2025 SCEC Final Report, Project #25229

Incorporating data from H/V observations into joint body wave-surface wave tomography: proof of concept

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March 9, 2026

1. Abstract

We proposed to test a new idea for incorporating results from Rayleigh wave ellipticity (RWE) inversions obtained from H/V measurements into body-wave and/or joint body wave-surface wave tomography as a proof of concept. The ultimate goal is to greatly improve constraints on S-wave velocity (Vs) structure as well as P-wave velocity (Vp) structure in tomographic models, especially at shallow depths and in basins. Our initial idea was to use layered (1-D) Vp and Vs models derived from the RWE observations to generate one-way P-wave and S-wave travel times from each 1-D model interface up to the station at the surface and include these as "virtual shot" data in our tomographic inversion. We recognize that these travel times are approximate, and the tomographic inversion will not fit them exactly (just as all data are generally not fit exactly), but we find that using these travel times leads to improvements in our velocity models, especially near the surface. We have also expanded the concept to utilize 1-D models from receiver function (RF) inversions and other sources of independently derived velocity models to provide constraints on our tomographic models.

2. Research Goals

The main goals of our work under SCEC award #25229 are to test the initial idea of using "virtual vertical seismic profiles" (VVSPs) derived from 1-D models that were obtained from RWE (H/V) inversions to provide constraints on shallow velocity structure in tomographic inversions.

3. Methodology

The VVSP concept emerged from discussions I had with Fan-Chi Lin at the 2024 SCEC annual meeting. He and I had both been working on modeling seismic structure in the San Francisco Bay (SFB) region using different methods, Rayleigh-wave ellipticity (H/V) and joint body-wave surface-wave tomography, respectively. Fan-Chi suggested I add H/V data and corresponding sensitivity kernels to the Fang et al. (2016) joint inversion code. I found that idea rather daunting. Instead, I realized that the layered velocity models that H/V analysis yields at each station could be used for generating vertical travel times from each layer boundary up to the surface (Figure 1), and those times could be used as observations in the joint tomographic inversion as if there were "check shots" beneath each station at every layer boundary. In fact, there are other types of possible sources of 1-D models from which such travel times can be obtained, making the VVSP concept very widely applicable.

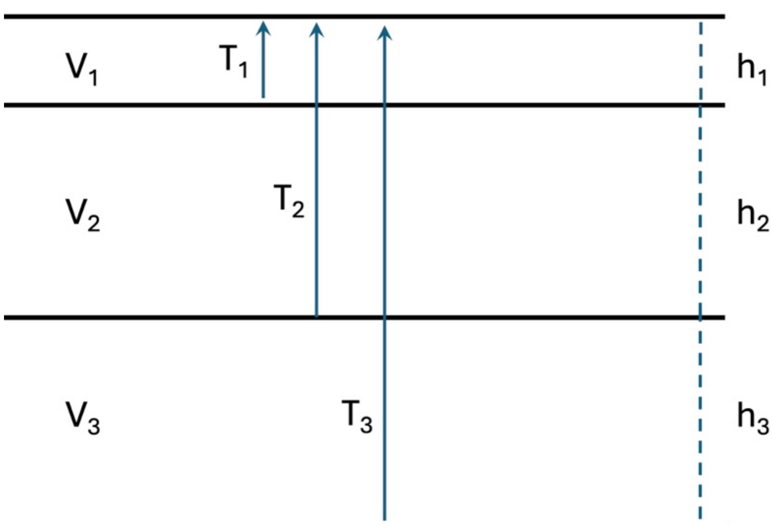

Figure 1. Cartoon illustrating the construction of virtual travel times from a layered model of the subsurface. One-way travel times from each interface up to the station at the surface are calculated and used as virtual active-source data, yielding the desired VVSP.

4. Results Obtained

As preliminary proof of concept, the Utah group derived 1-D Vs and Vp models from RWE observations for a set of 4 stations that fall within the model of Guo et al. (2025) in the SFB region. The inversion of the period-dependent H/V was done with fixed layer thickness and varying Vs and Vp, similar to Lin et al. (2014). We generated the virtual shot travel time data from these 1-D models, and used the virtual shot data to update the Guo et al. (2025) SFB 3-D Vp and Vs models in two steps, first inverting just the virtual shot data, and then reinverting the entire dataset including the virtual shot data, which were heavily weighted. In Figure 2, we show the Vs and Vp depth profiles through our current SFB model directly below these stations, Vs and Vp depth profiles from RWE for the 4 stations, and Vs and Vp depth profiles through the updated model resulting from both the inversion of the virtual shot data only and the second updated model using the original data plus the virtual shot data. Note the very large differences in Vs in the upper few kilometers of the RWE model compared to the original tomography models. The inversion using just the virtual shot data produces profiles that are closer to the RWE profiles in the top ~2 km but tend to have lower velocities in the deeper part. The second updated inversion profiles, using the original data plus the virtual shot data, fit both the shallow and deeper parts of the RWE profiles relatively well. This indicates that our two-step inversion procedure produces the desired results.

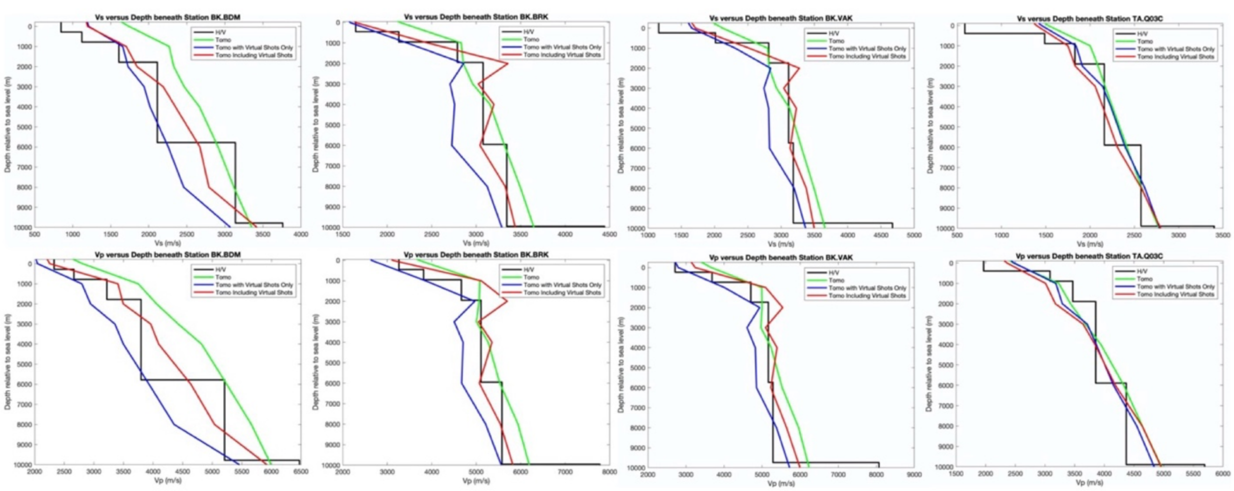

Figure 2. (top row) Vs models from original tomographic inversion in Guo et al. (2025) (green line, "Tomo"), H/V (black stair-step line, "H/V"), updated tomographic inversion just with virtual shot data (blue line, "Tomo with Virtual Shots Only"), and second updated tomographic inversion with original data and virtual shot data (red line, "Tomo Including Virtual Shots"), for the four stations within the SFB model domain. (bottom row) The same for Vp models.

H/V models are not the only option for creating VVSP data. There are a variety of seismic methods in addition to H/V that produce one-dimensional (1-D) models or measurements corresponding to the vertically varying structure beneath a given seismic station that can be used to create travel times that can be assembled together to make a VVSP. Examples include ambient noise autocorrelations and receiver function models. For well-constrained sedimentary basins, it is also possible to use vertical travel times to any point on the surface from the basement interface or any layer interface (and in fact even any point at depth!) to the surface through a well-constrained velocity model. These models could either be based on borehole and active source data (Plesch et al., 2021) or from a geologically based model incorporating constraints from potential field and other data (Brocher, 2006; Hirakawa and Aagaard, 2022). In principle, this strategy can be applied to any well-constrained velocity model, be it 1-D, 2-D, or 3-D.

For a second proof of concept, we used a basin model for the San Bernardino Basin (SBB) in Southern California from the SCEC Community Velocity Model (CVM) archive (Plesch et al., 2021) to create P and S-P VVSPs covering the entire basin at a spacing of 0.00166 degrees in latitude and longitude (less than 200 m). The model is based primarily on gravity (Andersen et al., 2004) combined with empirical density-velocity relations (Brocher, 2005). We are using the VVSPs at these points to update a tomographic model for the SBB that was created for a recent SCEC project. The tomographic update was performed using the simul2017 code (Eberhart-Phillips and Fry, 2017), which is the code used in the SCEC project that produced the starting model.

Representative cross-sections through the initial and inverted models for Vp/Vs are shown in Figure 3. The initial Vp/Vs model is nearly homogeneous, whereas in contrast the inverted model shows a factor of ~2 variation in Vp/Vs. The greatest depth extent of the high Vp/Vs anomaly occurs at about X = 80 km (Figure 3), perfectly consistent with the deepest part of the basin inferred from the gravity model (Figure 4). Thus, the VVSP inversion is performing precisely as desired. The current model result appears somewhat noisy, however, so further work is needed on regularization, model parameterization, and resolution analysis.

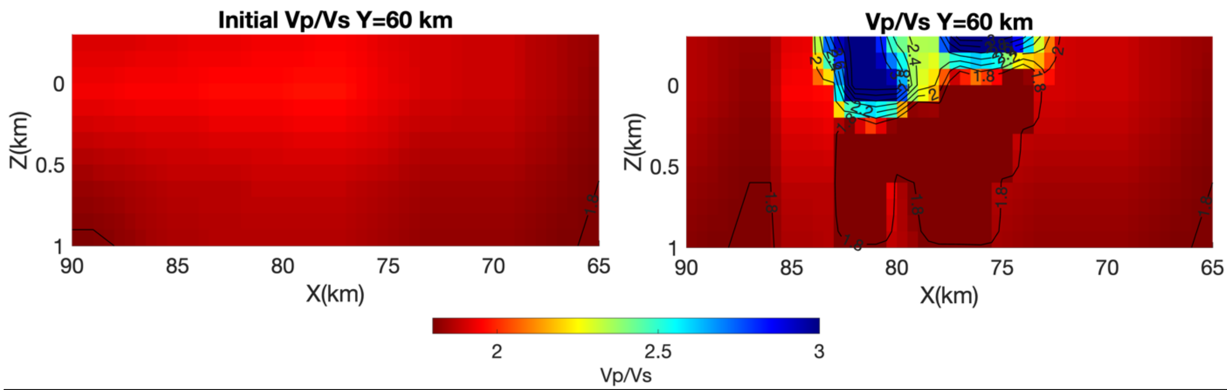

Figure 3. (left) Initial Vp/Vs model and (right) Vp/Vs model obtained by inverting the SBB VVSP data. Cross-sections are at 34.4° N, as marked in the following figure.

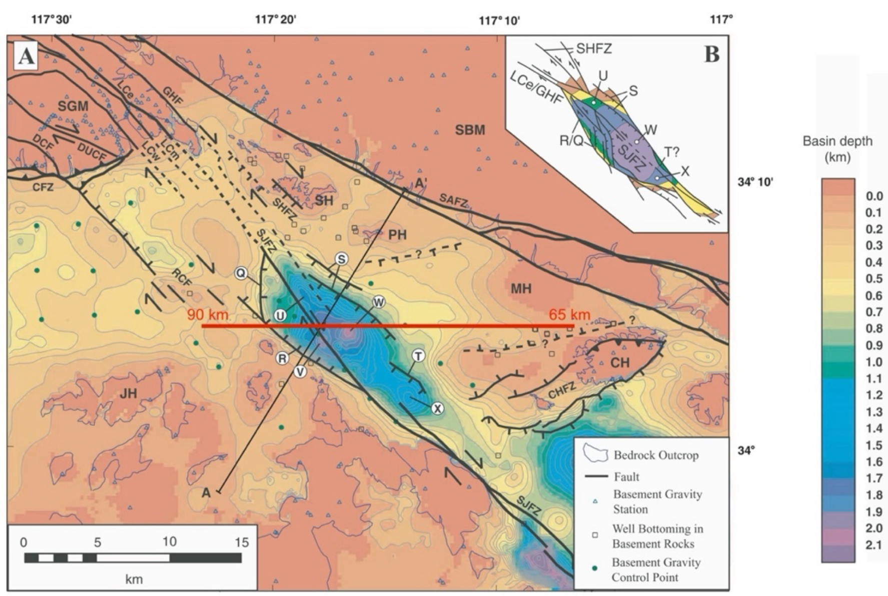

Figure 4. Three-dimensional basin depth inversion from gravity data (Andersen et al., 2004). The deepest part is centered around X = 80 km, consistent with the updated model in Figure 3.

5. Significance of Results

The results shown above demonstrate the potential for improving seismic velocity models using VVSP data. There are many potential sources of VVSP data, and this approach can be applied widely wherever travel-time-based tomography studies (body-wave, surface-wave, or joint body-wave and surface-wave) have been carried out. Although the discussion to this point has emphasized shallow structure and especially basin structure, applications to the deeper Earth are also possible. For example, we have begun to work on the Parkfield region where we will use 1-D receiver function models (Audet, 2015) to add to a body-wave tomography data set (Zeng et al., 2016) to better constrain crustal structure from the surface down to the Moho. Another important contribution the VVSP paradigm can make is to merging velocity models. The idea is that there is a regional velocity model, e.g., SCEC CVM-S or CVM-H, to which improvements are hoped to be made by embedding higher-resolution local models (e.g., Lu and Ben-Zion, 2022). Two major concerns are the introduction of artifacts around the boundary between the regional and local model and the incompatibility of the merged model with the data used to construct the regional model. Abrupt model changes at the boundary can cause unintended wavefield complexities when ground motion simulations are carried out. Replacing original regional model values with the different local model values will certainly mean that the new merged model will not fit the original data as well. Some techniques have been proposed for merging models in a way to avoid wavefield artifacts (Ajala and Persaud, 2021; Zhang and Ben-Zion, 2024), but I am not aware of a study that addresses the problem of incompatibility with the original data. The VVSP paradigm provides an approach that addresses both these concerns. The local model values replace the corresponding regional model values as usual, then comprehensive VVSP data are constructed from the local model for every cell or node of the model, and the heavily weighted VVSP data are then inverted with the original data set. The resulting model should be able to fit the original data equally well, and the dense VVSP data will keep the local model values nearly constant, with most of the perturbations to the local model occurring near its edges where the VVSP constraints will be least strong. Thus, this approach attempts to optimize preservation of the high-resolution local model while conforming to the original data set used to create the original model.

Finally, this SCEC project has served as leverage for the submission of a 2-year proposal to the National Science Foundation Structure and Physics of the Solid Earth program. If funded, that project will allow us to pursue broader applications of the VVSP paradigm, with an emphasis on contributions intended to improve earthquake hazard estimation by improving seismic velocity models.

6. Intellectual Merit

We are developing a new paradigm for adding independent constraints to travel-time-based tomographic inversions. The concept is based on using independently derived seismic velocity models from a variety of possible sources to extract 1-D velocity models beneath many points at the surface (either with or without a seismic station present, depending on the type of source) to create "virtual vertical seismic profiles" (VVSP) of one-way travel times from depth to the surface. These VVSP travel times are then added to tomographic inversions just as other active-source data are included. This strategy has proven successful in two demonstration cases.

7. Broader Impact

Given the broad use of travel-time-based tomographic methods by the scientific and industry communities, our novel paradigm can have very wide applicability. With support from other sources, the VVSP concept will be presented at the April 2026 SSA meeting, freely allowing others to take advantage of this new method. A proposed NSF project extending this work, if funded, will expand the assessment of the applicability of this paradigm to multiple additional scenarios, with an emphasis on contributions intended to improve earthquake hazard estimation by improving seismic velocity models.

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