Near-surface characterization using vertical array seismic data from smart DAS upholes

Abdulrahman Alshuhail, Ilya Silvestrov, Ali Aldawood, and Andrey Bakulin, Geophysics Technology, EXPEC Advanced Research Center, Saudi Aramco;
Mazen Alawaji, King Saud University, Saudi Arabia

Summary

The near surface continues to be a challenging imaging obstacle in arid environments. If not accounted for properly, strong heterogeneities in the near surface, such as karsts and sand dunes, can cause blurred and mispositioned events in the seismic image. Typically, seismic refraction tomography is applied to obtain the near-surface model. Although it is robust, refraction tomography has limitations such as non-uniqueness, hidden layers, and the need for an accurate initial model. We investigate whether the traditional limitations associated with refraction tomography can be relaxed by using shallow upholes fitted with vertical distributed acoustic sensing (DAS) arrays. DAS arrays can achieve a much smaller sampling interval, which increases the trace density. Moreover, the vertical arrays increase the directional diversity of ray paths. We analyze the effect of both properties in inverting for a near-surface model. The improved accuracy is demonstrated on the SEAM arid model, where we invert for the near surface using the traditional surface seismic geometry and compare it with the inverted model for the vertical DAS geometry.

Introduction

In arid environments the near surface can be complex, with features ranging from *wadis*, sand dunes, *sabkah*s, and karsts frequently encountered. These complexities appear as highly variable velocity anomalies that have a significant impact on wave propagation. If not taken into account and corrected, the near surface can significantly deteriorate the seismic image. Therefore, characterizing the near surface accurately is of upmost importance in arid environments, which still remains a challenge. In conventional seismic processing, a near-surface model is derived by picking first arrivals (direct and refracted waves) from the surface seismic data. Using these picks, refraction tomography is applied to invert for a near-surface model (Bishop et al., 1985; Docherty, 1992).

In its basic form, refraction tomography is based on minimizing the error between the observed and calculated first break arrival times. The method is a nonlinear inversion method, therefore, many local minima exist. If the initial model is not close to the actual model, one risks falling into a local minima. Multiscale optimization can help the method converge toward the global minimum (Bunks et al., 1995). However, arriving at the global minima is not guaranteed. Another challenge in refraction tomography is limited coverage. In conventional refraction tomography the sources and receivers are located along the surface and cover only a small portion of the body of interest. This makes the solution non-unique, increasing the null space and resulting in many different models that fit the data equally well.

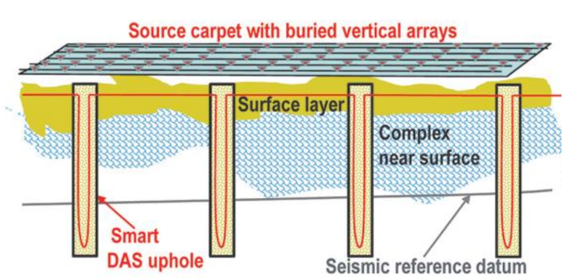

Figure 1: Schematic representation of the smart DAS geometry (Bakulin et al., 2017). Note that both surface and uphole data are acquired at the same time.

In addition, if the subsurface has a shallow velocity inversion (low velocity layer) it will be missed by conventional tomography. This effect is typically referred to as a hidden layer (Banerjee, 1975).

Over the past few years we have seen a revolution in utilizing distributed acoustic sensing (DAS) for seismic data acquisition (Daley et al., 2013; Mateeva, 2014). Some of the advantages associated with DAS over conventional geophones is that it allows recording multiple data sets with variable acquisition parameters with one continuous cable (Bakulin et al., 2018). In particular, the flexibility of the cable to conform to multiple geometries enables us to record surface data and uphole data at the same time. Bakulin et al. (2017) used this flexibility in geometry to design a seismic survey that utilized a single DAS cable for surface seismic and uphole data acquisition, which they called smart DAS upholes (Figure 1). Smart DAS upholes comprises a dense grid of shallow upholes that are fitted with cost-effective optical DAS fibers. The system allows imaging the deep subsurface and the near surface simultaneously.

10.1190/segam2019-3215594.1

This paper investigates if the smart DAS upholes geometry can alleviate many of the limitations associated with first break refraction tomography. The remainder of this paper is organized into three parts. First, we briefly explain the theory behind refraction tomography and show where these limitations come from. Second, we demonstrate the effect of inverting surface seismic data, smart DAS data, and their combination for the SEAM arid model (Oristaglio, 2015). Finally, the conclusions are presented.

Theory

Tomography can be defined as inversion that strives to estimate the model ($\boldsymbol{m}$) from the recorded data ($\boldsymbol{d}$), which can be waveforms or traveltimes. The $\boldsymbol{m}$ is related to the $\boldsymbol{d}$ by:

$$\boldsymbol{d} = \boldsymbol{L}(\boldsymbol{m}), \quad (1)$$

where $\boldsymbol{L}$ is the nonlinear forward modeling operator. The inverse can be described as:

$$\boldsymbol{m} \approx \boldsymbol{L}^{-1}\boldsymbol{d}. \quad (2)$$

To solve this equation for an over determined problem such as refraction tomography, a least squares solution that minimizes the error ($\boldsymbol{E}$) is normally employed:

$$E = \frac{1}{2}\|\boldsymbol{Lm} - \boldsymbol{d}\|^2. \quad (3)$$

Note that typically $\boldsymbol{L}$ is linearized, which requires the starting model to be close to the true model. For uncorrelated data errors with variance ($\boldsymbol{\sigma^2}$) the covariance matrix can be given by (Schuster, 2017):

$$\boldsymbol{C}_m = \sigma^2[\boldsymbol{L^T L}]^{-1}. \quad (4)$$

The covariance matrix helps in identifying how model errors depend on data errors and source receiver geometry. Some of the main factors that help decrease the value of $[\boldsymbol{L^T L}]^{-\boldsymbol{1}}$ are the number of rays and the diversity of angular coverage. With vertical arrays, both the number of rays (due to the fine sampling of DAS) and their angular coverage (due to the uphole geometry) will be significantly increased, which should help in reducing the null space.

Tomography via linearized inversion assumes that the initial model is close to the true model, due to the linearization of $\boldsymbol{L}$. With shallow upholes one can obtain a better initial model via actual velocity measurements in the subsurface.

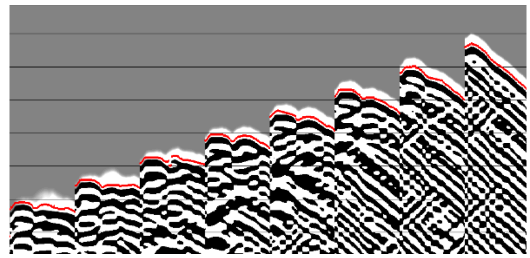

Figure 2: The first arrivals for vetrical array DAS data.

Smart DAS Tomography

To analyze the effects of geometry on tomography we generated elastic data using the SEAM arid model (Oristaglio 2015). Figure 3a shows the first 700 m of the model, which is our target for near-surface characterization. The model contains many near-surface features (such as the infill caves) that hinder conventional imaging if not taken into account. Note that velocity decreases at approximately a depth of 400 m, which will introduce a hidden layer. The survey consists of both a surface section and an uphole section. The surface receivers were spaced at 25 m on the surface. Upholes were spaced regularly at 250 m, reaching a depth of 650 m. The receiver spacing in the upholes was 6.25 m. Sources were fired at the surface at 25 m intervals. The survey is a fixed spread survey where all receivers were recording all shots with offsets up to 9 km. The initial model was obtained by plotting all the surface seismic traveltimes and estimating s simple three layer model (Figure 3b).

Initially, we picked the first arrivals of the surface seismic data. Common offset gathers were analyzed to ensure the correct event is picked and there is no cycle-skipping between shots. The tomographic inversion is run with a simple three layer initial model. Figure 3c shows the inverted near-surface model associated with surface seismic picks. The inverted model is generally a smooth representation of the true model. It represents the main features of the near surface such as the high velocity layer. However, the inverted model suffers from some limitations of refraction tomography. The major issue is the depth of investigation. Although the maximum offset is large (more 9 km) the depth of investigation is limited to 200 m. We analyzed the ray density to confirm the depth of investigation (Figure 3d). The reason behind this is because of the shallow high velocity layer. The path with the least time is associated with the high velocity layer, therefore, rays never penetrate it. This effect is also present between 7 km and 9 km where there is a low velocity inversion at the very shallow near surface (100 m). We calculate the datum statics (red line in

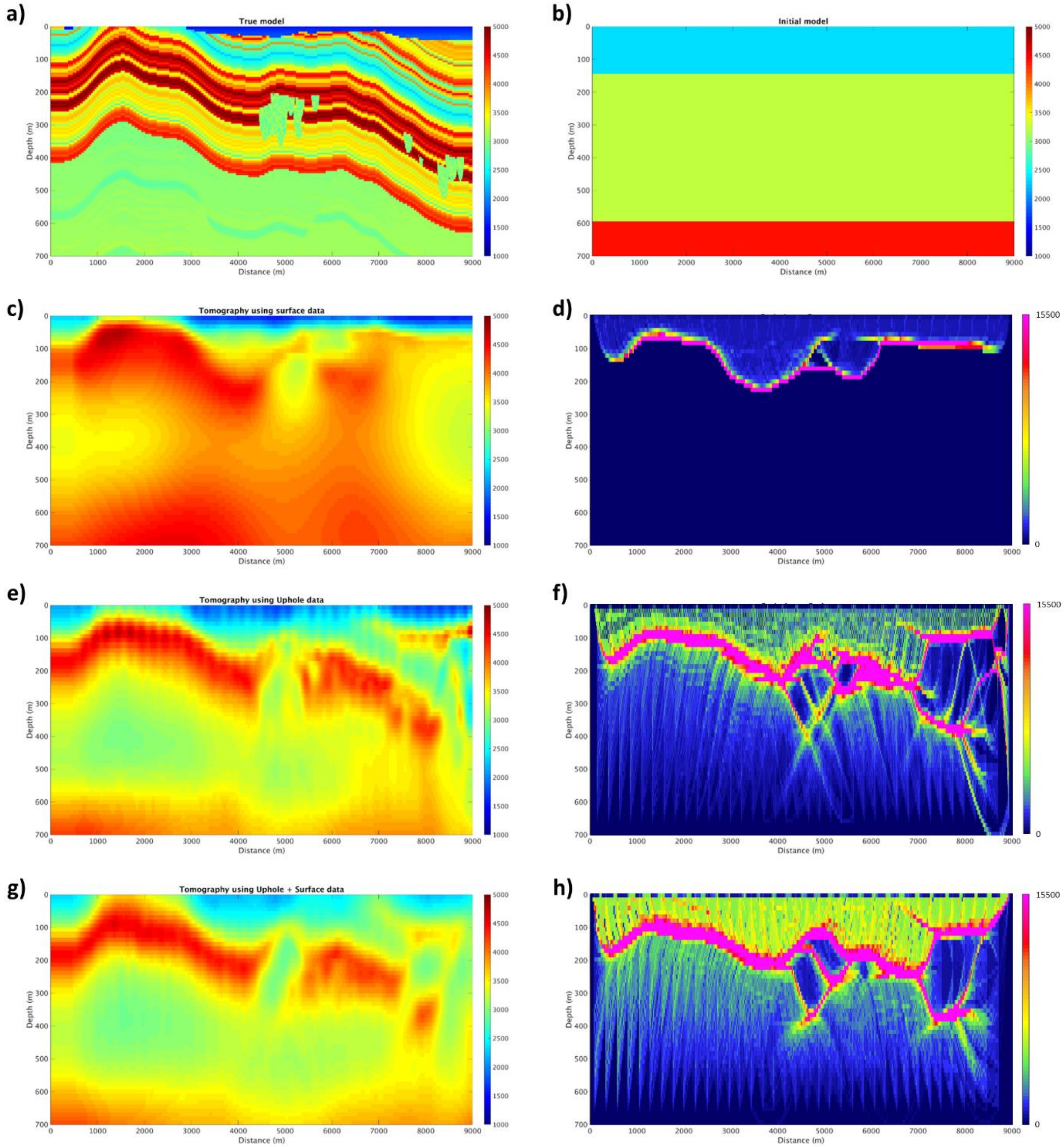

Figure 3: Smart DAS tomography, including (a) the true velocity model, (b) the initial velocity model, (c) tomogram for surface seismic data, (d) ray density for surface seismic data, (e) tomogram for uphole DAS data, (f) ray density for uphole DAS data, (g) tomogram for the combination of surface seismic and uphole DAS data, and (h) ray density for the combination of surface seismic and uphole DAS data.

10.1190/segam2019-3215594.1

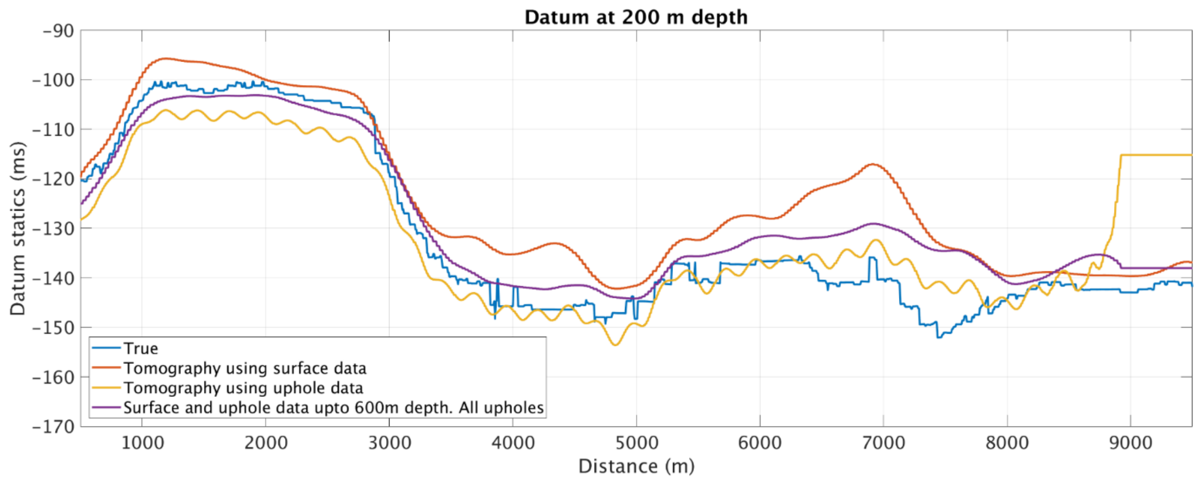

Figure 4: Comparison of the true datum statics (at 200 m), inverted datum statics for surface seismic data, inverted datum statics for uphole smart DAS data, and the datum statics for their combination.

Figure 4) and we find it follows the general trend but is not accurate.

Next, we pick the first arrivals of the upholes. The near offsets contain mostly direct waves. With increasing offset we notice that a large number of events are refracted arrivals (Figure 2).

Figures 3e and 3f show the inverted near-surface model and ray density associated with the uphole DAS traveltimes. The inverted model is a higher resolution model than the surface seismic segment. The edges of the different features a more clearly defined (compare the cave at 5 km). Another interesting feature is that the velocity inversion is well represented in the tomogram. Since the upholes penetrate to a depth of 600 m, tomography is able to provide updates at these depths. Figure 4 shows the datum statics, the yellow line shows the uphole DAS statics. Although the statics are accurate they are not perfect. We note that vertical stripes occur in the tomogram, which can be attributed to the acquisition footprint. Careful smoothing must be done to better represent the subsurface.

We combine the two data sets (surface and upholes) and jointly invert for the subsurface using all first arrival traveltimes. Figures 3g and 3h show the inverted near-surface model and the ray density associated with the surface and uphole traveltimes. No weighting has been applied; however, naturally more weight is given to the upholes due to the larger number of first arrival picks associated with them.

As in the uphole tomogram the combined tomogram is accurate. Note that the vertical stripes are no longer present as the surface data smoothed them out naturally.

Conclusions

Conventional refraction tomography is an attractive tool that has been used extensively in imaging the near surface. However, the method has assumptions that must be honored to arrive at an accurate solution. The main assumptions are that there are a sufficient number and diversity of rays intersecting the model. The flexibility of smart DAS geometry is able to increase the number and diversity of rays intersecting the model, which increases the resolution of the inversion result. We demonstrate the effects of geometry on tomography for the SEAM arid model. Tomography using the surface seismic data provides a low resolution model. Once we include the vertical DAS arrays we obtain a significant uplift in resolution and accuracy. We combine the two data sets and find that they generate the best results.

Acknowledgments

The authors thank Mohammed Almarzoug and Eyad Aljishi for help generating the different results.

10.1190/segam2019-3215594.1

REFERENCES

Bakulin, A., P. Golikov, R. Smith, K. Erickson, I. Silvestrov, and M. Al-Ali, 2017, Smart DAS upholes for simultaneous land near-surface characterization and subsurface imaging: The Leading Edge, **36**, 1001–1008, doi: 10.1190/tle36121001.1.

Bakulin, A., I. Silvestrov, and R. Pevzner, 2018, Surface seismic with DAS: Looking deep and shallow at the same time: 88th Annual International Meeting, SEG, Expanded Abstracts, 16–20, doi: 10.1190/segam2018-2995870.1.

Banerjee, B., and S. K. Gupta, 1975, Hidden layer problem in seismic refraction work: Geophysical Prospecting, **23**, 642–652, doi: 10.1111/j.1365-2478.1975.tb01550.x.

Bishop, T. N., K. P. Bube, R. T. Cutler, R. T. Langan, P. L. Love, J. R. Resnick, R. T. Shuey, D. A. Spindler, and H. W. Wyld, 1985, Tomographic determination of velocity and depth in laterally varying media: Geophysics, **50**, 903–923, doi: 10.1190/1.1441970.

Bunks, C., F. M. Saleck, S. Zaleski, and G. Chavent, 1995, Multiscale seismic waveform inversion: Geophysics, **60**, 1457–1473, doi: 10.1190/1.1443880.

Daley, T. M., B. M. Freifeld, J. Ajo-Franklin, S. Dou, R. Pevzner, V. Shulakova, S. Kashikar, D. E. Miller, J. Goetz, J. Henninges, and S. Lueth, 2013, Field testing of fiber-optic distributed acoustic sensing (DAS) for subsurface seismic monitoring: The Leading Edge, **32**, 699–706, doi: 10.1190/tle32060699.1.

Docherty, P., 1992, Solving for the thickness and velocity of the weathering layer using 2-D refraction tomography: Geophysics, **57**, 1307–1318, doi: 10.1190/1.1443198.

Mateeva, A., J. Lopez, H. Potters, J. Mestayer, B. Cox, D. Kiyashchenko, P. Wills, S. Grandi, K. Hornman, B. Kuvshinov, and W. Berlang, 2014, Distributed acoustic sensing for reservoir monitoring with vertical seismic profiling: Geophysical Prospecting, **62**, 679–692, doi: 10.1111/1365-2478.12116.

Oristaglio, M., 2012, SEAM phase II—Land seismic challenges: The Leading Edge **31**, 264–266, doi: 10.1190/1.3694893.