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Fréchet Kernels for Imaging Regional Earth Structure Based on Three-Dimensional Reference Models

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Abstract High-resolution images of three-dimensional (3D) seismic structures are not only of scientific interest, but also of practical importance in predicting strong ground motion after large earthquakes. Given the source and station distributions, resolutions in current regional seismic tomography studies have been limited by two types of simplifying practices: the adoption of high-frequency approximations such as the ray theory and the use of one-dimensional (1D) reference (starting) models. We have developed a new approach to compute accurate finite-frequency 3D Fréchet (sensitivity) kernels of observed travel time and amplitude anomalies relative to 3D reference models. In our approach, we use a fourth-order staggered-grid finite-difference method to model the seismic-wave propagation in 3D media, and the reciprocity property of the Green's tensor to reduce the number of numerical simulations. This approach accounts for the perturbations in compressional- and shear-wave speeds in the same way, leading to a capability of inverting for the shear-wave speed directly from seismic data. The algorithm is readily parallelized to allow for realistic regional high-resolution 3D tomography inversions. We have implemented the algorithm for the Southern California Earthquake Center (SCEC) Community Velocity Model, SCEC CVM 3.0, a complex 3D model for Southern California including a number of sedimentary basins. By enabling the inversion of 3D structural perturbations to 3D reference models, our approach provides a practical means of iteratively solving the nonlinear regional tomography problems.

Introduction

Reliable prediction of strong ground motion following large earthquakes is essential in assessing earthquake hazards and taking precautionary measures in order to reduce the human and property losses from earthquakes. In recent years, with the advancement in high-performance computing, seismologists have developed computer codes using a variety of numerical algorithms such as finite-difference (e.g., Frankel and Vidale, 1992; McLaughlin and Day, 1994; Olsen, 1994; Graves, 1996; Aoi and Fujiwara, 1999; Kristek *et al.*, 1999), finite-element (e.g., Bao *et al.*, 1998; Aagaard *et al.*, 2001), pseudospectral (e.g., Tessmer *et al.*, 1992; Igel, 1999) and spectral-element (e.g., Komatitsch and Vilotte, 1998; Komatitsch *et al.*, 2004) methods to simulate the complete time history of the ground motion with the purpose of providing a numerical shake table for engineers.

The accuracy of the simulated strong ground motion depends heavily on a realistic regional earth model. The ground motion can be greatly influenced by the three-dimensional (3D) subsurface seismic structures, most notably in a sedimentary environment such as the Los Angeles Basin (Fig. 1), where the seismic ground motion is amplified not only by the relatively soft sedimentary material, but more importantly through the trapping of basin edge generated reflected and/or refracted waves inside the basin and the constructive interference of these waves (e.g., Kawase, 1996; Graves *et al.*, 1998; Pitarka *et al.*, 1998; Davis *et al.*, 2000; Olsen, 2000). In addition, mapping the small-scale structural variations in and around the basin is also important to studying the source properties of the numerous small local earthquakes.

Up to now, 3D studies of the structure in the L.A. Basin and vicinity have primarily been focused on the *P*-wave speed and coming from three sources: travel-time tomography (e.g., Kohler, 1997; Hauksson, 2000), linear-array active-source surveys (Fuis *et al.*, 2001; Godfrey *et al.*, 2002), borehole as well as sedimentary age-depth data (Magistrale *et al.*, 1996; Magistrale *et al.*, 2000), and industry-data analysis (Süss and Shaw, 2003). Thus, the currently available L.A. Basin regional models either do not have sufficient spatial resolution or do not cover the entire region. The Southern California Earthquake Center Community Velocity Model (SCEC CVM) is created by adopting the regional tomography result of Hauksson (2000) as the background model and using the borehole and sedimentary