of the overall structure closure. Can this accuracy be achieved on routine basis? Geophysical methods such as tomography suffer from many limitations that results in significant uncertainty that is hard to quantify. The static errors introduce vertical shifts into the final seismic volume and might corrupt the interpretation results. An example of how these errors significantly affect the reservoir volumetric estimation is presented by Nosjean et al. (2017), where calculated volumes based on various processing with different near surface models are varied in a 3:1 ratio.

In this study we focus on one novel technique that utilizes Distributed Acoustic Sensing (DAS) for near surface characterization and imaging. This technique is based on innovative use of cheap DAS sensors to obtain uphole measurements, directly estimate long-wavelength static from a grid of upholes and obtain subsurface image using vertical arrays of same buried receivers.

Smart DAS upholes

Conventional seismic uphole requires moving single geophone up the hole and using hammer or weight drop source to obtain first breaks. Data quality is usually poor for several reasons. First, open hole results in variable coupling when wall-lock geophone is dragged along the rugose well. Shot signature is different for every level. It is difficult to achieve accurate depth control due to manual operation. At deeper depth, multiple excitations of the cheap weak sources are required to achieve robust first break. Operationally, uphole crew has to be continually on site during drilling to enter the hole and perform the survey as soon as it is completed to avoid potential collapse.

As an alternative, we propose novel method to acquire upholes with DAS fiber as seismic sensor string. Every meter of DAS cables acts as seismic sensor (Miller et al., 2012), therefore enabling multi-level array covering the entire length of the uphole from top to bottom. DAS cable is deployed in the hole right after drilling and permanently left in place due to insignificant cost. As a result, uphole survey can be acquired with a single shot. We refer to this new setup as smart DAS uphole. The advantages of the new approach are:

- Simplified operation. Fiber is installed after completion of the drilling and hole is immediately backfilled with connector left at the surface;
- Acquisition can be conducted any time later when significant number of upholes are drilled;
- Efficient risk-free acquisition with constant source signature. Each uphole takes several minutes since only single shot or sweep is required. No risk of collapse or stuck tool during acquisition.

Field testing of smart DAS upholes in Saudi Arabia

We conducted field test to validate this concept in onshore field in Saudi Arabia. Figure 1 shows wellhead of comple-

Figure 1. Wellhead of smart DAS uphole before installing protection cover.

Figure 2. Recording DAS upole with a mobile unit and vibrator. Single sweep is sufficient since receivers cover entire hole.

ted smart DAS uphole after backfill. Figure 2 shows recording of the uphole survey with mobile DAS unit. Field test demonstrated that either fluid or solid backfill is sufficient to obtain reliable DAS coupling with the formation. During conventional uphole acquisition any hole collapse may lead to loss of the tool and impede the survey. For DAS uphole any collapse after fiber installation is not a problem. Entering most upholes with DAS cables immediately after drilling was proven straightforward, whereas fluid or solid backfill, cementation or bentonite packing represent possible solutions providing good acoustic coupling.

Figure 3 shows sample record obtained with single vibroseis sweep and using DAS channels with vertical spacing of 4 m. Good-quality waveforms are observed all the way from surface to total depth of 125 m. Seismic reference datum was at around 90 m, but we have drilled deeper upholes in order to use them for imaging as explained later. As expected, accelerated weight drop provides somewhat sharper first breaks which is evident on

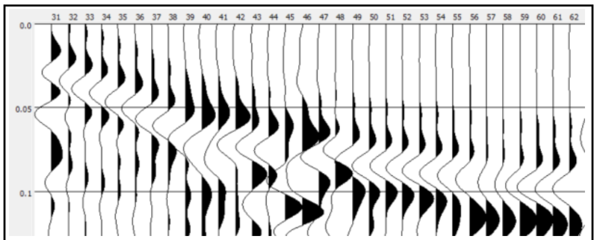

Figure 3. Waveforms recorded for DAS uphole #5 (144 m) with vibroseis.

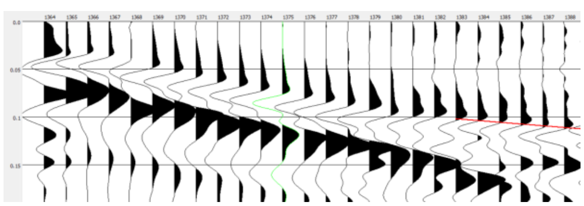

Figure 4. Waveforms recorded for DAS uphole #11 (112 m) with accelerated weigh drop source.

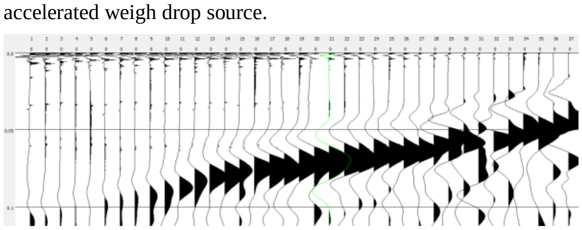

Figure 5. Waveforms recorded for conventional DAS uphole # 9 (138 m) using wall-lock geophone and accelerated weight drop source.

DAS fiber in another uphole (Figure 4). With proper backfill to the surface we have excellent quality of DAS channels all the way to the ground level. Figure 5 shows waveforms from conventional uphole acquired nearby using wall-lock geophone and weigh drop source. Comparing Figures 3-5, we generally observe similar or better quality of DAS waveform compared to conventional uphole that is recorded with 2 m spacing of geophones in the shallow part (50 m) simply to have better statistics for less consistent first breaks. In contrast, DAS uphole with 4 m sampling and identical source for all channels is clearly sufficient considering seismic frequency range used. Traveltime curves are compared in Figure 6. While shallow parts show good agreement, there are clear lateral variations of velocity in deeper layers even on such a small scale of less than one kilometer. These variations represent long-wavelength statics that need to be accurately described in order to reliably image low-relief structures.

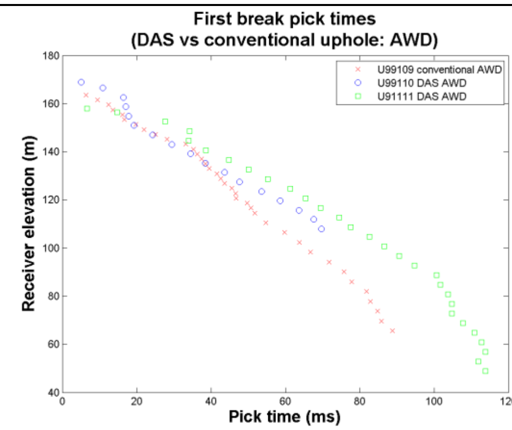

Figure 6. Traveltime picks obtained with various uphole measurements.

On demand smart DAS upholes

Smart DAS upholes enable straightforward on demand acquisition for specific prospects of interest. If there is significant uncertainty in the near surface model that may impact exploration, then collection of new on-demand smart DAS uphole can be requested. Drilling crew pre-drills all the upholes and installs the DAS fiber. Then recording crew comes and records all uphole survey with a single shot/sweep per uphole. Efficient acquisition allows bringing strong energy source such as vibroseis. This may deliver additional benefits such as shallow VSP that records primaries and multiples from the deep targets.

Building near-surface models with upholes

If on demand concept is adopted, then it becomes practical to perform regular grids of upholes over prospects of interest. Here we simulate such a scenario using SEAM Arid model (Oristaglio, 2015). Suppose we are looking for two low-relief structures in the area of interest 10 x 10 km (Figure 7a). Figure 7b shows true long-wavelength statics computed using SEAM Arid velocity model assuming seismic datum at 90 m depth. Largest structural uncertainty comes from errors in long-wavelength statics that distort the geometry and volume of the explored structures. Acquiring a patch of upholes on a grid 1x1 km requires 81 wells (Figure 8b). Assuming, that short-wavelength static can be estimated from seismic, we can simply interpolate long-wavelength statics from upholes into the entire volume and obtain reliable statics for the entire survey. Figure 8a confirms reliable mapping of both 10 and 20 ms low-relief structures with uphole-based statics. Considering larger exploration risks associated with low-relief structures and significant cost of drilling, such targeted grids of upholes should become useful tool in our geophysical toolbox. Uphole-based methods can provide direct and reliable static estimate not only for time imaging but also depth imaging and avoid depth mis-prognosis often encountered in areas with with complex near surface.

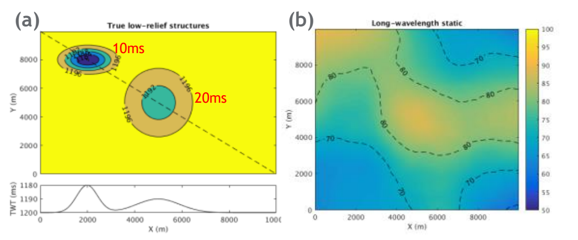

Figure 7. Synthetic low-relief structures (a) and long-wavelength static time-shifts (b) derived from near-surface part of SEAM Arid model.

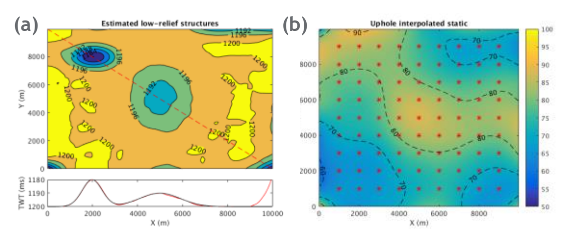

Figure 8. Structural map (a) and long-wavelength static values (b) derived from interpolating uphole grid drilled at 1x1 km.

Imaging with buried vertical arrays

Usage of disposable DAS sensors opens another opportunity namely to record higher-quality seismic reflection data with buried receivers. Bakulin et al (2012) compared seismic imaging obtain with surface and buried sensors at a single depth and showed superiority of the buried data. In case of smart DAS upholes, we obtain reflection records with entire vertical antenna. Figure 9 shows simulated common-receiver gathers in a realistic synthetic model representing field test site. With increasing depth of the sensor, we observe more and more reflection signal and less contamination by horizontally propagating energy in the near surface. Let us assume that we have instrumented 10 upholes of 200 m depth with a spacing of 400 m with DAS sensors. With 4-m depth spacing, we obtain 500-channel seismic array with buried vertical antennas that allows recording a reflection survey. Shooting 2D line of sources on top of the model, we obtain rather complete 2D seismic survey comparable to a surface seismic. While holes are sparse in horizontal direction, they compensate for it by recording vertical antennas that cover significant additional angles. Indeed, comparing angle illumination and coverage (Ikelle and Wilson, 1998), one can conclude that survey with buried vertical arrays may be equivalent to surface seismic. Depth imaging of buried array data produces result shown in Figure 10. While there are some shallow imaging artifacts, target low-relief structure at depth is well imaged. There are three main reasons why such surveys can be fit-for-purpose in the areas with near surface challenges:

- Grid of smart DAS uphole can completely resolve long-wavelength statics issue and deliver near surface model with accuracy needed for low-relief structures;
- Buried data is of higher signal-to-noise compared to surface reflection data and can provide angle coverage and images comparable to surface seismic;
- Using dense grid of smart DAS upholes for near surface characterization and imaging makes it a self-contained package that can de-risk prospects of interest.

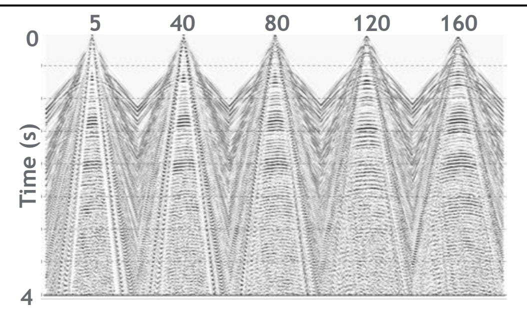

Figure 9. Synthetic common-receiver gathers in elastic model with the free-surface. Model is inspired by field test area.

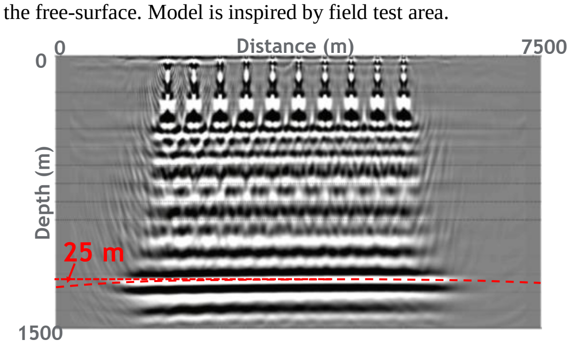

Figure 10. RTM image obtained with 10 holes of 200 m depth. Hole spacing is 400 m. Low-relief structure with vertical closure of 25 m is accurately imaged at depth of about 1.2 km.

Field testing of imaging with buried DAS arrays

While having DAS sensors in the smart upholes provides an opportunity to record them simultaneously, it would require multiple recorders which is currently expensive and less practical. To make it more efficient, we propose connect multiple upholes using single continuous fiber as shown in Figure 11. This requires running fiber up and down each hole with a loop at the bottom. We have performed a field test of such configuration and connected a series of upholes along the 2D line with a single fiber. In fact, sample records shown on Figures 3 and 4 represent downgoing fiber from a looped installations. Figure 12 shows representative common-receiver gathers from a single DAS uphole with a dense 2D line of vibroseis sources spaced at 10 m. DAS channels near the surface reveal record similar to surface seismic. While simulated data on Figure 9 shows reflections observed at the surface, real data reveals little or no reflected signal. This may be explained by significant near-surface scattering caused by small-scale shallow heterogeneities that remain unknown and uncaptured by our models. However, reflection signal becomes clearly observed on real data starting from 30 m depth and it becomes more similar looking to synthetic. We are in process of imaging such buried array data and will report our findings in future publications. We demonstrate that DAS data with buried vertical arrays can be successfully acquired and that such buried data has better signal-to-noise ratio compared to surface seismic.

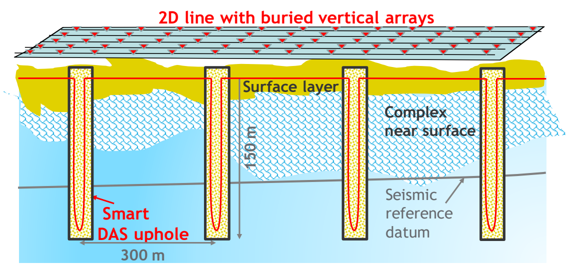

Figure 11. Smart DAS upholes connected by single continuous fiber enabling simultaneous recording of survey with buried vertical arrays using single DAS recorder.

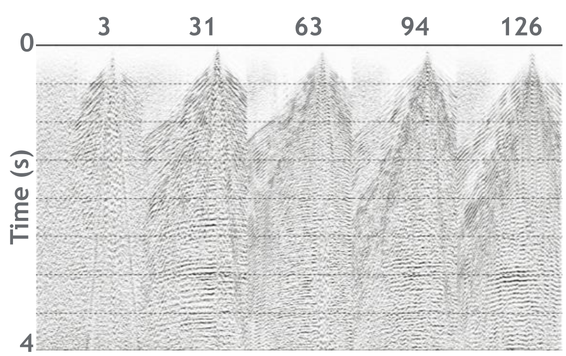

Figure 12. Common-receiver gathers for one of the smart DAS upholes as a function of DAS receiver depth. Shot line with 10 m spacing was acquired. Observe generally better visibility of reflection signal with increase in depth in agreement with simulations from Figure 9.

Conclusions

Smart DAS uphole is proposed as an alternative way of acquiring seismic uphole surveys. Cheap disposable DAS fiber is placed into the uphole after drilling and hole is immediately backfilled. No longer actual survey should be parallel to the drilling operation, since hole is instrumented and can be surveyed any time later when significant number of uphole locations are equipped with the fiber thus making operation simpler and more efficient. With sensors present from ground level to total depth, smart DAS uphole is acquired with a single source position. Identical source signature for all receivers provides superior quality of waveforms compared to conventional upholes. Stronger source such as weight drop or vibroseis can be justified due to significantly shorter acquisition. Side product such as zero-offset VSP recording targeting deep reflections can be obtained with vibroseis source. Such survey can be of value to establish origin of near-surface multiples that are often not recorded by conventional VSPs in deep holes due to multiple strings of casing with poor cement.

This new setup enables efficient acquisition of grids of on-demand smart DAS upholes at prospects suffering from near-surface challenges. We have shown that dense areal grids with a spacing of 1x1 km can completely resolve long-wavelength statics with sufficient accuracy to explore and delineate low-relief structure with vertical closure of less than 60 meters or 30 milliseconds.

Dense grids of upholes can be further connected with single fiber and enable acquisition of reflection seismic surveys with buried vertical arrays. Such surveys can provide alternative approach to image smaller prospect areas and serve as efficient surrogates for localized seismic surveys. Therefore, grids of smart DAS upholes represent a new system that can characterize near surface as well as produce reliable images of low-relief structures.

We have presented a 2D field experiment demonstrating validity of the component and the entire system. Smart DAS upholes were found of excellent quality whereas recorded seismic data with buried vertical arrays showed clear reflection signal on pre-stack records.

Acknowledgments

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