Journal of Applied Geophysics 133 (2016) 25–29

Contents lists available at ScienceDirect

Journal of Applied Geophysics

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

An efficient 3D traveltime calculation using coarse-grid mesh for shallow-depth source

Woohyun Son [a], Sukjoon Pyun [b,*], Ho-Young Lee [a], Nam-Hyung Koo [a,c], Changsoo Shin [d]

[a] Petroleum and Marine Research Division, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon 34132, Republic of Korea
[b] Department of Energy Resources Engineering, Inha University, 100 Inharo, Nam-gu, Incheon 22212, Republic of Korea
[c] Petroleum Resources Technology, University of Science and Technology (UST), 124 Gwahak-ro, Yuseong-gu, Daejeon 34132, Republic of Korea
[d] Department of Energy Resources Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea

ARTICLE INFO

Article history:
Received 11 July 2015
Received in revised form 6 July 2016
Accepted 26 July 2016
Available online 28 July 2016

Keywords:
3D
First-arrival traveltime
SWEET
Equivalent source distribution
Coarse grid

ABSTRACT

3D Kirchhoff pre-stack depth migration requires an efficient algorithm to compute first-arrival traveltimes. In this paper, we exploited a wave-equation-based traveltime calculation algorithm, which is called the suppressed wave equation estimation of traveltime (SWEET), and the equivalent source distribution (ESD) algorithm. The motivation of using the SWEET algorithm is to solve the Laplace-domain wave equation using coarse grid spacing to calculate first-arrival traveltimes. However, if a real source is located at shallow-depth close to free surface, we cannot accurately calculate the wavefield using coarse grid spacing. So, we need an additional algorithm to correctly simulate the shallow source even for the coarse grid mesh. The ESD algorithm is a method to define a set of distributed nodal sources that approximate a point source at the inter-nodal location in a velocity model with large grid spacing. Thanks to the ESD algorithm, we can efficiently calculate the first-arrival traveltimes of waves emitted from shallow source point even when we solve the Laplace-domain wave equation using a coarse-grid mesh. The proposed algorithm is applied to the SEG/EAGE 3D salt model. From the result, we note that the combination of SWEET and ESD algorithms can be successfully used for the traveltime calculation under the condition of a shallow-depth source. We also confirmed that our algorithm using coarse-grid mesh requires less computational time than the conventional SWEET algorithm using relatively fine-grid mesh.

1. Introduction

Recent advances of 3-dimensional (3D) seismic survey led to the development of the data processing technique for 3D seismic data. In particular, the use of 3D reverse-time migration to find out subsurface structure attracted a lot of attention (Abdelkhalek et al., 2009; Araya-Polo et al., 2009; Kim et al., 2011; Yoon et al., 2003). As the reverse-time migration became more popular, more accurate velocity model was needed. As a result, recent researches in data processing area are focusing on the accurate velocity model building, and full waveform inversion is one of the available techniques. Recently, 3D full waveform inversion is challenged by many geophysicists (Ben-Hadj-Ali et al., 2009; Plessix, 2009; Pyun et al., 2011b, Son et al., 2014). Under these circumstances, we face a practical problem that the reverse-time migration requires enormous computational costs to verify the usefulness of inversion results. Therefore, a cost-effective migration technique is needed to verify the waveform inversion results. Although Kirchhoff migration is not as accurate as reverse-time migration, it is efficient enough to verify 3D inversion results.

There are many traveltime calculation algorithms for Kirchhoff migration such as various ray tracing methods (Coultrip, 1993), eikonal solvers (Vidale, 1988; Vidale, 1990) and wave-equation-based algorithms (Shin et al., 2002, 2003; Qin et al., 2005). Although ray tracing methods or eikonal solvers are much more efficient than wave-equation-based methods, wave-equation-based methods can properly handle caustics and other problems related to ray theory. In addition, wave-equation-based methods can compute amplitudes simultaneously. So, in this study, we use a wave-equation-based algorithm called the SWEET (suppressed wave equation estimation of traveltime) (Yang et al., 2003), which solves the wave equation in the Laplace domain. In this algorithm, a seismic trace is considered as a series of weighted spikes. By solving the wave equation in the Laplace domain, all the spikes except the first-arrival event are attenuated and become negligible. Thus, a seismic trace originating a series of weighted spikes can be approximated by a single spike. As a result, the first-arrival traveltime can be extracted from the solution of wave equation in the Laplace domain.

To solve the Laplace-domain wave equation, we use a standard finite-element method exploiting the combination of consistent and lumped mass matrices. The resultant matrix equation is solved by preconditioned conjugate gradient method. A numerical modeling by the Laplace-domain

* Corresponding author.
E-mail address: pyunsj@inha.ac.kr (S. Pyun).

http://dx.doi.org/10.1016/j.jappgeo.2016.07.025

wave equation shows less numerical dispersion error than time-domain or frequency-domain (Shin et al., 2002; Shin and Cha, 2008). This characteristic enables us to adopt large grid spacing for the numerical modeling. However, this choice hinders exact simulation of a shallow-depth source for the modeling with a coarse grid in acoustic media. Cha and Shin (2010) used adaptive meshes to solve this problem, but, due to its adaptive nature, its implementation is very complicated and the algorithm does not converge well where iterative solver is used. Therefore, we introduce the equivalent source distribution (ESD) algorithm (Pyun et al., 2011a) which approximates the shallow-depth source regardless of the grid spacing. In this paper, we propose an efficient 3D traveltime calculation method for the shallow-depth source by combining the SWEET algorithm and the ESD algorithm. Numerical experiments for a homogeneous model and the SEG/EAGE 3D salt model are performed to confirm the effectiveness of our method.

2. Conventional traveltime calculation using SWEET algorithm

The SWEET algorithm, which was suggested by Shin et al. (2002), calculates the first-arrival traveltime by solving the Laplace-domain wave equation. Yang et al. (2003) applied the SWEET algorithm to a 3D problem using a direct sparse matrix solver. To calculate first-arrival traveltime, the SWEET algorithm makes use of an assumption that a seismic signal is equal to a series of weighted spikes (Fig. 1). Multiplying this signal by exponentially decreasing function of time, amplitudes of all spikes except first-arrival signal are attenuated and become negligible (Fig. 2). Therefore, the seismic signal in the time domain, which is a series of weighted spikes, can be approximated to a single spiky pulse (Shin et al., 2002). This spiky pulse equals the first-arrival signal in the time domain. Although the principle of the SWEET algorithm can be easily explained in the time domain, the actual traveltime calculation is performed in the Laplace domain. The first-arrival traveltime is calculated using the Laplace-domain wavefield and its derivative. The first-arrival traveltime t is expressed as

$$t(x,y,z,s_{opt}) = -\frac{1}{u(x,y,z,s_{opt})}\left[\frac{\partial u(x,y,z,s_{opt})}{\partial s}\right], \tag{1}$$

where u is the Laplace-domain wavefield, s is the Laplace-domain variable and s_{opt} is an optimal Laplace damping constant. We can determine the optimal Laplace damping constant as follows (Shin et al., 2002):

$$s_{opt} = \frac{2\pi v_{ave}}{G\Delta} \tag{2}$$

where v_{ave} is the average velocity of a given model, Δ is the grid spacing, and G is the number of grid points per pseudo-wavelength. The Laplace-

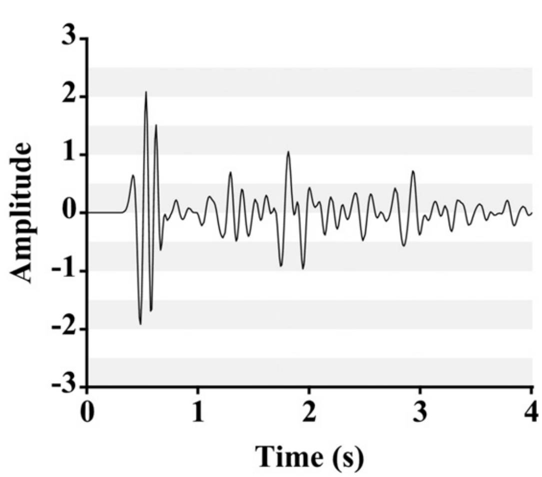

Fig. 1. A seismic trace is approximated as a series of weighted spikes.

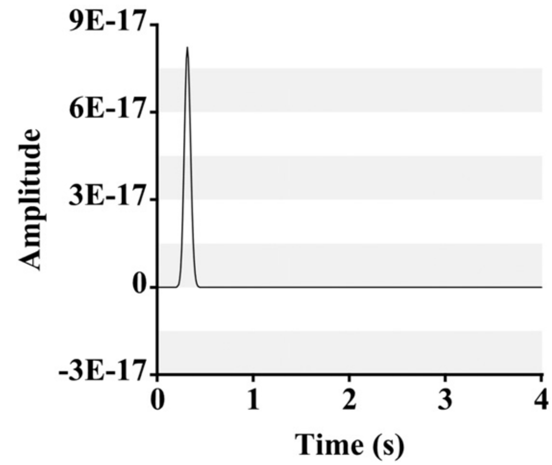

Fig. 2. A damped wavefield obtained by multiplying a damping factor e^{-100t}.

domain wavefield is obtained by solving the 3D acoustic wave equation in the Laplace domain as follows:

$$\frac{s^2}{v^2}u - \frac{\partial^2 u}{\partial x^2} - \frac{\partial^2 u}{\partial y^2} - \frac{\partial^2 u}{\partial z^2} = f, \tag{3}$$

where v is the propagation velocity in the medium and f is the source function in the Laplace domain. Using the finite-element method, Eq. (3) can be expressed as the linear algebraic system (Marfurt, 1984) as follows:

$$\mathbf{Su} = \mathbf{f}, \tag{4}$$

with

$$\mathbf{S} = \mathbf{K} + s^2\mathbf{M}, \tag{5}$$

where $\mathbf{S}$ is the impedance matrix, $\mathbf{u}$ the wavefield vector in the Laplace domain, $\mathbf{f}$ the source vector in the Laplace domain, $\mathbf{K}$ the stiffness matrix, and $\mathbf{M}$ the mass matrix. In this paper, we apply perfectly matched layer (PML) boundary condition to eliminate unwanted edge reflections (Cohen, 2002). To efficiently solve Eq. (4), we use the preconditioned conjugate gradient method (Pyun et al., 2011b). The partial derivative of wavefield in Eq. (1) is calculated by a back-propagation algorithm (Shin et al., 2002) as follows:

$$\frac{\partial \mathbf{u}}{\partial s} = \mathbf{S}^{-1}\left(-\frac{\partial \mathbf{S}}{\partial s}\mathbf{u}\right). \tag{6}$$

3. Efficient traveltime calculation using SWEET and ESD algorithms

In general, the forward modeling algorithm can exactly calculate the wavefield when the source is located at a grid point and the grid spacing is small enough to avoid numerical dispersion. In particular, the Laplace-domain wave equation allows accurate modeling for relatively large grid spacing when the source is located at a grid point. However, if a real source is located at shallow-depth close to free surface, we cannot accurately calculate the wavefield using coarse grid spacing. So, we generate distributed sources equivalent to the original point source to exploit the coarse grid spacing by the equivalent source distribution (ESD) algorithm. The ESD algorithm is a method to define distributed nodal sources that approximate a real source at the inter-nodal location in a velocity model with large grid spacing (Pyun et al., 2011a). Fig. 3 shows the conceptual illustrations of the ESD algorithm. Pyun et al. (2011a) suggested this algorithm to perform more efficient and accurate modeling of the 3D Laplace-domain wave equation for a coarse