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Full waveform inversion using a decomposed single frequency component from a spectrogram

Jiho Ha [a], Seongpil Kim [a], Namhyung Koo [a], Young-Ju Kim [a], Nam-Sub Woo [a], Sang-Mok Han [a], Wookeen Chung [b],*, Sungryul Shin [b], Changsoo Shin [c], Jaejoon Lee [c]

[a] *Korea Institute of Geoscience and Mineral Resources, Republic of Korea*
[b] *Korea Maritime and Ocean University, Republic of Korea*
[c] *Seoul National University, Republic of Korea*

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ABSTRACT

Although many full waveform inversion methods have been developed to construct velocity models of subsurface, various approaches have been presented to obtain an inversion result with long-wavelength features even though seismic data lacking low-frequency components were used. In this study, a new full waveform inversion algorithm was proposed to recover a long-wavelength velocity model that reflects the inherent characteristics of each frequency component of seismic data using a single-frequency component decomposed from the spectrogram. We utilized the wavelet transform method to obtain the spectrogram, and the decomposed signal from the spectrogram was used as transformed data. The Gauss–Newton method with the diagonal elements of an approximate Hessian matrix was used to update the model parameters at each iteration. Based on the results of time–frequency analysis in the spectrogram, numerical tests with some decomposed frequency components were performed using a modified SEG/EAGE salt dome (A–A′) line to demonstrate the feasibility of the proposed inversion algorithm. This demonstrated that a reasonable inverted velocity model with long-wavelength structures can be obtained using a single frequency component. It was also confirmed that when strong noise occurs in part of the frequency band, it is feasible to obtain a long-wavelength velocity model from the noise data with a frequency component that is less affected by the noise. Finally, it was confirmed that the results obtained from the spectrogram inversion can be used as an initial velocity model in conventional inversion methods.

1. Introduction

The physical properties of the Earth can be determined from a seismic dataset using full waveform inversion methods. Lailly (1983) and Tarantola (1984) proposed such a method using the back-propagation technique, and since then, many waveform inversion methods have been developed in the domains of time (Bunks et al., 1995; Choi and Alkhalifah, 2011, 2018; Fu and Symes, 2017; Gauthier et al., 1986; Sheen et al., 2006; Shipp and Singh, 2002; Tarantola, 1984; Yang et al., 2015; Zhang et al., 2016; Zhu and Fomel, 2016) and frequency (Ben-Hadj-Ali et al., 2011; Brossier et al., 2010; Huang et al., 2017; Geller and Hara, 1993; Li et al., 2013; Oh and Min, 2017; Pratt, 1999; Pratt et al., 1998; Pratt and Shipp, 1999; Operto et al., 2004; Shin and Min, 2006; Tao and Sen, 2013; Wang et al., 2016; Xu and McMechan, 2014). However, while it is possible to construct well-resolved velocity structures using these inversion methods, the results of the inversions have suffered from a lack of low-frequency components and local minima (Chung et al., 2010; Park et al., 2013; Shin and Ha, 2008). To resolve these problems, a variety of approaches such as time domain inversion using a multi-scale method (Baeten et al., 2013; Bunks et al., 1995; Ravaut et al., 2004; Sirgue and Pratt, 2004), have been employed. However, while a reasonable initial velocity model can be obtained using travel-time tomography, there are limitations to obtaining a well-resolved velocity model at shallow depths (Chung et al., 2010). To overcome this limitation, the inherent low-frequency component in a dataset can be utilized to conduct a full waveform inversion and, by employing various transformation methods (e.g., Laplace transform, envelope function, and energy stack) to obtain a long-wavelength velocity model. In addition, many recent studies have proposed methods for generating low-frequency components and for updating low-wavenumber for solving the nonlinear problem. Alkhalifah (2015) proposed that the low-wavenumber can be updated when low-frequency components are not included in seismic data. In addition, methods have been developed based on extracting the update along the wavepath of reflected wave (Alkhalifah and Wu, 2016; Wu and Alkhalifah, 2015; Xu et al., 2012; Zhou et al., 2012).

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* Corresponding author.
E-mail address: wkchung@kmou.ac.kr. (W. Chung).

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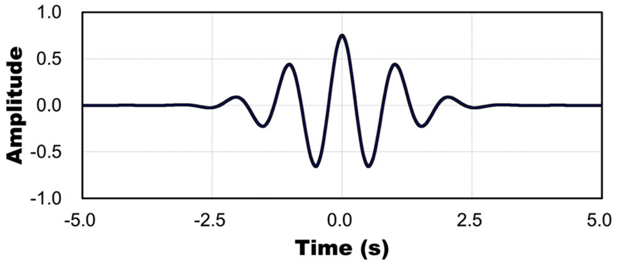

Fig. 1. Basis function for wavelet transform—Morlet signal.

In order to obtain a long-wavelength velocity model, Shin and Cha (2008) first performed a waveform inversion in the two-dimensional (2D) Laplace domain. Because low-frequency components are reconstructed using Laplace waveform inversion, a long-wavelength velocity model can be obtained (Chung et al., 2010; Ha and Shin, 2012; Park et al., 2013; Shin and Cha, 2008, 2009; Shin and Ha, 2008). Laplace waveform inversion is now also used in elastic (Chung et al., 2010) and acoustic-elastic coupled media (Bae et al., 2010), in addition to three-dimensional (3D) acoustic media (Pyun et al., 2011). Furthermore, various objective functions in the Laplace domain are used to construct improved velocity models from field datasets (Park et al., 2013). Research on improving the usefulness and efficiency of inversion techniques in the Laplace domain for noisy data has continued up to the present day. In addition, using the envelope function, Wu et al. (2014) proposed using seismic envelope inversion to reduce the initial velocity model dependence of waveform inversion. To obtain enhanced ultra-low-frequency data, they applied the envelope function to a seismic dataset. Furthermore, seismic data transformed using the envelope function include rich low-frequency information. However, the envelope inversion is applied to all frequency components, which is incapable of addressing specific frequency components individually. This means there are limitations when strong noise is occurring in a specific frequency component.

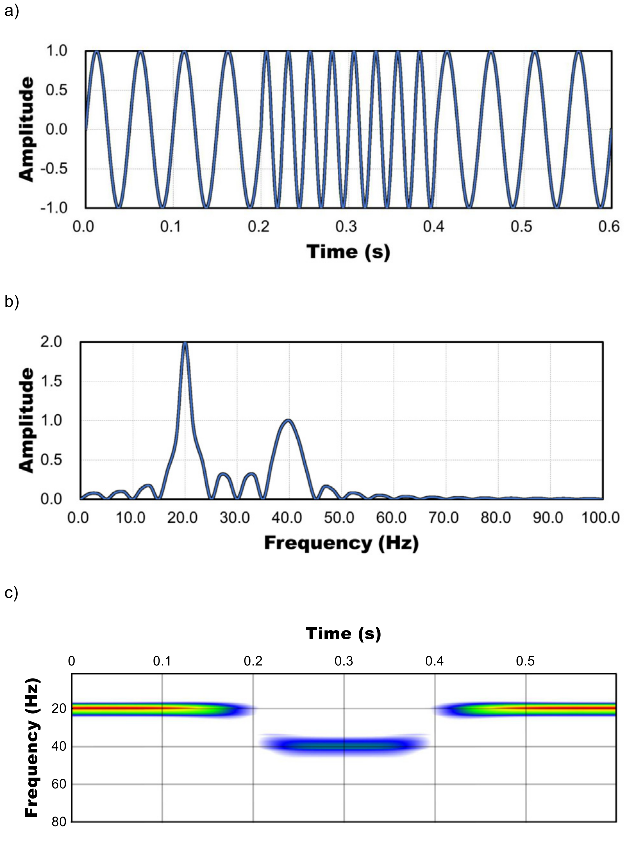

Fig. 2. Comparison among signals in the (a) time signal, (b) frequency spectrum, and (c) spectrogram.

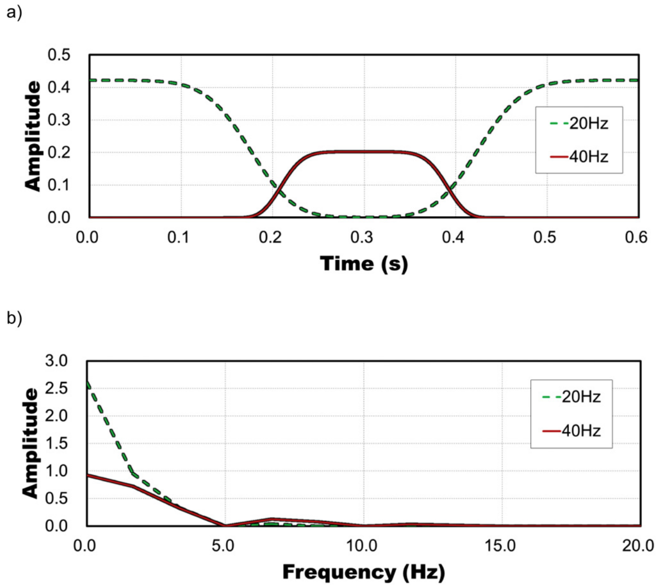

Fig. 3. (a) Transformed data from the spectrogram and (b) frequency spectra of the transformed data.

In this study, we propose a new full waveform inversion technique using a single-frequency component from a spectrogram for use in obtaining a long-wavelength velocity model. This method is referred to as “spectrogram inversion” in this study. A spectrogram is usually employed to analyze the time-varying frequency characteristics of seismic data (Chakraborty and Okaya, 1995); however, it is also utilized to enhance the low-frequency component in this study. The wavelet transform method is used to obtain a spectrogram. First, a spectrogram is generated using a trace extracted from observed and calculated data. A single frequency component is decomposed from the spectrogram, and the decomposed signal becomes a transformed trace. These transformations are applied to the entire observed and calculated datasets for spectrogram inversion.

While it can easily be adopted when general data are used that have been obtained directly by solving the wave equation, this was difficult in the present study because we used transformed data as a wavelet transform that was applied to the general data. Therefore, the partial derivative wavefield of the transformed data was approximated using a Taylor series expansion.

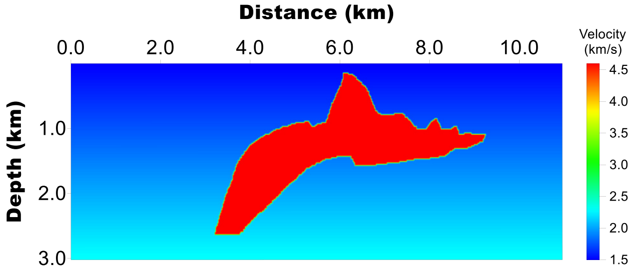

Fig. 4. A modified SEG/EAGE salt model for a local minima test.