A multi-period inversion of broadband seismic waveforms for 3-D velocity structures

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A precise velocity structure model is necessary to predict long-period ground motions during large earthquakes and analyze source processes using long-period waves. Many studies have reported that 3-D velocity structures formed by sedimentary basins or accretionary wedges along subduction zones can significantly affect the generation and propagation of long-period seismic waves. In terms of including the various effects of the 3-D velocity structures, a waveform inversion for 3-D velocity structures using the time history of long-period ground motions is the most effective. These were several studies that estimated 3-D velocity structures by waveform inversions. Aoi (2002) proposed a method that estimates the 3-D depth of the boundary between sediment and bedrock. Iwaki and Iwata (2011) applied the method of Aoi (2002) to real data observed in the Osaka basin, Japan. Hikima (2006) formulated an inversion procedure for 3-D velocity structures, in which observed waveforms are initially inverted for layer thicknesses in 2-D cross-sections and a 3-D velocity structure model is subsequently constructed by interpolating the results of the 2-D inversions. In southern California, the estimations of the seismic velocity and the intrinsic attenuation were performed by the numerical simulations of wave propagation in combination with the adjoint method (e.g., Askan and Bielak, 2008; Tape *et al.*, 2010).

Seismic waveforms with a period range such as 2-20 s are often used to evaluate long-period ground motions. Thus, it is important to construct a velocity structure model which well reproduces the waveforms filtered over this period range. In this study, we attempt to develop a waveform inversion method for 3-D velocity structures that are responsible for broad-period ground motions. We first divide the inverted period range into multiple period ranges such as 10-20, 5-20, and 2-20 s. We start our inversion with the waveforms with only the longer-period range (10-20 s). The solution for the current period range is used as an initial guess for the next period range, which includes the shorter period (5-20 s). The inversion is continued until the period range matches the broadest period (2-20 s). The velocity structure model is composed of homogeneous layers, and the layer thicknesses are set as model parameters, just as Hikima (2006) did. The model parameters are estimated by solving a non-linear damped least-squares problem, which is an iterative procedure. In the inversion using only longer-period waveforms (10-20 and 5-20 s), we can use coarse inversion grids (e.g., Bunks *et al.*, 1995); in the inversion using the waveforms with the broadest period (2-20 s), a reasonable initial guess leads the iteration to achieve a fast convergence. Thus, our inversion procedure is better than conventional waveform inversions in terms of reducing the total number of 3-D forward simulations. Furthermore, we can stably estimate the model parameters for a complex velocity structure with multiple layers.

We calculate the partial derivatives with respect to model parameters using finite-difference approximation, where the difference between the unperturbed and slightly perturbed synthetic waveforms is taken. The synthetic waveforms are calculated by a 3-D finite element method with voxel meshes (Koketsu *et al.*, 2004; Ikegami *et al.*, 2008). We also use the modified Levenberg-Marquardt method to make the iteration stable. At each iteration, the model parameters are solved by the singular value decomposition of the Jacobian matrix. We performed several numerical experiments to confirm the validity of our inversion procedure. We will show the results and discuss the performance of the recovery of broad-period data as well as the optimal way to divide the inverted period range.

Keywords: Velocity structure model, Waveform inversion, Broadband seismic waveform, Damped least-squares method, Non-linear problem