Disseminating, Improving and Validating 3-D Seismic Velocity Models for California

Cliff Thurber, University of Wisconsin-Madison

Research supported by SCEC awards #25209 and #25229 and USGS awards G22AP00246, G22AP00248, G24AP00092, and G24AP00093

ABSTRACT

I report on progress on three collaborative efforts to disseminate, improve, and validate 3D seismic velocity models for different regions of California, with support from SCEC and the USGS. The main focus is on northern California. The dissemination effort aims to incorporate additional northern California 3D models into the SCEC Community Earth Model (CEM) platform, primarily via the Unified Community Velocity Model (UCVM) platform. To date, the statewide 3D model of Lin et al. (2010) has been restored in the UCVM and the new 3D Vp and Vs models of the San Francisco Bay (SFB) region of Guo et al. (2025) have been added. Efforts are underway to add the 3D Vp model of Thurber et al. (2009) for northern California and the 3D Vp and Vs models of Zeng et al. (2016) for the greater Parkfield region. Improvement efforts involve development of new SFB region Vp and Vs models (Guo et al., 2025) using joint body wave-surface wave inversion and an improved version of the Fang et al. (2016) code. We are also evaluating a novel idea for taking Rayleigh wave ellipticity modeling results and turning them into "virtual shots" on a "virtual seismic profile" to add to body-wave data sets. Finally, validation efforts are being pursued along two different fronts. One is direct validation of model improvement via wavefield simulations, and the other is indirect validation by comparing 3D models obtained with two different joint inversion codes.

VELOCITY MODEL DISSEMINATION

A new version of the SCEC Unified Community Velocity Model (UCVM) software framework, UCVM v25.7, has just been released and is available at:

https://github.com/SCECcode/UCVM

See poster #329 by Su et al. With guidance and assistance from Mei-Hui Su and Phil Maechling, our dissemination effort has added two models to the CVM archive, the statewide 3D model of Lin et al. (2010) (Figure 1a) and new 3D Vp and Vs models of the San Francisco Bay (SFB) region (Guo et al., 2025) (Figure 1b). In addition, two more models have been prepared for addition to the UCVM archive, the northern California Vp model of Thurber et al. (2009) (Figure 1c) and the Parkfield region Vp and Vs models of Zeng et al. (2016) (Figure 1d). Some UCVM models have also been contributed to the EarthScope's Earth Model Collaboration (https://ds.iris.edu/ds/products/emc/) (EMC). Pathways are now established to prepare models of interest for submission of additional model either to UCVM or EMC, or both. There are also capabilities to convert models to other formats of interest, for example SW4, but these capabilities are early in their development.

Another related development is the new CVM Explorer (see poster #325 by Marshall et al.). Figures 1 a and b are both from the CVM Explorer. The CVM Explorer allows easy access to a range of seismic velocity models using the UCVM package. The interface allows for downloading data in csv format and has various visualization capabilities including horizonal slices, vertical cross sections, and vertical profiles.

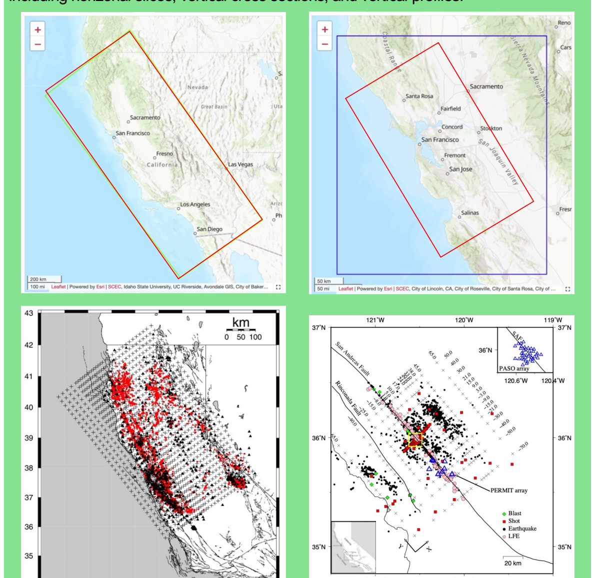


Figure 1. Maps showing the coverage region of (a) the statewide model of Lin et al. (2010), both Vp and Vs, but with a much coarser Vs model, (b) the new SF Bay model of Guo et al. (2025), both currently in the UCVM; (c) the northern California Vp model of Thurber et al. (2009), and (d) the Parkfield region Vp and Vs models of Zeng et al. (2016), prepared for inclusion in the UCVM.

VELOCITY MODEL IMPROVEMENT

We take two approaches for improving seismic velocity models. One is to improve existing tomography models by jointly inverting body-wave and surface-wave data, using a modified version of the code of Fang et al. (2016). Incorporating both body-wave arrival time data and surface-wave dispersion data in a joint inversion capitalizes on the different advantages of the two data types, in particular, providing additional constraints on S-wave structure, which is typically not well resolved with body-wave data alone. The application of this method to the San Francisco Bay (SFB) region is described in detail in Guo et al. (2025). Cross-sections from the new model are shown in Figure 2.

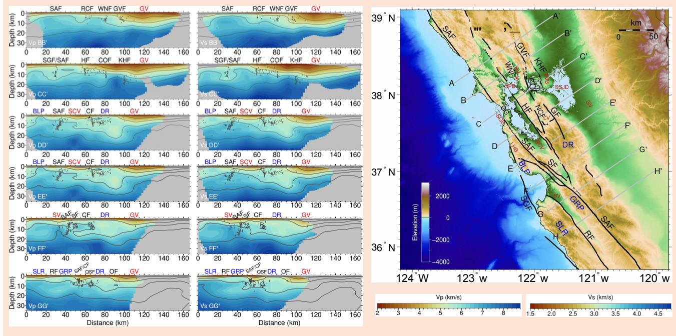


Figure 2. Cross-sections of Vp and Vs from the new SF Bay model of Guo et al. (2025) along 6 of the profiles (BB' to GG') shown on the right. Research done collaboratively with Taka'aki Taira , Avinash Nayak, and Evan Hirakawa

The other approach is a novel way to incorporate results from modeling Rayleigh wave ellipticity (H/V) data into body-wave tomography. The idea is quite simple. Take the 1D Vp and Vs models resulting from inverting the H/V data and compute the one-way vertical travel time from interfaces in the Vp and Vs models up to the station at its proper elevation and treat those travel times as if they were from shots at the model interfaces (Figure 3). We adopt the terms "virtual shots" and "virtual seismic profiles" for these data. They can be incorporated directly into tomography just as any other active-source data. Although the 1D models and the virtual shot data from them are approximate, the virtual shot data provide independent constraints on the structure, which is especially valuable for Vs at shallow depths. The preliminary 1D models from H/V were provided by HyeYoung Kim and Fan-Chi Lin (see Lin et al. poster #028). Taking the Guo et al. (2025) models as the starting models and inverting the virtual shot data for two clusters of stations (Figure 4) yields estimates of Vp and Vs versus depth for these stations. Examples are shown for Vs in Figure 5 for the stations crossing Santa Clara Valley. Velocities are generally significantly slower for the model from the virtual shot data compared to the Guo et al. (2025) Vs model. Velocity reductions are similar for the Vp models. We believe the slower structures are more likely to be correct. Once we invert a complete set of virtual shot data, we will use wavefield simulations to ascertain if the obtained model fits waveform data better than the Guo et al. (

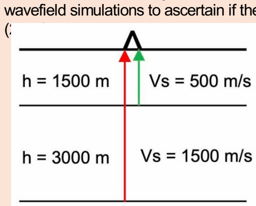
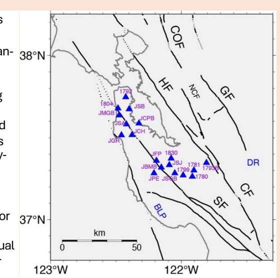


Figure 3. Cartoon illustrating how we create "virtual shot" data on a "virtual seismic profile" by computing the one-way vertical travel times from layer boundaries in the 1-D H/V model up to the station at the surface (green and red paths) for Vs and Vp.

Figure 4. Two clusters of stations for which HyeYoung Kim and Fan-Chi Lin produced preliminary 1D H/V models by combining ZZ and ZR cross-correlations or RZ and RR cross-correlations to yield the frequency-dependent Rayleigh wave ellipticity at the receiver station, and inverting the results for a 1D model. We then used to compute virtual shot data. See poster #028 by Lin et al.



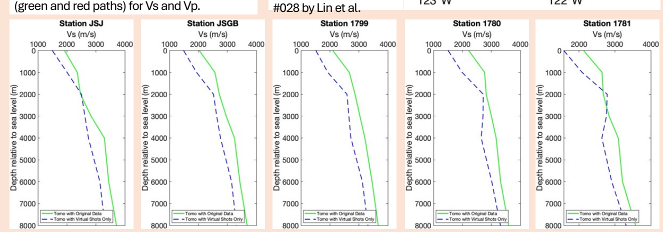


Figure 5. Depth profiles from the initial Vs models from Guo et al. (2025) (green lines) and models from the virtual shot inversion (dashed lines) for stations running west to east across Santa Clara Valley. The redu
ctions in Vs near the surface are on the order of 25%.

The virtual VSP strategy can be applied to more than just 1D models from Rayleigh wave ellipticity. Other possibilities are zero-offset reflection data, 1D models from autocorrelations, receiver functions

VELOCITY MODEL VALIDATION

We are taking two approaches to validating the Guo et al. SF Bay velocity model. One is by comparing performance to other models using metrics of interest. We follow the approach of Hirakawa and Aagaard (2022), using the same set of 20 SF Bay area earthquakes and the same wavefield simulation code, SW4. The ground-motion simulations were performed with four different velocity models that cover the SF Bay area: (a) the new Guo et al. (2025) model, (b) the Thurber et al. (2009) model, which was the starting model for the tomographic inversion of Guo et al. (2025), and (c) USGS model v21.1 (Hirakawa and Aagaard, 2022). The trends in our findings show that the new Guo model performs notably better than the Thurber model in the metrics effective amplitude spectra (EAS), peak ground velocity (PGV), cumulative absolute velocity (CAV), and duration of Arias intensity (Duration) (Figure 6, left panels). The Guo model performs better than the Thurber model on all measures and compares well with the USGS model for EAS and PGV. The USGS model is clearly superior for CAV and Duration, which we attribute to the complex low velocities in the near surface in the USGS model that the tomographic models are unable to resolve. Comparing time to the maximum amplitude arrival (mainly S at these distance), the Guo model and the USGS model perform equally well, with much poorer performance by the Thurber model. This reflects generally slower S-wave velocities in the Guo model.

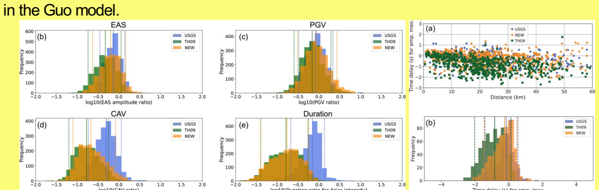


Figure 6. Comparison of metric performances for the USGS, Thurber (TH09), and Guo (NEW) models.

The other approach is by comparing the model results from two inversion codes, the modified version of the Fang et al. (2016) code jointtomoBS and the Eberhart-Phillips et al. (2023) code simul2023. The two codes have several similarities but some important differences. The most important difference is in the way the sensitivity of the surface-wave data to model perturbations is determined. For jointtomoBS, surface-wave paths are determined at each period (Figure 7a), the path is discretized, and at each path point using 1D depth sensitivities with respect to model perturbations are determined (Figure 7b). For simul2023, for each period, sensitivities over depth for a given point in the group velocity map are computed for an area whose horizontal dimension increases with [illegible] osed to along a path.

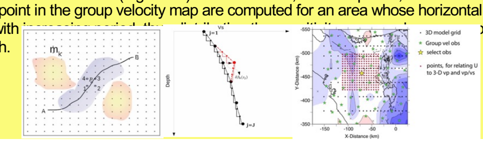


Figure 7. (left) For each period, a path through the velocity map (phase or group) is computed, and (center) travel time sensitivities are computed with respect to perturbations within the 3D velocity model. (right) Example of box for computing model sensitivities at points (red dots) in a volume surrounding a model point in a group velocity map (yellow star). Small dots are model nodes; stars are nodes of the group velocity map. Box width increases with increasing period. From Eberhart-Phillips and Fry (2017).

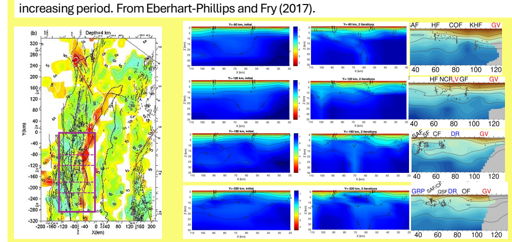


Figure 8. Two-iteration results from simul2023. Far left: map from Thurber et al. (2009) showing locations of Vp cross-sections through (left to right) the starting model, the two-iteration result, and the Guo et al. (2025) model along approximately the same profiles. The agreement is encouraging. More results coming!

REFERENCES

Eberhart-Phillips, D., Thurber, C., Rietbrock, A., Fry, B., Reyners, M., & Lanza, F. (2024). Simul2023: a flexible program for inversion of earthquake data for 3-D velocity and hypocenters or 3-D Q (simul2023 is update of simul2017: doi.org/10.5281/zenodo.5746046). Zenodo. https://doi.org/10.5281/zenodo.10695070

Fang H., Yao, H., Zhang, H., Huang, Y. C., & van der Hilst, R. D. (2015). Direct inversion of surface wave dispersion for three-dimensional shallow crustal structure based on ray tracing: Methodology and application. GJI, 201, 1251-1263. https://doi.org/10.1093/gji /ggv080

Guo, H., Taira, T., Nayak, A., Thurber, C., & Hirakawa, E. (2025). Three-dimensional seismic velocity models for the San Francisco Bay region, California from joint body-wave and surface-wave tomography validated by waveform simulation. JGR:SE, 130, e2025JB031377. https://doi.org/10.1029/ 2025JB031377

Hirakawa, E., & Aagaard, B. (2022). Evaluation and updates for the USGS San Francisco bay region 3D seismic velocity model in the East and North Bay portions. BSSA, 112, 2070–2096. https://doi.org/10.1785/0120210256

Lin, G., Thurber, C. H., Zhang, H., Hauksson, E., Shearer, P. M., Waldhauser, F., et al. (2010). A California statewide three-dimensional seismic velocity model from both absolute and differential times. BSSA, 100, 225–240. https://doi.org/10. 1785/0120090028

Thurber, C., Zhang, H., Brocher, T., & Langenheim, V. (2009). Regional three-dimensional seismic velocity model of the crust and uppermost mantle of northern California. JGR, 114, B01304. https://doi.org/10.1029/2008JB005766

Zeng, X., Thurber, C., Shelly, D. R., Harrington, R. M., Cochran, E. S., Bennington, N. L., Peterson, D., Guo, B., & McClement, K. (2016). 3-D P- and S-wave velocity structure and low-frequency earthquake locations in the Parkfield, California region. GJI, 206, 1574-1585, https://doi.org/10.1093/gji/ggw217