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Ground rolls attenuation via gradient flow regularization

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ABSTRACT

We propose a novel method for seismic ground rolls attenuation by employing the dips differences between ground rolls and reflective signals. The dips differences are modeled by gradient-direction differences, and the overall gradient directions are termed gradient flow. Typically, there are frequency overlap between the ground rolls and reflective signals. But, the gradient flow of a signal needs only the direction information of the gradients, not the exact scale information, and thus, can be extracted using only part of the signal. Firstly, gradient flows for the desired ground rolls and reflective signals are calculated according to the low-frequency part of the ground rolls and high-frequency part of the reflective signals via the structure tensor method. Then, an optimization model is built, which regularizes the separated ground rolls and reflective signals to have the desired gradient flows. An efficient algorithm is designed by employing the specific structure of the finite difference matrices, which are used for calculating the gradients. The optimization problem is strictly convex, and is guaranteed to converge with arbitrary initialization. The method we propose is easy to use, as only two weighting parameters of the regularization terms are set manually to tune the energy distribution of the ground rolls and reflective signals. We demonstrate effectiveness of the proposed method with two field data tests. Compared with the traditional high-pass filtering method and two improved methods, the method we propose attenuates more ground rolls and eliminates less reflective signals, and increases the lateral coherence of the restored reflective signals at the same time.

1. Introduction

Ground rolls are a main type of coherent noise in most land seismic datasets and bottom node based marine seismic datasets. Ground rolls often seriously conceal the reflected seismic events with their high amplitude (Claerbout, 1983; Saatilar and Canitez, 1988; Henley, 2003). Attenuation of ground rolls is an important seismic processing task, both for recognition of useful reflections and for subsequent processing steps such as velocity analysis, stacking, or migration (Mcmechan and Sun, 1991).

Ground rolls typically have high amplitude, low frequency, low velocity and large dips. These distinctive characters can be employed to separate ground rolls from reflective signals. The bandpass filters and frequency-wavenumber (f-k) filters are applied in the frequency domain, and are the most widely used ways for ground rolls attenuation. But the f-k filters can cause serious distortion of the signal when the amplitude of the ground rolls are much higher than the reflective signals (Karsli and Bayrak, 2004). The bandpass filtering method often removes the low-frequency content of reflective signals when attenuating ground rolls, as there are typically frequency overlap between the ground rolls and reflective signals. And the frequency cut-off often cause some artifacts in the reflective signals (Mcmechan and Sun, 1991). Matching filter (MF) is one widely used approach to solve the frequency-overlapping problem. The MF method uses the low-pass filtered data as the initial estimation for the ground rolls, and then match the initially estimated ground rolls to the raw seismic data via solving a least square problem. The MF method uses stationary filters, which limits its performance for nonstationary seismic datasets. A nonstationary matching filtering method was proposed to deal with the nonstationary character of seismic data (Jiao et al., 2015). Chen et al. (2015) applied local signal-and-noise orthogonalization (SNO) to improve the performance of the bandpass filtering method. Firstly, most ground rolls are separated with traditional bandpass filtering method at the cost of losing some reflective signals. Then, the initial guess of the local ground rolls are projected to the local reflections to restore the eliminated reflections. Multiresolution analysis techniques have been adapted successfully for ground rolls attenuation, such as the wavelet (Deighan and Watts, 1997; Matos and Osrio, 2002), curvelet (Yarham and Herrmann, 2008; Neelamani et al., 2008; Liu et al., 2018), and shearlet (Hosseini et al., 2015; Zhang et al., 2010). Other methods include the singular value decomposition (Kendall et al., 2005; Cary and Zhang, 2009; Porsani et al., 2010), empirical mode

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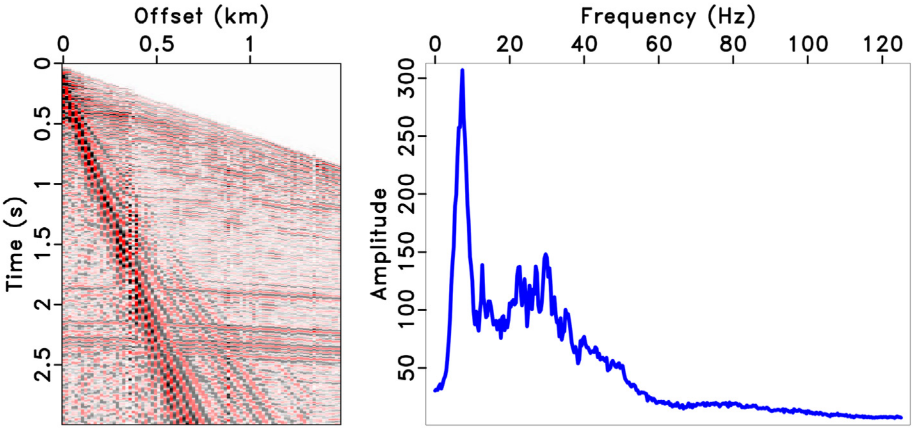


(a) (b)

Fig. 1. A field data and the average spectrum of all its traces. (a) Raw field data. (b) Average spectrum.

decomposition (Bekara and van der Baan, 2009), variational mode decomposition (Liu et al., 2015), Karhunen-Lueve transform (Londono et al., 2005; Liu, 1999), Wiener-Levinson algorithm (Karsli and Bayrak, 2004), interferometric ground-roll removal (Halliday et al., 2007, 2010), the S transform (Askari and Siahkoohi, 2007; Tan et al., 2013), morphological component analysis in the curvelet domain (Yarham et al., 2006), etc. More advanced methods for ground rolls attenuation is always in demand.

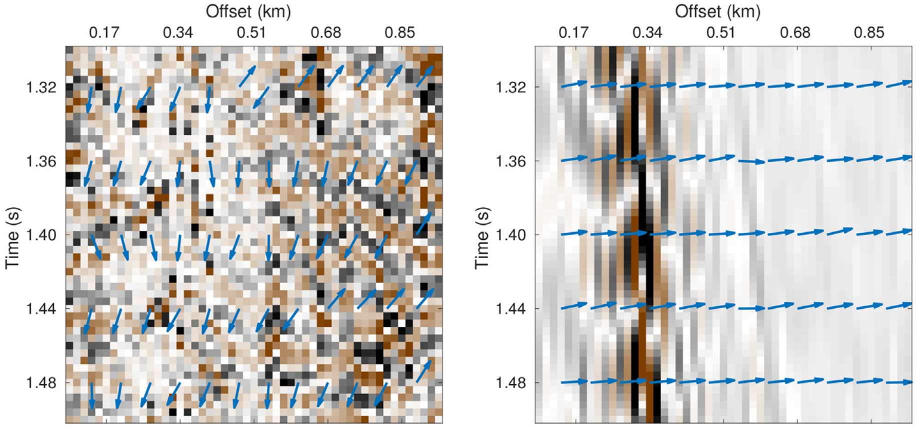
We propose a novel method for ground rolls attenuation by employing the dips information. The dips information is indicated by the gradient directions of all data points in a seismic image, which are termed gradient flow in this paper. Firstly, a low-pass filter is adopted to get the low-frequency energy of the ground rolls, and a high-pass filter is used to get the high-frequency energy of the reflective signals. By avoiding the frequency overlap, we calculate respectively the gradient flows for the ground rolls and reflective signals via the structure tensor method (Jahne, 2000; Luo et al., 2006). The gradient flows only contain information of the gradient directions, without the information of the exact scales of the gradient vectors. Then, an optimization model is built via regularizing the separated ground rolls and reflective signals to have the desired gradient flows. An efficient algorithm, which takes use of the specific structure of the finite difference matrices, is designed to solve the model based on the discrete Fourier transform (DFT). For simplicity,in following sections we refer to the proposed model as gradient flow regularization (GFR) method. We demonstrate effectiveness of the proposed method with two field data examples. Compared with the traditional high-pass filtering method, the MF method and the SNO method, the method we propose attenuates more ground rolls and eliminates less reflective signals, with a better lateral coherence for the restored reflections.

2. Theory

Firstly, we show the basic idea of using gradient flows as regularization terms to separate ground rolls and reflective signals. Then, we build the GFR model as a convex optimization problem and design an efficient algorithm to solve the model. Fig. 1a shows a land shot gather which was used for groundroll-separation tests in reproducible documents for Fomel (2002) and Liu and Fomel (2013) in the *Madagascar* open-source software package (Fomel et al., 2013). Fig. 1b shows the trace averaged frequency spectrum of this field data. A frequency overlap exists in the frequency domain. The traditional bandpass filtering process can be expressed as:

$$\hat{\mathbf{d}} = .\mathscr{F}^{-1}.\mathscr{B}\mathscr{F}(\mathbf{d})$$

where $.\mathscr{F}$and $.\mathscr{F}^{-1}$ stand for the forward and inverse Fourier transforms, $\mathbf{d}$ and $\hat{\mathbf{d}}$ denote the raw data and filtered data. $.\mathscr{B}$ denotes a bandpass filter, which can be created by combining a low-pass filter with a high-pass filter. For the groundroll-separation problem, only the high-pass filter is needed. The frequency boundary (FB) of the high-pass filter is



(a) (b)

Fig. 2. Windowed gradient-flow sections. (a) Calculated from high-frequency part of the reflective signals. (b) Calculated from low-frequency part of the ground rolls.