Journal of Applied Geophysics 112 (2015) 226–235

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Suppression of strong scattered waves using the transverse component

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A R T I C L E I N F O

Article history:
Received 30 July 2014
Accepted 24 November 2014
Available online 2 December 2014

Keywords:
Borehole-related scattered waves
Suppression
Borehole seismic
Multicomponent
Transverse component
Correlation

A B S T R A C T

Scattered waves are commonly recorded in borehole seismic data sets. These waves must be suppressed to improve the signal-to-noise ratio of seismic reflection and transmission data. We propose a method to suppress scattered waves of the radial and vertical components by using the transverse component for the borehole seismic data. This method assumes that the transverse component only contains linearly polarized scattered waves, the radial and vertical components contain the scattered and other waves, and the scattered waves are strong in some frequency range. This method first determines the frequency range of strong scattered waves. Based on this frequency range, model data of strong scattered waves are formed by bandpass filtering the transverse component. Amplitude coefficients of scattered waves for the radial and vertical components are determined by correlating these components respectively with the transverse component in the frequency range of scattered waves. Thus, scattered waves can be estimated and suppressed from the radial and vertical components. Tests on zero-offset and walkaway VSP field data illustrate the effectiveness of this method. Comparisons show that this method can suppress strong scattered waves more effectively than the frequency-domain median filtering method. This method can be applied to suppress the noise provided that it meets the above assumptions.

1. Introduction

Borehole environment is generally quieter than surface environment, which leads to weaker random noises in the borehole than those on the surface. Therefore, borehole seismic data are commonly thought to have a higher signal-to-noise ratio (SNR) than surface seismic data. However, borehole-related scattered waves, dependent on borehole coupling, casing ringing, frequencies and incident angles of incident waves, etc. (e.g., Lee, 1987; Peng et al., 1993), are usually recorded in VSP or crosswell data sets. These scattered waves must be suppressed to improve the SNR of borehole seismic reflection and transmission data.

Borehole-related scattered waves may be generated by tube waves, direct waves, etc. (e.g., Bakku et al., 2013; Karpfinger et al., 2012; Lee, 1987; Peng et al., 1993). Because almost no literatures reported suppressing scattered direct waves, we mainly summarize methods of suppressing tube waves and scattered tube waves, although these waves have been used to estimate elastic parameters of rocks (e.g., Bakku et al., 2013; Karpfinger et al., 2012).

Tube waves and scattered tube waves may be caused by irregularities in the borehole (Hardage, 1983) and lithology variations in the formation (Peng and Toksöz, 1992). Experimental techniques have been developed to suppress these waves by installing hardware (e.g., Daley et al., 2003; Milligan et al., 1997; Pham et al., 1993). In addition to hardware for suppressing tube waves, several data processing techniques have also been advanced as follows. Considering that the polarization direction of particle motion for tube wave is nearly horizontal and that for P-wave is nearly vertical, Campbell (1990) adopted polarization filtering to attenuate the tube wave of vertical component of zero-offset VSP. Herman et al. (2000) proposed a method based on modeling the scattered tube waves and then subtracting them from the total data set. Spatial median filtering is commonly applied to attenuate the high-amplitude noise in time domain. Similarly, Campbell et al. (2013) introduced spatial median filtering to attenuate the high-amplitude noise in frequency domain. Of these three methods, the modeling method needs a fine estimation of the impedance function, the polarization filtering method is suitable to zero-offset VSP only, and the frequency-domain median filtering method cannot achieve good suppression effects when high-amplitude noise occurs in several successive traces. Note that the polarization filtering method is for suppressing tube waves, and the modeling method and the frequency-domain median filtering method are for suppressing scattered tube waves.

In this paper, we develop a method to suppress the vertical and radial components of the borehole-related scattered waves using the

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http://dx.doi.org/10.1016/j.jappgeo.2014.11.021
0926-9851/

transverse component for the borehole seismic data. It has advantages of weak assumption, easy implementation and good suppression.

2. Method

In the effective frequency band of the borehole seismic data, three-component (3C) data mainly consist of P-waves, S-waves, direct tube waves, and scattered waves. Each component of raw 3C seismic data records these waves. After rotation of the horizontal components for the orientation of the geophones, raw horizontal components are transformed to the radial and transverse components. We assume that polarization directions of strong scattered waves are not parallel to the radial plane formed by source and receiver, and those for other waves are nearly parallel to this plane. Note that our assumption for the borehole seismic data is significantly different from that of Campbell (1990) for zero-offset VSP. Then, based on our assumption, scattered waves exist in three components and other waves mainly exist in the radial and vertical components. Therefore, waveforms of scattered waves can be obtained directly from the transverse component. Based on least squares, the amplitude coefficients of scattered waves in the radial and vertical components can be calculated by correlating these components with the transverse component. Then, scattered waves can be estimated and suppressed from the radial and vertical components. The procedure of the proposed method is as follows:

(1) Rotate horizontal components to obtain the radial and transverse components $R_{\mathrm{raw}}(t)$ and $T_{\mathrm{raw}}(t)$.
(2) Determine the frequency range of strong scattered waves where large and abnormal amplitude exists by analyzing amplitude spectra of $R_{\mathrm{raw}}(t)$, $T_{\mathrm{raw}}(t)$ and the vertical component $V_{\mathrm{raw}}(t)$.
(3) Filter 3C data using this frequency range to obtain filtered data $R_{\mathrm{filtered}}(t)$, $T_{\mathrm{filtered}}(t)$ and $V_{\mathrm{filtered}}(t)$ containing strong scattered waves.
(4) Extract waveforms of scattered waves directly from the filtered transverse component $T_{\mathrm{filtered}}(t)$ (model data for scattered waves).
(5) Compute amplitude coefficients c_V and c_R of scattered waves by correlating the filtered vertical and filtered radial components with the filtered transverse component, where $c_V = \phi(V_{\mathrm{filtered}}, T_{\mathrm{filtered}})/\phi(T_{\mathrm{filtered}}, T_{\mathrm{filtered}})$, $c_R = \phi(R_{\mathrm{filtered}}, T_{\mathrm{filtered}})/\phi(T_{\mathrm{filtered}}, T_{\mathrm{filtered}})$, ϕ denotes the correlation of two functions. Appendix A gives the detailed derivation for c_V and c_R. The amplitude coefficients should change with time if the polarization direction of scattered waves varies with time. In this paper, we use a moving window to calculate the amplitude coefficients.
(6) Estimate scattered waves $c_R T_{\mathrm{filtered}}$ and $c_V T_{\mathrm{filtered}}$ in the radial and vertical components using their waveforms from step (4) and the amplitude coefficients from step (5).
(7) Subtract scattered waves from the radial and vertical components.

Appendix B gives the definition of strong scattered waves. If inequality (Eq. (B.2)) is satisfied, scattered waves are strong and can be suppressed. In other words, when $|\phi(S_{\mathrm{filtered}}, T_{\mathrm{filtered}})| > |\phi(N_{\mathrm{filtered}}, T_{\mathrm{filtered}})|$, where $S_{\mathrm{filtered}}(t)$ and $N_{\mathrm{filtered}}(t)$ represent scattered waves and non-scattered waves in the filtered vertical (or radial) component, energy of scattered waves in the vertical (or radial) component can be reduced after applying the proposed method.

3. Examples

We give two examples for field 3C VSP data to illustrate the effectiveness of the proposed scheme. One is for zero-offset VSP data and the other is for walkaway VSP data.

3.1. Example for field zero-offset 3C VSP

The first example is for zero-offset 3C VSP field data to suppress the strong scattered waves in the vertical component.

Fig. 1 shows the zero-offset 3C VSP records after geophone orientation. The geophone depth increases from 640 m to 790 m with an increment of 5 m, and data at 690 m, between traces 10 and 11, are invalid and shown as a trace with zero values. The offset is 17.8 m and the azimuth of well-source line is 35.2°. The source is air gun and sampling rate is 1 ms. Note that in this paper, the waveforms of each sub-figure have

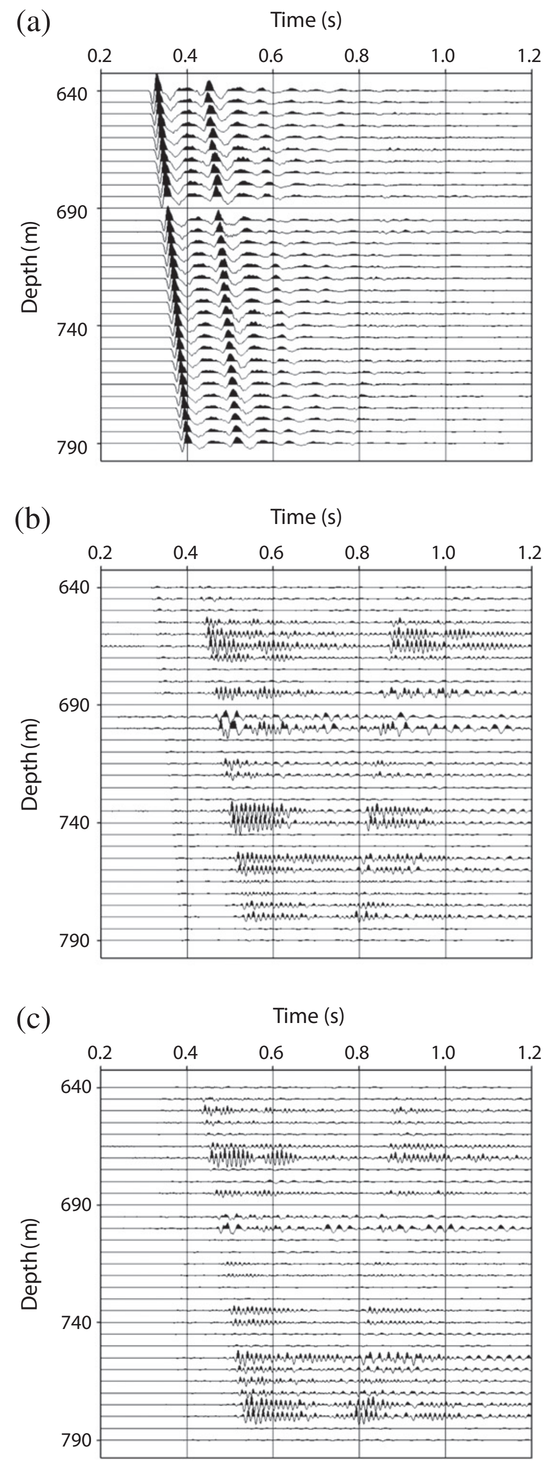

Fig. 1. Zero-offset VSP records after orientating geophones. (a) Vertical component. (b) Radial component. (c) Transverse component.