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Full-3D, Full-Wave Seismic Tomography for Crustal Structure in Southern California, USA

CHEN Po

Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071, USA

Southern California is one region where the seismic hazard is high and the subsurface geological structure is complex. Three-dimensional structural heterogeneities, in particular, thick sedimentary basins, can have significant influence on the ground motion generated by disastrous earthquakes. To better quantify seismic hazards in Southern California, we need to improve our three-dimensional seismic structure model of the subsurface.

In the past, researchers in the Southern California Earthquake Center (SCEC) have created two three-dimensional Community Velocity Models for Southern California, code named CVM-S (Magistrale et al, 1996) and CVM-H (Süss & Shaw, 2003). The CVM-S model was constructed by embedding rule-based basin structure models within a background seismic velocity model determined from regional travel-time tomography (Hauksson 2000). The basin structure models were based on empirical rules that relate the P-wave speed to the age and depth of the sediments. The S-wave speed was then scaled from the P-wave speed by assuming a certain Possion’s ratio. The CVM-H model was mainly constructed from sonic logs and the stacking velocities from petroleum-industry reflection profiles (Süss & Shaw, 2003). Preliminary waveform comparisons in the Los Angeles Basin region (Chen et al., 2007a) have shown that both CVM-S and CVM-H provided substantially better fit to the observed waveform data than the laterally homogeneous Standard Southern California Crustal Model (SoCaL) (Hadley & Kanamori, 1977) and a set of path-averaged one-dimensional models derived from CVM-S by averaging slownesses along the source-receiver paths. The CVM-H model provided a slightly better fit to observed P waves than the CVM-S model while the CVM-S model fit the observed S waves slightly better than the CVM-H model. Both CVM-H and CVM-S can be used as starting models in full-3D waveform tomography.

In Chen et al. (2007a), a full-3D waveform tomography based on the SI method was carried out for the crustal structure of the Los Angeles Basin region using the CVM-S model as the starting model. The resulting model, LAF3D, provided substantially better fit to the observed waveforms for frequencies up to 1.2 Hz. It was the first successful full-3D waveform tomography using real earthquake waveform data in structural seismology. In Tape et al. (2009), the adjoint method was applied to improve the CVM-H model in a region that covers Southern California. After 16 iterations, their model provided significantly better fit to the observed waveforms over the period range 2-30s. Their model revealed strong crustal heterogeneities that were not in their starting model CVM-H and correlates well with local geology.

In our current study, we are extending our full-3D, full-wave tomographic inversion region from the Los Angeles Basin to Southern California. Our starting model is the 3D SCEC CVM-S version 4.0 (CVM-S4). Our forward and adjoint elastic

Email: pchen@uwyo.edu

wave-equation solver is the 4th-order staggered-grid finite-difference code provided by Kim Olsen and Yifeng Cui (personal communication). At the current stage, we have carried out 23 iterations. The first 20 iterations were conducted using the adjoint method (e.g., Tromp et al., 2005; Tape et al., 2009) and the last 3 iterations were carried out using the scattering-integral method (e.g., Zhao et al., 2005; Chen et al., 2007ab). In our inversion, we included waveform data from more than 210 local small to moderate-sized earthquakes recorded at more than 230 local three-component broadband seismic stations. In addition to waveform recordings from local earthquakes, we also included 3000 ambient-noise Green's functions obtained by cross-correlation vertical-component ambient-noise recordings at more than 230 local stations.

1 Inversion

In full-3D, full-wave tomography, the starting model, as well as the derived model perturbation, is three-dimensional in space, and the Fréchet derivatives are computed using the full physics of three-dimensional wave-propagation. Both the adjoint method, which back-propagates the misfit measurements from the receivers to image the structure, and the scattering-integral method, which sets up the inverse problem by calculating and storing the Fréchet kernels for each misfit measurement, are full-3D, full-wave tomography techniques and they are based on identical physical principles. However, which technique is more computationally efficient depends upon the overall problem geometry, particularly on the ratio of sources to receivers, as well as trade-offs in computational resources, such as the relative costs of compute cycles to disk storage (Chen et al., 2007b). When sufficient disk storage is available and the number of seismic sources is comparable to or larger than the number of receivers, the scattering-integral method is computationally more efficient because it provides not only the gradient, but also an approximate Hessian of the objective function, which allows us to utilize optimization algorithms with faster convergence rates. The approximate Hessian becomes more accurate when the misfit measurements become smaller through the iterations. The receiver-Green's tensors (RGTs), which are the spatial-temporal strain-fields generated by a unit impulsive force acting at the receiver location, are used for computing the Fréchet kernels for individual misfit measurements in the scattering-integral method. The RGTs can also be used for highly efficient earthquake source parameter inversions by applying the reciprocity principle.

In our tomographic inversion, we used the adjoint method for the first 20 iterations, when the misfit measurements are still quite large, and switched to the scattering-integral method to speed up the convergence for the latest 3 iterations, when the misfit measurements are relatively small and the approximate Hessian provided by the scattering-integral method is reasonably accurate. In the 20 adjoint iterations, the first 5 iterations were carried out using only the frequency-dependent phase-delay misfits measured on the Rayleigh waves of the vertical-component ambient-noise Green's functions. These 5 iterations corrected the large-scale errors in our starting model CVM-S4 and reduced the frequency-dependent phase-delay misfits measured on the ambien-noise Green's functions by over 50%. Using this tomographically corrected 3D seismic velocity model, we computed and archived the RGTs for all the seismic stations used in our inversion. These RGTs were then used to invert for the centroid moment tensors (CMTs) of all the earthquakes used in our inversion by applying the reciprocity principle (Lee et al., 2011). Compared with the CMT solutions provided by the local seismic network, our refined CMT solutions significantly improved the fit to the observed seismic waveforms. Starting from the 6th iteration, the waveforms of the earthquakes are included into our tomographic inversion and the forward wave-fields from the earthquakes were computed using our refined CMT solutions, which were fixed through the rest of the adjoint and scattering-integral iterations. After the 20 adjoint iterations, the total reduction in phase-delay misfit for both ambient-noise Green's functions and earthquake waveform recordings is over 70% and the reduction in waveform misfit for earthquake waveform recordings is over 50%. The latest 3 scattering-integral iterations have further reduced the misfit in phase-delay and waveform by over 15%.

2 Conclusion

Our current tomographically improved 3D seismic velocity model CVM4SI23 seems to provide a better correlation with local geology than the starting model. The largest perturbation occurs in the southern part of the Great Valley at shallow depths. The maximum velocity reduction reaches about 45% relative to the starting model. Significant reduction in S-wave velocity is also observed in the Coast Range and the offshore basins. In particular, the size of the offshore basins has been extended at shallower depths in CVM4SI23. The southern part of the San Andreas fault is delineated by a low-velocity trend that extends from the north of the Salton trough to the Garlock fault. The S-wave velocity in the Mojave block and the Sierra Nevada region has also been reduced slightly relative to the starting model, but is still much higher than the average S-wave velocity to the west. The S-wave velocity east of the Mojave block has been reduced significantly. Some of the features at shallower depths seem to persist through middle crust. At 10 km depth, the S-wave velocity in the Coast Range and the offshore basins has been reduced. The low-velocity anomaly east of the Mojave block is expanded. At 20 km depth, the S-wave velocity in the Great Valley is increased, while in and around the Mojave block, it is reduced. In general, it seems that our updated model CVM4SI23 enhances the velocity contrast that was already in the starting model. At shallower depths, our updated model provides better correspondence with surface geology.

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