geoconvention Virtual Event September 21-23 2020
CSPG • CSEG • CWLS • GAC • MAC • IAH

Seismic illumination analysis through physical modeling

Nasser Kazemi, Joe Wong, Hongliang Zhang, Kevin Bertram, Kris Innanen, and Roman Shor
University of Calgary, Canada
nasser.kazeminojadeh@ucalgary.ca

Abstract

The efficiency of seismic acquisition design, imaging, and interpretation, depends on how well the seismic raypaths cover the subsurface. In surface seismic acquisition, the sources and receivers are deployed at or near the surface. As the sources fire from the surface and the receivers record the reflected seismic energy, depending on the complexities of the subsurface structure, the ray path coverage can be drastically non-uniform. Rays follow the shortest path; hence, they tend to bend toward high-velocity zones and deviate from low-velocity regions. This behavior results in having specific regions in the subsurface where seismic energy penetrates weakly. These regions are in the shadow zone of the seismic acquisition. Also, the logistics and economic constraints can limit the extent and density of the seismic sources and receivers, which in turn can reduce the ray path converge of the subsurface. To analyze the causes, extent, and impacts of non-uniform subsurface illumination and to provide potential solutions for achieving a uniform illumination, we undertake a physical modeling project. We designed a 2.5D physical model that consists of a high-velocity blocking object submerged in the water and three target objects under the blocking part. The physical model is designed to reflect the difficulties encountered in sub-salt illumination, such as the reservoirs in the Gulf of Mexico, Mississippi Canyon.

Deficiencies in seismic illumination can be mitigated if deep subsurface sources are used in the acquisition. Drillbit-rock interactions generate significant elastic waves at locations deep below the surface. Moreover, since drilling anyway is necessary, using the drillbit-rock interaction as a seismic source comes with no extra cost or interruption in the drilling process. The possibility exists that the drillbit is a viable subsurface seismic source and that seismic-while-drilling (SWD) is a practical method for improving seismic illumination. The unique raypaths of the SWD dataset are complementary to that of surface raypaths, and it brings an opportunity to address seismic illumination issues. However, the drillbit source signature has a complicated characteristic compared to impulsive surface sources. The drillbit source signature is non-impulsive and correlative. To generate this complicated source signature for physical modeling purposes, we need electronically to produce complex non-impulsive high-voltage waveforms that represent the vibrations generated by drilling and use them to drive our subsurface piezoelectric transducer sources.

This writeup covers the steps that we have taken to build the physical model, gather the data, and analyze the illumination issues in the lab.

Introduction

In geophysical studies, physical modeling is of great importance, and it has been used as a cheap and repeatable alternative for field data acquisition. Its applications range from validating the convolutional theorem to the analysis of the wave propagation in highly heterogeneous and anisotropic environments (Kosloff and Baysal, 1983; Cheadle et al., 1991; Wong et al., 2009; Isaac and Lawton, 1999; Guo et al., 2014). The idea is to design controlled experiments, which are downscaled versions of potentially interesting geological features relevant to oil and gas reservoirs. For example, analyzing the seismic response of different geological settings to the acquisition parameters can help geophysicists in optimizing such parameters before acquiring the field data. The physical modeling

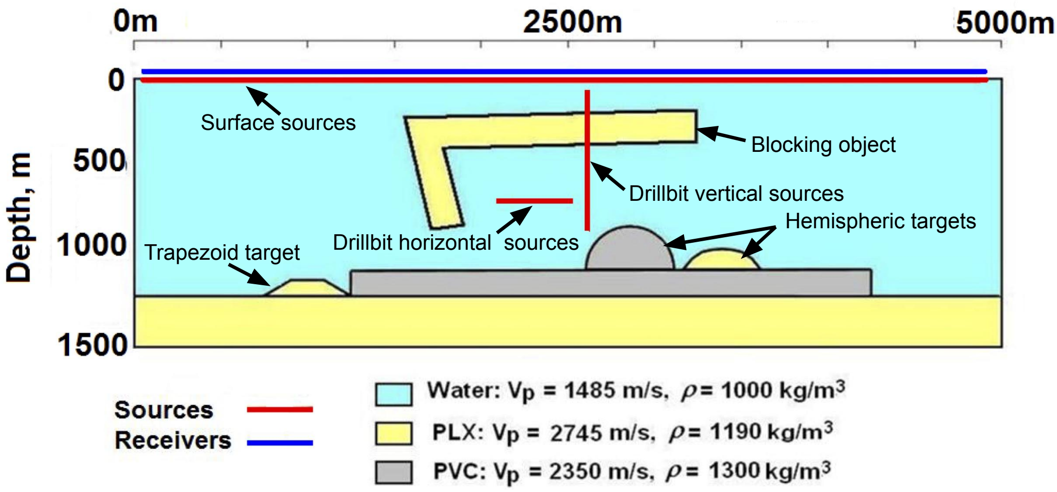

Figure 1 *A physical model for studying seismic illumination, showing surface and subsurface sources with receivers that are listening at the surface. The high-velocity sill-and-dike body acts as a blocking structure. The water-air interface is about 1350m above the receiver survey line.*

can be considered as a transitional phase from pure numerical modeling using the synthetic models and field-scale experiments. Another important benefit of such experiments is that it is affordable for research communities compared to acquiring expensive field data. It also provides high-quality data to test the new algorithms on controlled experiments with user-friendly acquisition parameters.

A challenging concept that geophysicists face in seismic acquisition, imaging, and interpretation of seismic data, is non-uniform subsurface illumination. Seismic illumination studies can shed light on the seismic wave propagation behavior in the complex subsurface structures and provide a framework for moving towards a uniform subsurface illumination. In complex structures, it is possible that wave energy penetrates only weakly or not at all into some areas, causing seismic shadows (i.e., the illumination problem). The deficiencies in seismic illumination can be mitigated if deep subsurface sources are used in the acquisition (Kazemi et al., 2018, 2019). For example, Drillbits generate significant elastic waves that have unique raypaths compared to surface sources at locations deep below the surface. Moreover, since drilling anyway is necessary, using the drillbit-rock interaction as a seismic source comes with no extra cost or interruption in the drilling process. The possibility exists that the drillbit is a viable subsurface seismic source and that seismic-while-drilling (SWD) is a practical method for improving seismic illumination.

To validate these concepts, the CREWES seismic physical modeling group, in collaboration with the University of Calgary Department of Chemical and Petroleum Engineering, has undertaken a physical modeling project to investigate the benefits of subsurface sources such as drillbit in improving the subsurface illumination. Here, we explain the steps that we have taken to build the physical model, gather the data, process the data, and analyze the illumination issues.

Physical modeling setup

We design a simple 2.5D model to simulate a sub-salt imaging problem (Figure 1). The model helps to investigate subsurface illumination issues. The upper sill-and-dike structure represents a salt body and is made of acrylic plastic (Plexiglas). Its primary velocity (2745 m/s) is almost twice as fast as that of the surrounding water (1485 m/s). The deeper trapezoidal and hemispheric bodies represent the targets. The upper high-velocity body acts as a blocking structure. It bends the raypaths toward itself and away from the low-velocity objects in the deeper section of the model so that, by using surface only sources and receivers, the underlying hemispheric and trapezoid targets will not be uniformly illuminated.

To analyze the subsurface illumination, we acquired impulsive source data using sources and receivers above the high-velocity blocking structure. A standard 2D survey with 50m source spacing and 5m receiver spacing resulted in 101 shot gathers each with 1001 channels. The receivers are listening to all shots similar to Ocean Bottom Cable (OBC) seismic survey. The super CMP gather is displayed with AGC in Figure 2a. The seismograms also can be sorted into common-source gathers, an example of which is shown in Figure 2b. The data contain not only reflection events but also converted waves, diffractions, water column and internal multiples, and systematic noise. For example, in Figure 2, reflections from the targets lie above 1700ms. The prominent isolated feature in the middle of the plot at about 900-1000ms is due to internal multiple reflections in the water column. The hyperbola at 1800-2000ms is the primary reflection from the water-air interface about 1350 above the source and receiver survey lines. Also, some features appear to be unrelated to the targets on the schematic diagram of Figure 1. The nearly flat event running right across the display at about 900-950ms is a water-column multiple. Other events are internal multiples, PSP conversions, edge, and corner diffractions, out-of-plane diffractions, and reflections from the walls of the water tank holding the model. These extraneous events can pose challenges to imaging and full-waveform inversion algorithms.

In addition to the surface-only surveys, we recorded data with sources at many locations beneath the sill-and-dike shooting up to the surface receiver line (see Figure 1). The subsurface source lines on the figure represent possible positions of a drillbit acting as a subsurface source. In horizontal drilling, we recorded 83 drillbit sources at the depth of 750m starting from 2100m in the horizontal location with the horizontal drillbit source interval of 10m. The data acquired in such subsurface-to-surface shooting add extra illumination due to their unique raypaths compared to that of surface acquisition and help to image that part of the geology not illuminated by surface-only sources and receivers. Figure 3 is a plot of seismograms collected for one such subsurface source. The asymmetrical appearance of this display is caused by the dike portion of the high-velocity blocking structure. To properly model the subsurface sources that represent the drillbit-rock interaction behavior, we need electronically to produce complex non-impulsive high-voltage waveforms in the lab (Figure 3a). The second alternative would be to scale up the model and drill the rock. Simulating the drillbit source signature and scaling up the model is currently in progress. In the interim (Figure 3c), we acquired subsurface source data with an impulsive source waveform and then convolved them with the simulated drillbit source signature.

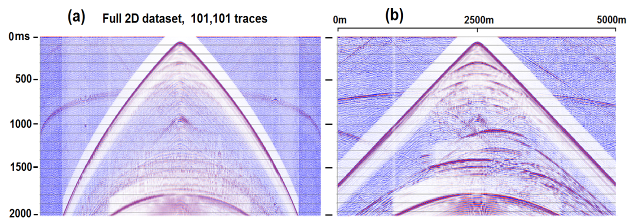

Figure 2 *(a) Full dataset (A super CMP gather) acquired in the 2D multi-fold surface survey. (b) An example of a CSG gather.*

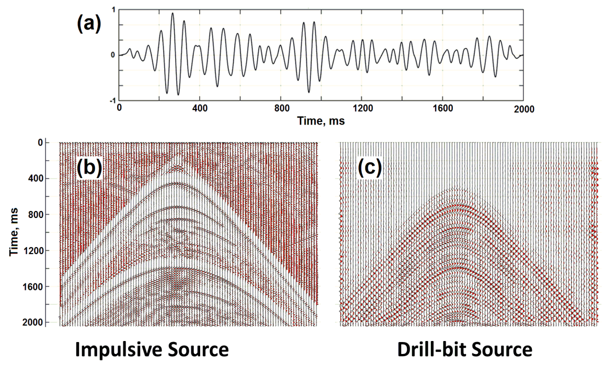

Figure 3 *(a) A drill-bit source waveform. (b) CSG of seismograms due to a subsurface source. (c) CSG of traces resulting from the convolution of (b) with the drill-bit waveform of (a). The visually distinct events in (b) are lost.*

The data acquired in this project is used to produce images of the acrylic sill-dike structure and the trapezoidal and hemispheric targets below. However, before that, we must resolve imaging challenges posed by the following factors: radiation/reception patterns of the piezopin transducers, non-stationary waveforms, PSP conversions, internal multiples, and systematic noise. In the next section, we explain the processing and imaging steps in more detail.

Data processing and Imaging

The systematic noise arises from water-column multiples, out-of-plane diffractions, reflections from the walls of the water tank, and internal reflections within the geological bodies. To prepare the data for imaging purposes, we carry out several processing steps. First, we apply automatic gain control (AGC) to compensate for attenuation. Then, we apply the blind deconvolution algorithm developed by Kazemi and Sacchi (2014) to estimate/remove the source signature of the transducer from the data. Finally, we sort the data in CMP gathers and apply a predictive deconvolution algorithm to attenuate the water column and internal multiples. It is worth noting that the corrections for radiation/reception patterns of the piezopin transducers are not applied to the data. The data also include converted (PSP) waves that can be a challenge for acoustic imaging algorithms. CMP gathers before and after processing is depicted in Figure 4. Most of the multiples are attenuated and the transducer source signature is removed from the data. In the case of SWD data, we apply AGC to compensate for attenuation and blind deconvolution to remove the drillbit source signature from the data. Then, similar processing steps to that of surface seismic are implemented on the data. Figure 5 shows the raw and processed SWD shot gathers. After processing the data, the events are clear, and the multiples are attenuated.

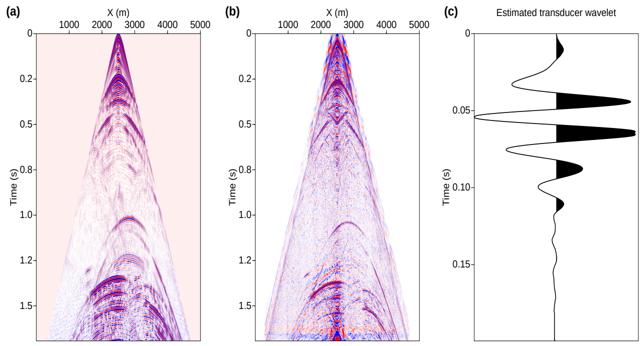

Figure 4 *Surface shot gathers. a) Raw shot gather. b) Processed shot gather. c) Estimated transducer's source signature.*

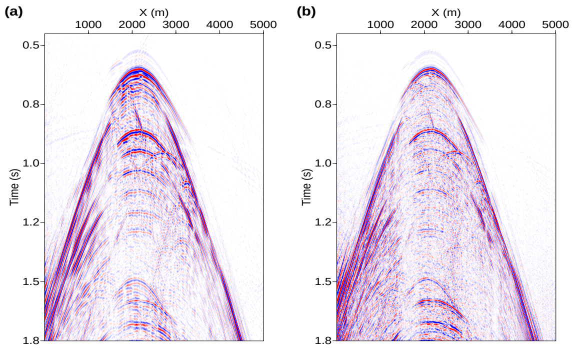

Figure 5 *Seismic-while-drilling shot gathers with an impulsive source. a) Raw shot gather. b) Processed shot gather.*

Next, we produce pre-stack RTM images of the processed surface seismic and seismic-while-drilling datasets. The algorithm works in the shot gather domain. The depth velocity model should be provided by the kinematic analysis of the data. A time-to-depth conversion is necessary to convert the time velocity profile to the depth velocity. We deliver the depth images using the depth velocity and processed shot gathers. Figure 6-left shows the depth image by using the surface seismic data. The main features of the model are properly imaged, but some boundaries have been distorted. Illumination problems are obvious in the hanging wall of the blocking structure. The blocking structure also generates its shadow zone so that the underlying targets are difficult to image. The arrows in Figure 6 show the parts of the model that surface-only data struggles to provide a reliable image. We also provide an RTM image by using the SWD data (Figure 6-right). The SWD data have unique raypaths, and they are complementary to the surface only acquisition. Accordingly, the SWD data provided an opportunity to image parts of the subsurface that are in the shadow zone of the surface seismic acquisition. Figure 6-right shows that the SWD imaging method gives better illumination in the challenging parts of the model such as the hanging wall and the underlying targets. Moreover, we observe that the water-PVC boundary is nicely imaged by the SWD data. On the other hand, in the case of surface seismic data, the portion of the water-PVC boundary under the hanging wall was not properly imaged. It is also worth mentioning that both images suffer from fictitious events and noise, which can be related to multiple residuals, converted waves, off-plane events, and aliasing in the data. For example, two fictitious events, in the surface image, on top of the hemispheric events can be the mispositioned events due to PSP converted waves. Note that we used primary velocity to image the subsurface. The next step is to generate long drillbit source signatures in the lab and provide 3D elastic images.

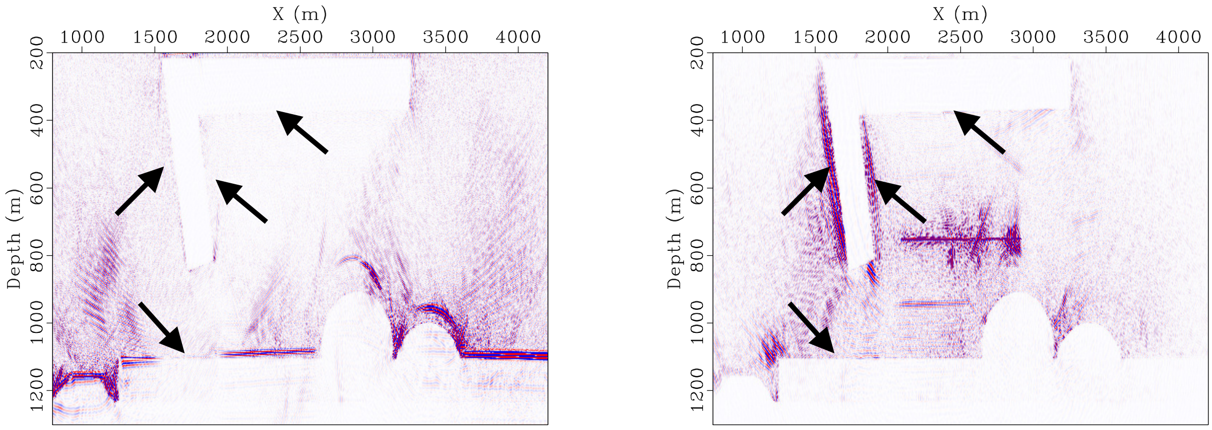

Figure 6 *Prestack depth migrated images. Left) Surface seismic image. Right) Seismic-while-drilling image. The arrows show the parts of the model that surface-only data struggles to provide a reliable image. The footprint of SWD sources can be seen under the blocking object.*

Conclusions

Through physical modeling, we studied the non-uniform subsurface illumination inherent in surface seismic data. We designed a 2.5D model so that a high-velocity blocking structure would make it difficult to image underlying targets with surface-only seismic data. We acquired a 2D surface-only seismic dataset and also a 2D seismic-while-drilling (SWD) dataset over this model. We implemented a proper workflow to process both datasets and produced pre-stack RTM images by using surface-only and SWD datasets. The migrated images indicated that the SWD data is effective in mitigating several of the illumination deficiencies existing in the surface-only dataset.

Acknowledgment

The authors acknowledge financial support from CREWES sponsors, NSERC grant No. CRDPJ 461179-13. This work is also supported by the University of Calgary's Canada First Research Excellence Fund Program, the Global Research Initiative in Sustainable Low Carbon Unconventional Resources.

References

Cheadle, S. P., R. J. Brown, and D. C. Lawton, 1991, Orthorhombic anisotropy: A physical seismic modeling study: Geophysics, **56**, 1603–1613.
Guo, J., S. Xue, Q. Zhao, and C. Yang, 2014, Ultrasonic imaging of seismic physical models using a phase-shifted fiber Bragg grating: Optics express, **22**, 19573–19580.
Isaac, J. H. and D. C. Lawton, 1999, Image mispositioning due to dipping TI media: A physical seismic modeling study: Geophysics, **64**, 1230–1238.
Kazemi, N. and M. D. Sacchi, 2014, Sparse multichannel blind deconvolution: Geophysics, **79**, V143–V152.
Kazemi, N., R. Shor, and K. Innanen, 2018, Illumination compensation with seismic-while-drilling plus surface seismic imaging: Presented at the 80th EAGE Conference and Exhibition 2018.
Kazemi, N., D. Trad, K. Innanen, and R. Shor, 2019, Joint Least-Squares RTM of Surface Seismic and Seismic-While-Drilling Datasets: 81st EAGE Conference and Exhibition 2019, 1–5.
Kosloff, D. D. and E. Baysal, 1983, Migration with the full acoustic wave equation: Geophysics, **48**, 677–687.
Wong, J., K. W. Hall, E. V. Gallant, M. B. Bertram, and D. C. Lawton, 2009, Seismic physical modeling at the University of Calgary, *in* SEG Technical Program Expanded Abstracts 2009, 2642–2646. Society of Exploration Geophysicists.