Detection and correction of surface- and acquisition-related inconsistencies: A case study in land vibrator data

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Summary

Analyzing seismic amplitude trends requires stability of the seismic wavelet in both amplitude and phase. Unfortunately, in land acquisition, the filter applied as energy travels through the near-surface can have a dramatic impact on both. Here, we extend previous work on proposing detailed QC methods for surface-consistent deconvolution of land dynamite data to land vibrator data. In the process, we uncover and attenuate an apparent acquisition abnormality, and we produce seismic data more amenable to sensitive post-migration analysis and inversion.

Introduction

The analysis of seismic amplitudes requires wavelet amplitude and phase to be stable and consistent across geological formations. With a stable seismic wavelet, amplitude versus offset analysis (AVO) or other trends can yield invaluable details regarding target reservoirs and the overlying geology. These details are instrumental in the success of difficult hydrocarbon plays. While much attention has historically been given to preserving amplitudes during pre-processing and migration, the focus of this work is on the impact of surface-consistent deconvolution to address phase and amplitude inconsistencies due to the impact of near-surface geology, acquisition parameters and irregularities.

The near-surface geology often consists of unconsolidated material which can cause a non-negligible distortion of the seismic wavelet's phase and amplitude. Moreover, the interaction between the seismic source or receiver and the near-surface (coupling) may exhibit significant variations across a seismic survey, depending on terrain, topography, and weather. While such variations are technically geological, they often interfere with the correct imaging of target prospects, and it is desirable to remove them. Land vibrator data are particularly susceptible to the effects of the near-surface, as the points of both emission (source) and recording (receiver) lie at or very near the surface. This is in contrast to dynamite acquisition which may largely obviate the source-side effects through a large-enough charge depth. The goal of surface-consistent deconvolution is to remove these surface-related deviations in the wavelet through calculation of a set of operators (or filters) – one for each shot and each recording channel (Taner and Koehler, 1981).

In this work, we present a new application of the quality control (QC) of the surface-consistent deconvolution solution which first appeared in Zhang, et al. (2015). As a part of this QC, artificial abnormalities in the source-side operators were observed. We concluded that the surface-consistent deconvolution detected an irregularity in the source-side acquisition parameters. We provide an example of this irregularity and show that the deconvolution solution successfully removes this acquisition-consistent disparity from the seismic data.

Surface-consistent deconvolution

In the practice of surface-consistent spiking deconvolution, a collection of operators is calculated: One operator for each shot and each receiver, along with operators corresponding to each grid-based common mid-point (CMP) location and each offset class and a single global average operator which captures residual effects common to all traces in the seismic survey (Morley and Claerbout, 1983, Garceran and Le Meur, 2012). In theory, application to every trace of every filter corresponding to that trace should give a spiked wavelet. However, the effects captured by the CMP and offset operators are typically regarded as related to the true subsurface geology and AVO effects. Therefore, those operators are not usually applied. In this context, performing surface-consistent deconvolution implies the application of only the source- and receiver-side operators as well as the average operator. The phase component of the global operator is applied during deconvolution to achieve a zero-phase wavelet, while the amplitude term acts as a whitening factor for the seismic amplitude spectrum. The amplitude component of the average operator is calculated along with all other operators, but it can be applied at any point prior to migration, depending on processing requirements.

In processing seismic vibrator data, it is typical to apply a theoretical minimum-phasing filter based on the survey sweep parameters. Ideally, this converts the data from mixed-phase (zero-phase Klauder wavelet convolved with the minimum-phase earth and instrument responses) to minimum-phase. The goal of surface-consistent deconvolution is to remove phase and amplitude distortions in the data related to the near-surface, resulting in a zero-

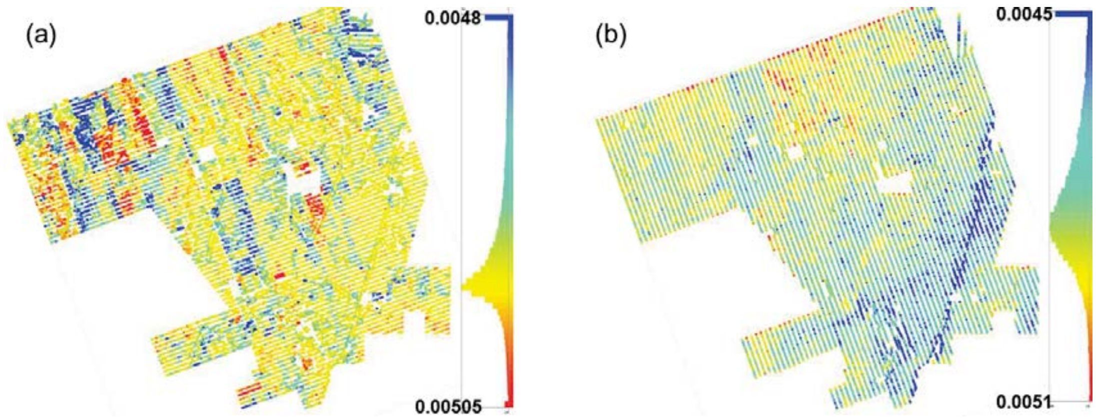

Figure 1: The average squared amplitude (energy) of (a) source and (b) receiver operators.

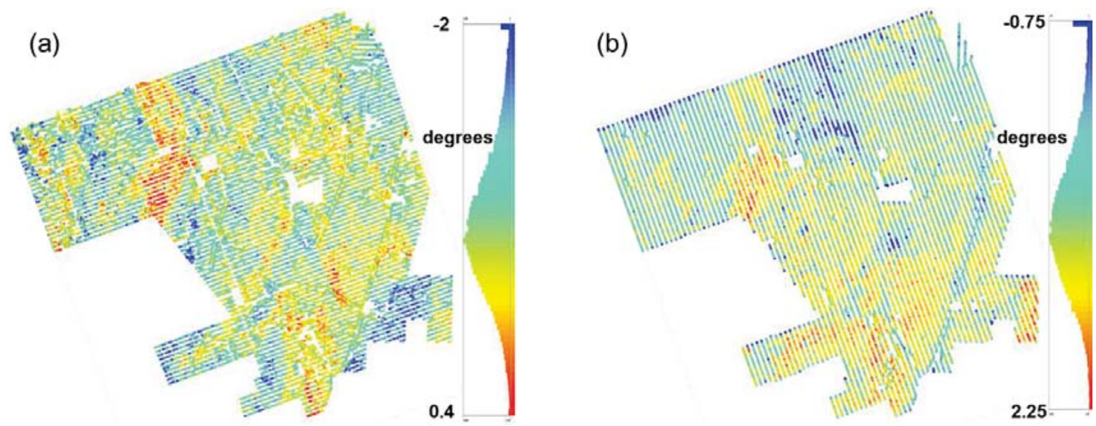

Figure 2: The angle of deviation from zero-phase of (a) source and (b) receiver operators.

phase seismic wavelet. The zero-phase seismic wavelet is generally easier for interpretation and more robust to bandwidth variation than the minimum-phase seismic wavelet.

The size of a typical seismic survey and subtle complexity of the near-surface effects generally necessitates a statistical solution for the surface-consistent deconvolution operators. These same factors complicate the evaluation of the survey-wide quality of the deconvolution application, leading us to use an innovative QC method (e.g., Zhang et al., 2015) on land Vibroseis data.

The most common QC is to compare the seismic data to well synthetics. We expect that the seismic should be closer to zero-phase after deconvolution. The weaknesses of this QC are twofold: This QC is only valid for the locations and times where well synthetics are available, and it is not clear from such a check whether the deconvolution solution is truly surface-consistent. Trace-by-trace deconvolution methods could provide similar improvement, but may obscure or destroy the underlying seismic amplitude-versus-offset trends which are crucial to interpretation in subtle plays.

Thus, we propose to use the QC method described by Zhang, et al. (2015), who evaluated the quality of a surface-consistent deconvolution solution applied to land dynamite data. In that work, the authors compared the total statics map (weathering and residual) with a map of the average phase of each shot and receiver operator. In this paper, we focus on the application and QC of surface-consistent deconvolution to land vibrator data. Most notably among their differences, dynamite and vibrator data experience different surface-coupling effects on the source side, and vibrator data generally possesses a worse signal-to-noise ratio. In particular, we compute source- and receiver-centric operator QC maps. We use these maps to compare the macro-scale trends of the deconvolution operators to the average weathering velocities, derived independently from refraction tomography as part of the refraction statics solution. Common trends observed between these two maps

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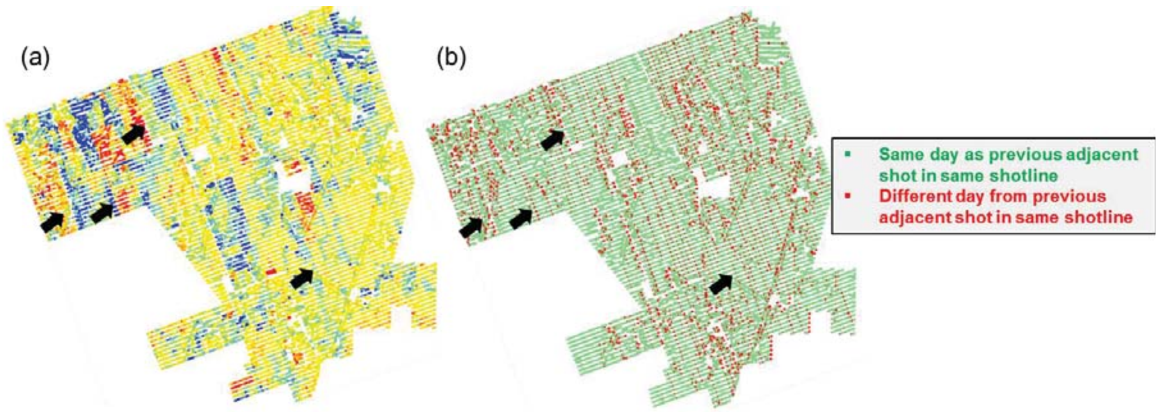

Figure 3: (a) source operator energy; (b) shooting day change within one shot line from observer logs. A sudden change in source operator energy between adjacent sources (a few of which are highlighted by arrow) indicates they were acquired on different days.

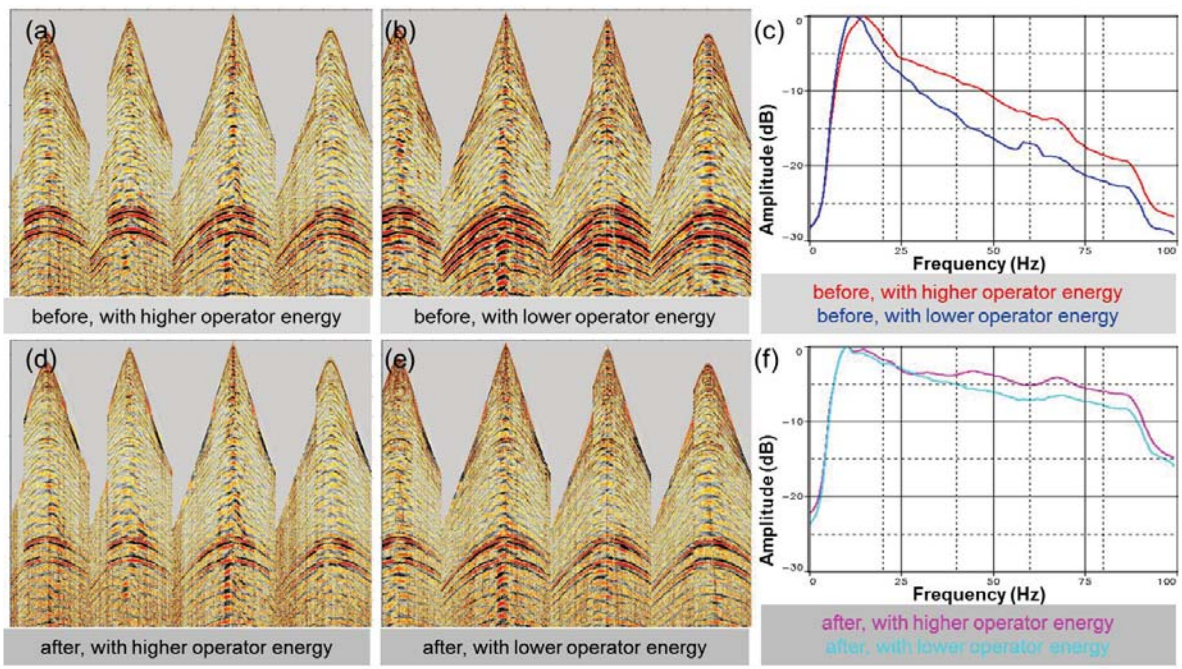

Figure 4: Two adjacent shot gathers located on two sides of the source operator energy map boundary and their amplitude spectra before surface-consistent deconvolution (a-c) and after surface-consistent deconvolution (d-f). The amplitude spectra (calculated within a 1300ms-long window around main events) are much closer after deconvolution.

can provide validation of the surface-consistency of the deconvolution solution and, in the present case, reveal inconsistencies in the acquisition. For our QC, we compute the operator energy, i.e., the summation of the squared amplitude of the operator, and the angle of deviation from zero-phase for both source and receiver operators. Here, angle of deviation from zero-phase is defined as the phase maximizing the generalized correlation function between the operator and its zero-phase equivalent (Taner, Koehler and Sheriff, 1979).

Real data analysis

Our data set is from the onshore US. We examine in detail the surface-consistent deconvolution solution applied to the survey. Prior to calculation and application of the surface-consistent deconvolution operators, the data were converted to minimum-phase using the Klauder wavelet. In addition, multiple passes of noise attenuation, surface-consistent statics, surface-consistent amplitude correction, and a phase-only constant Q correction were applied. Figures 1

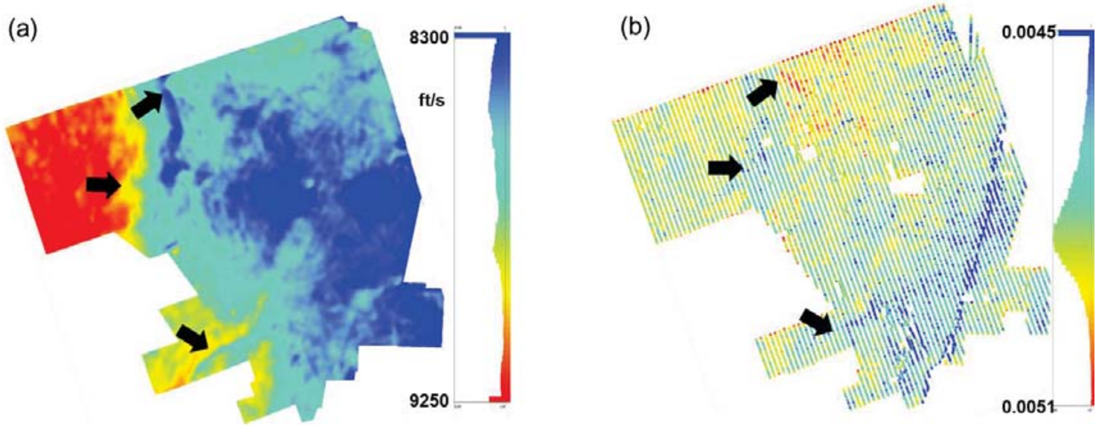

Figure 5: (a) Average weathering velocity, 100ft-1100ft below surface level; (b) receiver operator energy.

and 2 show the amplitude and phase information extracted from the source- and receiver-side operators of the surface-consistent deconvolution solution. Two representative attributes are displayed: the average squared amplitude and the angle of deviation from zero-phase. Note that the straight line apparent at the southeast corner of the receiver maps coincides with a road cutting through the survey.

Curiously, we found that many boundaries occurred in the shot operator energy map of Figure 1a. These lines are oriented perpendicular to the orientation of the shot lines. A natural question is whether the boundaries were due to deconvolution artifacts, or if the deconvolution operators were registering some inconsistency in the acquisition (acquisition footprint). To check this, we retrieved the shooting date for each source point from observer's logs. We found that these boundaries often coincided with a change in shooting date within an individual shot line – refer to Figure 3. We believe that an acquisition-related inconsistency was detected by the surface-consistent deconvolution as a set of local anomalies, in turn leading to the creation of many of these operator boundaries. When possible, we prefer to remove these types of acquisition-generated effects through surface-consistent deconvolution, for they may imprint and obscure the subsurface geology and disrupt AVO effects.

To verify that these differences in the operators were reflected in the seismic data, we retrieved a pair of shot gathers from the deconvolution input data which lie on either side of one of these boundaries (Figure 4a, b). Comparing the two shot gathers, a clear difference in the character of the seismic data was observed, with one gather exhibiting a much larger power at low-frequencies, and significantly more ringing in this spectral band (Figure 4c). After surface-consistent spiking deconvolution, the shot gathers were more similar in spectral character (Figure 4d-f). The source-side deconvolution operators successfully removed the bulk of the acquisition-related footprint from the seismic data.

Discussion

The surface-consistent deconvolution solution applied to land vibrator data successfully compensated the wavelet distortion due to both the weathering layer and acquisition irregularities. Reassuringly, the acquisition footprint apparent in the source operators did not 'leak' into the receiver operators, validating the robustness of the approach. While the average squared amplitude of the source operators was found to be highly indicative of the day-to-day variations in acquisition settings, the corresponding receiver operator map showed little correlation to the acquisition calendar. Instead, the receiver operator energy displayed a reasonably good correlation with the weathering layer velocity (Figure 5).

We further observed that, relative to the amplitude-related quantity, the phase-based operator QC provided a more robust measurement in correlating with the weathering layer velocity for both sources and receivers, exhibiting only minor influence from the acquisition footprint (see Figure 2), thus providing additional confidence in the surface-consistency of the deconvolution solution.

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