SUBSURFACE VELOCITY-MODEL BUILDING USING ENHANCED 3D SEISMIC-WHILE-DRILLING DATA

M. Almarzoug[1], I. Silvestrov[1], A. Bakulin[1], A. Aldawood[1]

[1] Saudi Aramco

Summary

Seismic-while-drilling (SWD) provides a cost-effective method to acquire borehole geophysical data without interfering with the drilling operations. SWD data can assist in building accurate shallow subsurface models that can be used for geological interpretation. Here, we analyze SWD data acquired in a desert environment using novel wireless surface receivers placed in an areal 3D geometry around the well. Since the drillbit signal is unknown, top-drive and downhole sensors were used to record the drillbit signature. We utilize the pilot from the downhole sensor that recorded a more accurate version of the drillbit signature to deconvolve drillbit gathers. This approach enhanced the data quality compared to a previous study that employed the top-drive pilot. An advanced workflow that involves vertical stacking of drillbit gathers and nonlinear beamforming was applied to further improve the data quality. The first break picks from geophones within 180-500 m from the well were vertically projected, averaged, and smoothed to construct a robust zero-offset 1D velocity profile. To generate a velocity model that considers offset-dependent velocity information, a 3D traveltime inversion was implemented for depth range 190-800 m which yielded an accurate near-surface velocity model.

Subsurface velocity-model building using enhanced 3D seismic-while-drilling data

Introduction

Seismic-while-drilling (SWD) utilize the drillbit as a seismic source to acquire reverse vertical seismic profiling (rVSP) data (Rector and Marion, 1991). SWD eliminates the need for well intervention and installing downhole receivers to acquire conventional VSP data, that require additional rig time. In addition, SWD offers many real-time geophysical applications such as while-drilling checkshots, ahead-of-the-bit predictions, and imaging ahead and around the drillbit (Poletto and Miranda, 2004). These applications can assist in steering drilling operations by detecting potential drilling hazards, updating formation tops and velocity models, and locating the drillbit on surface seismic volumes.

SWD data often suffer from a low signal-to-noise ratio (SNR) primarily due to the weak emitted energy by the drillbit sources. Intense noise related to drilling operations is recorded by the surface receivers around the well, obscuring the desired downhole source signal. Typical SWD acquisition surveys utilize a limited number of receivers that are positioned along 2D lines, which restricts the usage of data enhancement workflows. To overcome these challenges, Al-Muhaidib et al. (2018) and Bakulin et al. (2020) presented a SWD acquisition system called Drilling Camera (DrillCAM). DrillCAM uses a large number of wireless receivers placed in a 3D geometry to increase the fold of the recorded weak signals. Moreover, the utilization of wireless sensors allows for the adaptation of several acquisition geometries while drilling for different objectives. The redundancy of the data also helps resolve the issue of random and coherent noise associated with drilling operations by adapting advanced workflows to enhance the SNR of while-drilling data.

The system’s first deployment was used to acquire SWD data in a desert environment with complex near-surface geology. 2D lines in such a complex environment would not be optimal as the data would require 3D data-enhancement procedures to suppress the noise and enhance the desired data. DrillCAM utilized 2,500 vertical-component wireless geophones placed around the well to acquire a 3D SWD dataset to avoid this issue. A 3C top-drive sensor was installed on the rig to record the drillbit signature propagated through the drillstring. Furthermore, a memory-based 3C downhole sensor, installed close to the drillbit, was utilized to record a more accurate drillbit signal. As a result, the 3D dataset enabled the use of a more specialized workflow to enhance data quality and maximize data usage.

This paper presents the results of characterizing the subsurface section, particularly the shallow part corresponding to the complex near-surface encountered in a desert environment. The pilot from the downhole sensor was used to deconvolve the recorded drillbit gathers. Bakulin et al. (2020a) presented the results of using the top-drive sensor pilot for deconvolution, which yielded an acceptable checkshot profile. However, data quality restricted the first break picks to below a drillbit source depth of 565 m. Only the best-quality single sensor was used to reconstruct a time-depth curve. This study shows that utilizing the redundant receiver data and the downhole sensor yields a more accurate velocity information starting from a shallower depth than the one with the top-drive sensor.

Data acquisition and processing

DrillCAM data was acquired using 2,500 vertical component wireless geophones placed around the well with an interval of 25 m along the North-South and East-West directions (Figure 1). The first acquisition layout was used to drill up to 800 m depth. A patch of 2,000 receiver stations was positioned inside a 1.1 km x 1.1 km grid centered around the well (Figure 1a). The second layout was utilized for the drilling section below 800 m, represented by orange dots in Figure 1b. In this geometry, seven 2D lines extending in the North-South direction and seven other orthogonal lines in the East-West direction were deployed to acquire reverse walkaway VSP data. Aldawood et al. (2021) stacked the seven 2D lines for each direction. They used them to generate a subsurface image of the shallow and deeper sections.

The SWD acquisition system also utilized 3C top-drive and downhole sensors to record the drillbit’s signature. The downhole sensor used in this study requires a special workflow to correct for the time delay between the downhole and GPS-synchronized top-drive sensors. Also, the internal clock has both linear and nonlinear drifts that need to be corrected before using the cleaner downhole pilot for deconvolution. To align the downhole sensor's signal with the ones recorded by the top-drive and geophone sensors, Egorov et al. (2021) used a global optimization approach to determine the time shift and linear drift. They then determined the nonlinear drift using a correlation-based approach.

To process the data, vertical stacking of drillbit gathers over every drill pipe's interval (~10 m) was applied to enhance the SNR. Bakulin et al. (2020a) demonstrate how the stacking process is performed to obtain enhanced drillbit gathers. SWD data tend to have a linear surface noise associated with drilling operations. Unlike the drillbit's signal, the noise emitted from drilling equipment has a low dominant frequency. To improve the SNR, a 20-Hz low-cut filter was applied to suppress the surface noise and boost the subsurface drillbit's signal. To further increase the SNR, nonlinear beamforming (NLBF) was applied to the full 3D dataset (Bakulin et al., 2020b). This method uses a data-driven approach to determine the local moveout and stack accordingly. Combining these steps significantly enhanced the SWD waveforms, allowing to pick accurate first arrivals.

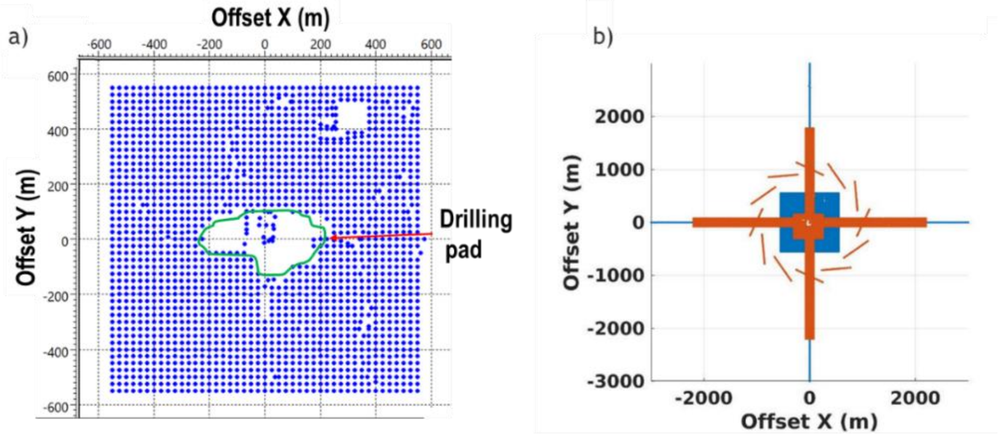

Figure 1 *Acquisition geometry with the well located at the center: (a) geometry for the first 800 m drilled section; the area surrounded by green is where the drilling rig is placed; (b) geometry below 800 m is shown in orange, while the blue square corresponds to the first layout shown in (a).*

1D velocity profile

SWD data is typically used to reconstruct a checkshot profile by selecting the best-quality single geophone positioned near the well; overlooking sensors that are in close proximity of the well and have extensive surface-related linear noise. Bakulin et al. (2020a) study focused on utilizing the top-drive pilot for deconvolution, which can be obtained in real-time for immediate processing. They generated a velocity profile from a single sensor at an offset of 475 m from the well. The data quality limited the first breaks picks to depth levels deeper than 565 m. As a result, they were not able to obtain velocity information shallower than 565 m. In this experiment, we utilize the pilot from the downhole sensor which was operating at a starting depth of 170 m. After data enhancement, we were able to pick first-break (FB) traveltimes for a drillbit depth as shallow as ~190 m. Only picks from geophones within 180-500 m from the well were considered to generate the 1D velocity profile as shown in the traveltime map in Figure 2.

Next, we compare the velocity profile constructed from the top-drive pilot with the one obtained from the downhole pilot. A vertical projection of the FB traveltimes, based on straight ray assumption, was implemented to all receivers in Figure 2 to utilize the redundancy of the contributing sensors. To remove the jittering and construct a more realistic 1D velocity profile, we computed the mean at every depth level and applied a smoothing and decimation to obtain a traveltime pick every 20 m. In the case of the checkshot profile from the top-drive pilot, the traveltimes from a single sensor at an offset of 475 were projected and smoothed. Figure 3a illustrates a comparison between the two projected profiles after smoothing. As shown, the two profiles are similar. However, the velocity profile from the downhole pilot extends to a shallower part. Also, it is less oscillatory, especially at the deeper levels.

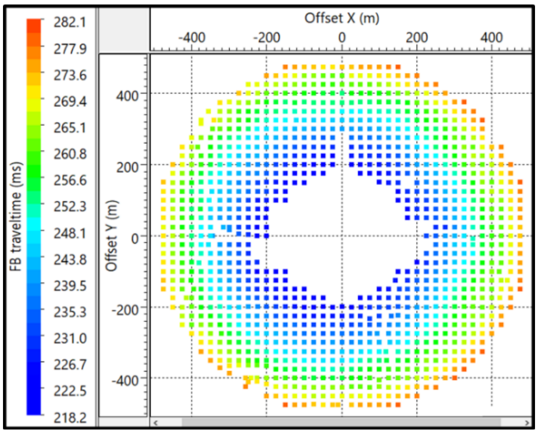

Figure 2 *Firs-break traveltimes map from a depth level of 589 m with an offset between 180 and 500 m from the well.*

Additionally, a 1D traveltime inversion was run for both cases, and the interval velocities are shown in Figure 3b. Unlike the time-depth curves plot, a clear distinction is observed between the interval velocities generated from the top-drive and downhole pilots. It is expected that the velocity information obtained from the downhole sensor to be more robust due to the utilization of a more accurate drillbit signal for deconvolution. In addition, the redundancy in the 3D data as a result of using many geophones has helped minimize the first break picking uncertainty.

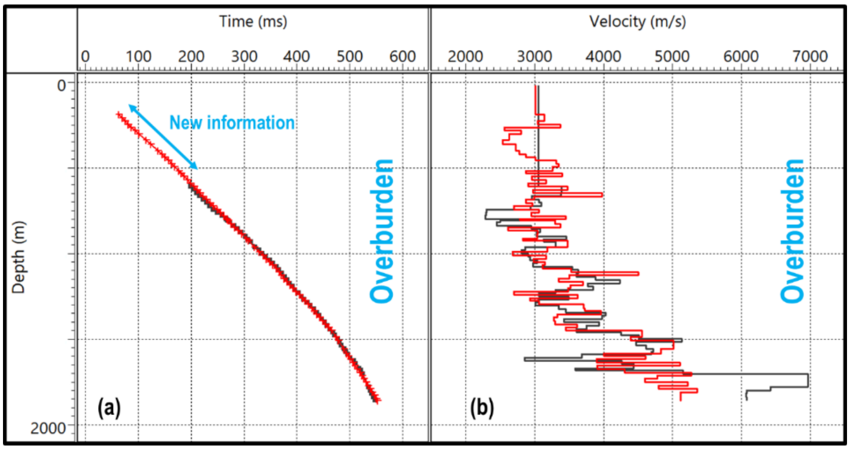

Figure 3 *1Derived time-depth curves and 1D velocity models: (a) time-depth curves; (b) inverted 1D velocity profiles. The traveltimes from the top-drive pilot are black, whereas the traveltimes from the downhole pilot are red.*

3D velocity model building

The straight ray assumption made in the previous section neglects the offset-dependency of the velocity information, thus reducing the accuracy of the retrieved velocity model. This section uses 3D SWD data from a depth range between 190 and 800 m to build a more robust velocity model that incorporates velocity information dependent on offset. For this depth range, the data was acquired with the receiver geometry shown in Figure1a, where there are 63 depth levels with FB traveltime picks. A 3D traveltime least-square inversion was utilized to build a laterally-homogenous velocity model (Figure 4). According to the 1D velocity profile, a model with a constant velocity of 3000 m/s can be chosen as an appropriate starting model for the inversion algorithm. As shown in Figure 4, the 3D traveltime inversion was able to resolve the layers' velocities with large contrasts starting with a constant homogenous background velocity.

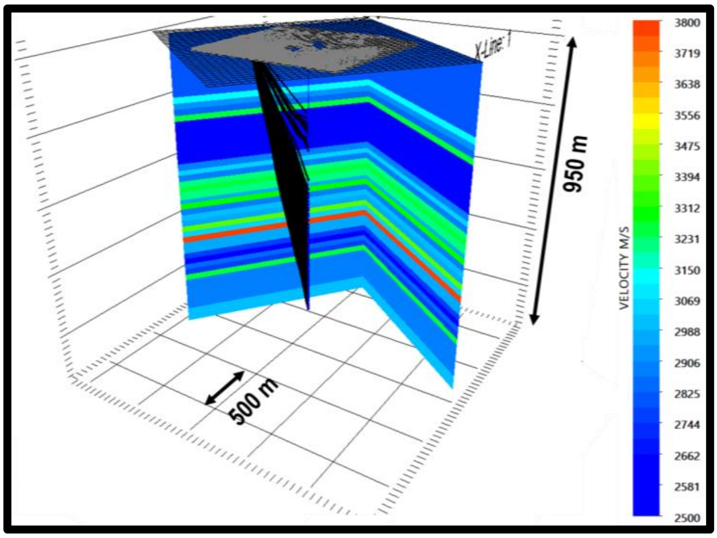

Figure 4 *1D velocity model generated by 3D traveltime inversion. The black lines correspond to the rays received by a single surface geophone from multiple drillbit depth levels.*

Conclusions

A seismic-while-drilling acquisition system was employed with a large number of wireless surface receivers in a 3D geometry to boost the drillbit's weak signal and suppress surface drilling-related noise. Advanced data enhancement workflow that includes vertical stacking of drillbit sources and local stacking with nonlinear beamforming of receivers helped increase the SNR of the 3D data, thus allowing picking accurate first-break traveltimes. A comparison between the reconstructed checkshot profiles from the top-drive pilot and downhole pilot revealed that the two profiles are similar; however, the profile obtained from the downhole pilot resolved an additional 375 m of velocity information in the shallow section due to the utilization of a more accurate drillbit's signature to deconvolve the SWD waveforms. To build a more accurate 1D velocity model that accounts for offset-dependent velocity information, a 3D traveltime inversion was applied on the 3D SWD data for the shallow subsurface (190-800 m). The redundancy in the data was critical to minimize the effect of random noise on traveltime picks and reconstruct a robust laterally-homogenous near-surface velocity model.

References

Aldawood, A., Hemyari, E., Silvestrov, I., & Bakulin, A. [2021] Imaging ahead of and around the bit in a desert environment: DrillCAM field trial with wireless geophones and top-drive sensor. *The Leading Edge*, **40**(5), 374-381.

Al-Muhaidib, A., Liu, Y., Golikov, P., Al-Hemyari, E., Luo, Y. and Al-Ali, M. [2018] DrillCam: A fully integrated real-time system to image and predict ahead and around the bit. *SEG Technical Program Expanded Abstracts 2018*, 719-723.

Bakulin, A., Aldawood, A., Silvestrov, I., Hemyari, E., and Poletto, F. [2020a] Seismic-while-drilling applications from the first DrillCAM trial with wireless geophones and instrumented top drive. *The Leading Edge*, **39**(6), 422-429.

Bakulin, A., Silvestrov, I., Dmitriev, M., Neklyudov, D., Protasov, M., Gadylshin, K., and Dolgov, [2020b] Nonlinear beamforming for enhancement of 3D prestack land seismic data: *Geophysics*, **85**, 1MJ-Z13.

Egorov, A., Silvestrov, I., Bakulin, A., Golikov, P. [2021] Automated data-driven alignment of near-bit and top-drive vibration sensors for seismic while drilling and beyond, *Geophysical Prospecting*, **6**(7), 1560-1568.

Poletto, F. and Miranda, F. [2004] Seismic while drilling: Fundamentals of drillbit seismic for exploration: Elsevier.

Rector, J.W. and Marion, B.P. [1991] The use of drillbit energy as a downhole seismic source. *Geophysics*, **56**(5), 628-634.