3-D Velocity Model Building and Numerical Simulations of Basin Resonance: The Los Angeles Basin – 99HQGR0011

Annual Project Summary – 2000

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Program Element 1 SC
Key Words: Wave Propagation, Strong Ground Motion, Neotectonics, Tectonic Structures

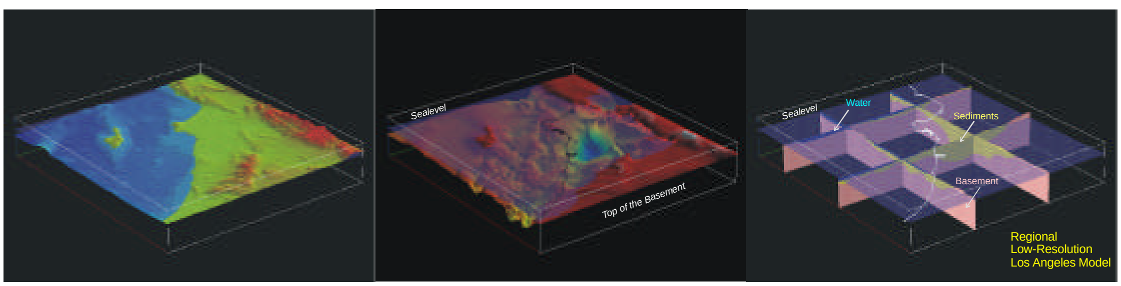
Summary

In the second year of our project, we have refined and extended our detailed 3D velocity models of the Los Angeles basin, which are based on petroleum industry borehole and seismic reflection data. We have also implemented the 3D spectral element method (SEM) on a newly constructed Pentium PC cluster at the California Institute of Technology. Tests were performed of the new version of the SEM program and on the PC cluster, using a representative 1D velocity model and a simplified version of the 3D velocity model. These initial tests confirm that the SEM as implemented accurately reproduces 1D synthetic seismic results from numerical techniques such as discrete wavenumber technique (DWN), and is viable for future use in simulations using realistic 3D velocity models of the Los Angeles basin.

3D Velocity Model Construction

The previous year's efforts included assembly and processing of an industry database of velocity information in the Los Angeles basin, which consists of more than 150 sonic logs and 7000 stacking velocity measurements. Processing of the velocity information included evaluation of various interpolation schemes in the 3D volume analysis program GOCAD. Based on comparisons of these techniques, we settled on a kriging approach to velocity interpolation that involves performing a variance analysis, defining the correlation ellipse, and using the ellipse parameters to guide interpolation. The initial version of the 3D velocity model was derived from stacking velocities using this kriging interpolation process. Comparison of stacking velocities with sonic log velocities showed that stacking velocities systematically overestimate sonic velocities by about 5%. Recent work has involved calibration of stacking-derived velocities to borehole sonic logs to correct for this overprediction. Currently, both calibrated stacking velocities and borehole sonics are being used to interpolate a 3-D sediment velocity volume. A newly compiled basement surface describes the base of this sedimentary layer. A regional basement map was compiled from Blake (1992) and internal studies (C. Rivero, A. Larson, written communication, 2000) covering onshore and offshore areas. Ongoing mapping efforts will help to refine the geometry of the basement surface, which will have major influences on wave propagation and resonance in the numerical simulations.

The model contains three modules with different spatial resolutions, with increasing resolution with decreasing volume. The lowest resolution and largest model is shown in Figure 1. The highest resolution module consists of two vertically deformed regular grids with the interpolated velocity structure. The lowest and medium resolution modules are mainly used to describe geometries, and in these modules a linear velocity function is used to describe velocities in the sedimentary layer. Topographic (GTOPO30) and bathymetric information was used to define the top of the velocity volumes. The surface geology was mapped onto the topographic surface and used to define the outcrop of basement in the model.



Model Surfaces

Figure 1. Construction of the lowest resolution module of the velocity model. The topography, basement surface, and solid representation of the velocity volume are shown from left to right.

The bulk of the industry data lies within the extent of the highest resolution module. The high resolution model is characterized by a heterogeneous, spatially varying velocity gradient with maximum velocities of about 5000 m/s in the sedimentary section. The variability of the observed velocities increases with depth, indicating structural and sedimentological complexity. Stratigraphic surfaces were constructed to assess the velocity characteristics of the model and to derive a method of extending the velocity model beyond the borehole coverage.

Model Extension

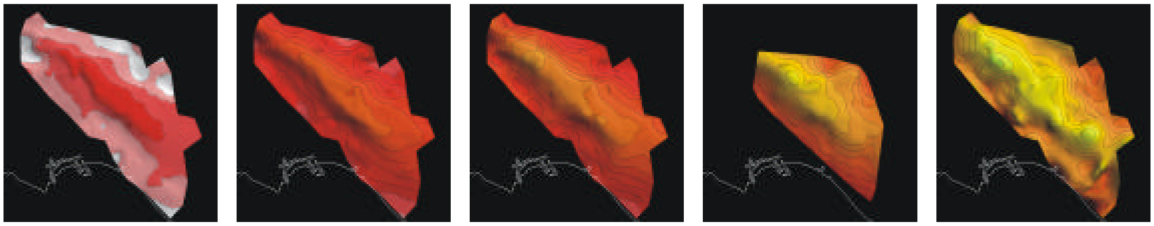


Figure 2. Contour maps (in msec) of the top of the Fernando, Repetto, Delmontian and Luisian Formations and the top of the basement, from left to right.

Our analysis of the stacking and sonic velocities indicated that there are no consistent, basin-wide strong velocity contrasts across these stratigraphic interfaces, and so they do not govern the interpolation of the high-resolution velocity model. Based on the previously calibrated stacking and sonic velocities, high-resolution velocity models were interpolated directly from velocity measurements for the internal parts of the basin (Figure 3). It is useful, however, to assess and characterize the interpolated velocity structure within the stratigraphic framework, because this allows for extrapolation of the velocity structure to areas beyond the borehole and seismic reflection coverages.

To extend the model into regions where no direct velocity measurements are available, a mapping method was developed in offshore areas, by which bathymetric depth, stratigraphic thickness, and total depth were related to measured velocities. A similar approach was adopted onshore, where measured velocities were related to the position of the top of their stratigraphic unit, the stratigraphic thickness of the unit, and the total depth of the measurement. In areas without borehole or stacking velocity measurements, these proxies are mapped and the derived empirical relations are used to extrapolate velocities from the calculated model. Comparisons in test areas where borehole and reflection data were present, but were omitted from the initial interpolation, show that there is reasonably small variation between predicted and observed velocity values. Refinement of this technique is still underway.

The surfaces representing stratigraphic interfaces in the medium and low resolution models were each interpolated separately from surface geology and well tops. This allows for flexible parameterization of the model for use in simulations. In future work, comparison of synthetic simulations of those earthquakes will be used to make adjustments to the geometry and velocities in the model, and so flexibility in making changes to interfaces in the model is desirable. Unrealistic instantaneous steps in velocity can be avoided by interpolating along major geologic trends and honoring the basement surface as the major velocity interface in the basin.

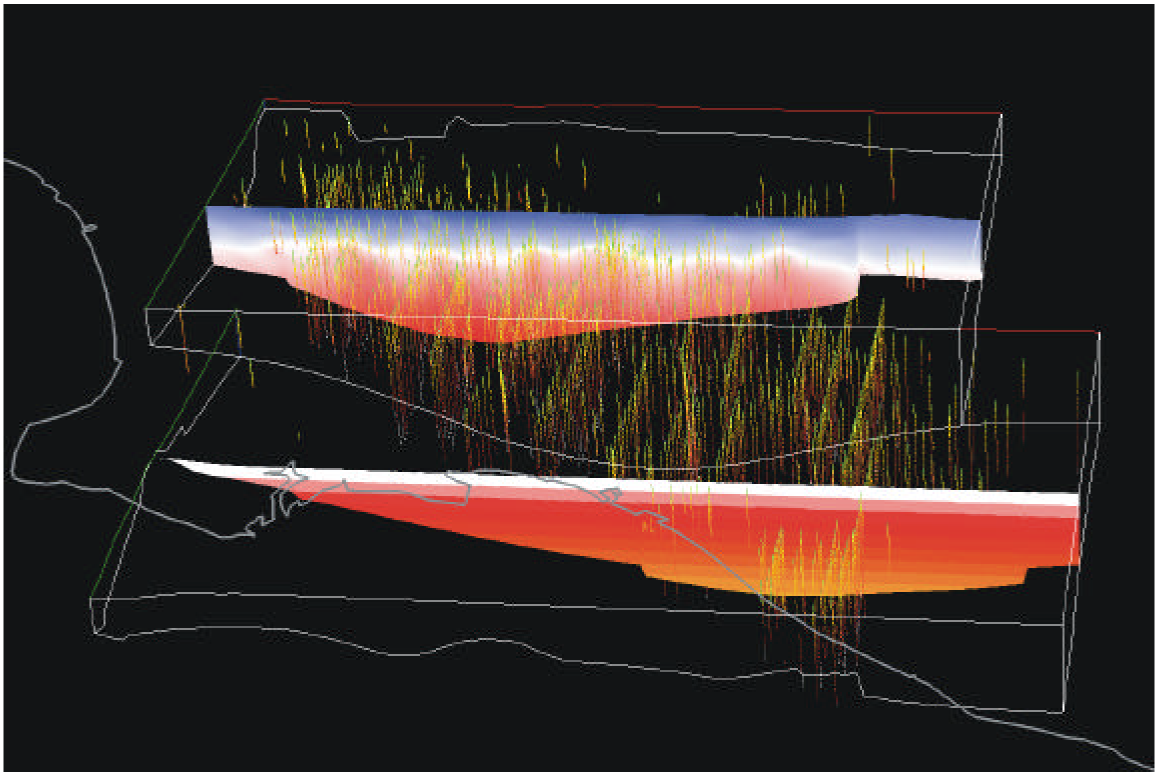


Figure 3. Extent of the two highest resolution modules. The stacking velocities used to interpolate velocities across the model are shown at every location. The northern cross section shows velocity with depth across the basin, and the southern cross section shows the depth extent of the basin.

3D Modeling of Earthquake Generated Waves

The spectral element method (SEM) derived by Komatitsch (see Komatitsch and Tromp, 1999 for details) combines the flexibility of a finite-element method with the accuracy of a spectral method. It has many advantages over more commonly used finite-difference methods. These include the incorporation of free-surface topography, which is crucial in accurate representation of surface waves; inclusion of a fluid-solid interface, important in offshore regions and in global calculations for the core-mantle and inner core boundaries; incorporation of attenuation, by means of inclusion of a series of memory variables representing standard linear solids which mimic an absorption band solid as attenuation; and anisotropy, which may be an effect in the lower crust under southern California.

The SEM has been tested previously with global simulations and 1D velocity models on a regional scale. However, due to the changes in SEM implementation required for installation on the 156 processor Pentium PC cluster Beowulf at Cal Tech and the combination of the global and basin-scale versions of the code, further 1D velocity model testing was considered appropriate. To this end a simulation using a variation of the SoCal 1D velocity model (Dreger and Helmberger, 1990) was conducted. A 500m thick sedimentary layer was added at the surface, to make the simulation more comparable in velocity variation and frequency content to future simulations. The velocity model is shown in Figure 4.

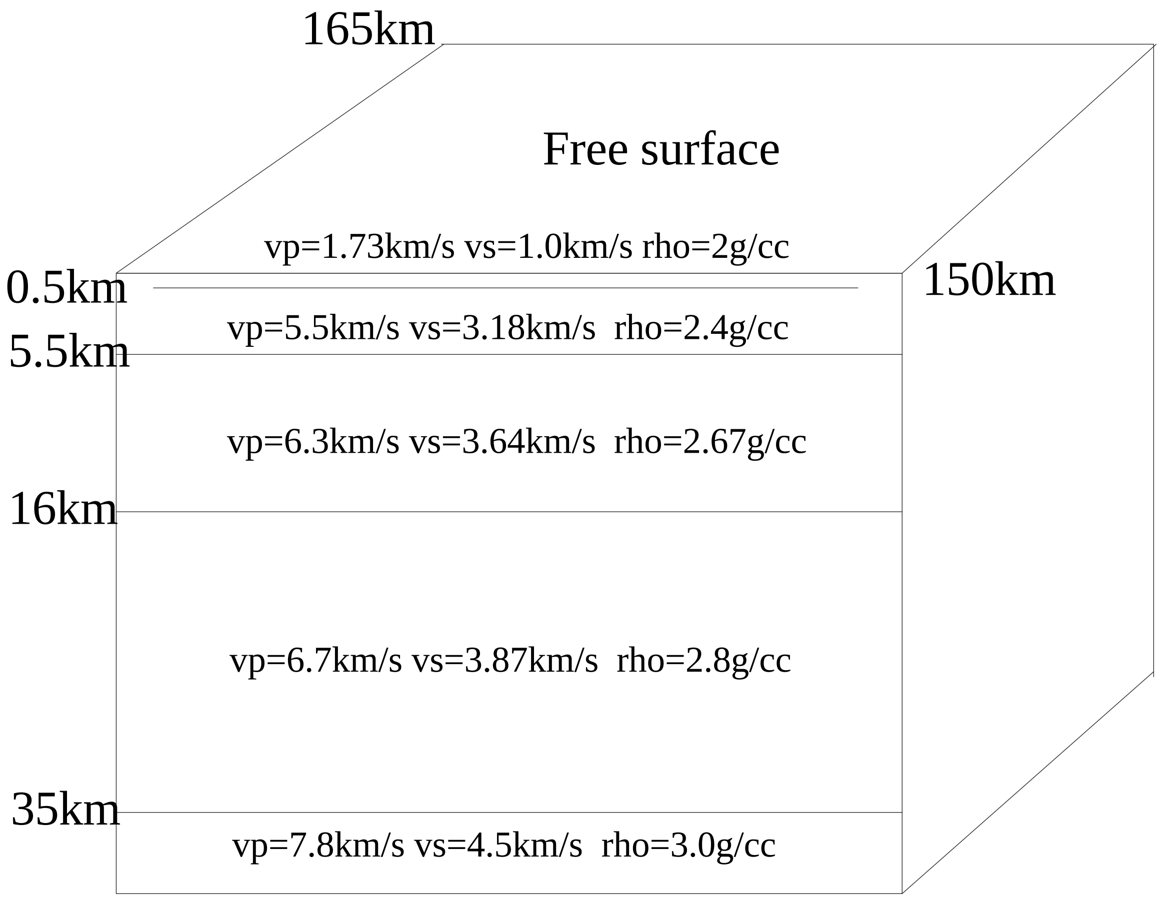
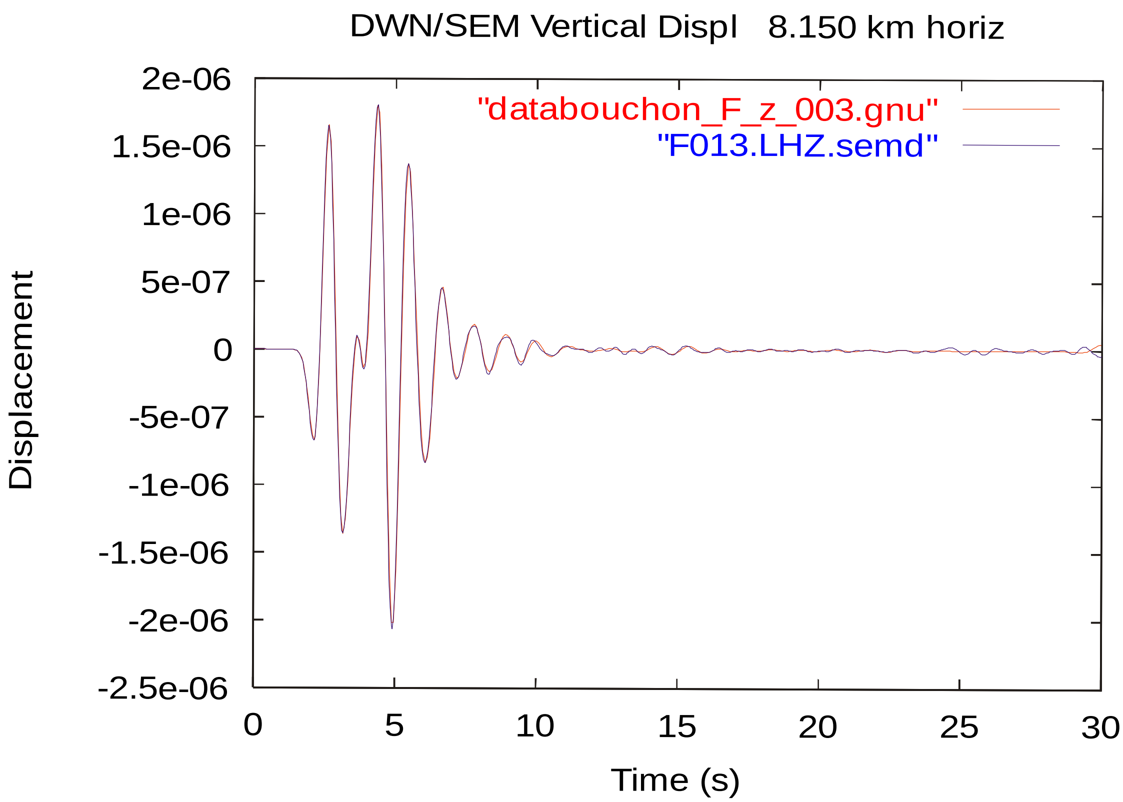


Figure 4. 1D velocity model used in initial SEM PC cluster simulation.

The lowest vs of 1 km/s allows us to use a element size of 667 m with 5 points per element, and 240 elements in each direction. The simulation uses a vertical force located at a depth of 11.5 km, in the upper crustal layer. The time variation of the source is a Ricker wavelet with a central and maximum frequencies of 0.8 and 2 Hz, respectively. The simulation uses a time step of 6 milliseconds, which with further optimization of the mesh could be much higher, and using 150 processors we are able to simulate 144 seconds of wave propagation in 4.5 hours. The results are compared to DWN results in Figure 5 and the agreement is quite good.



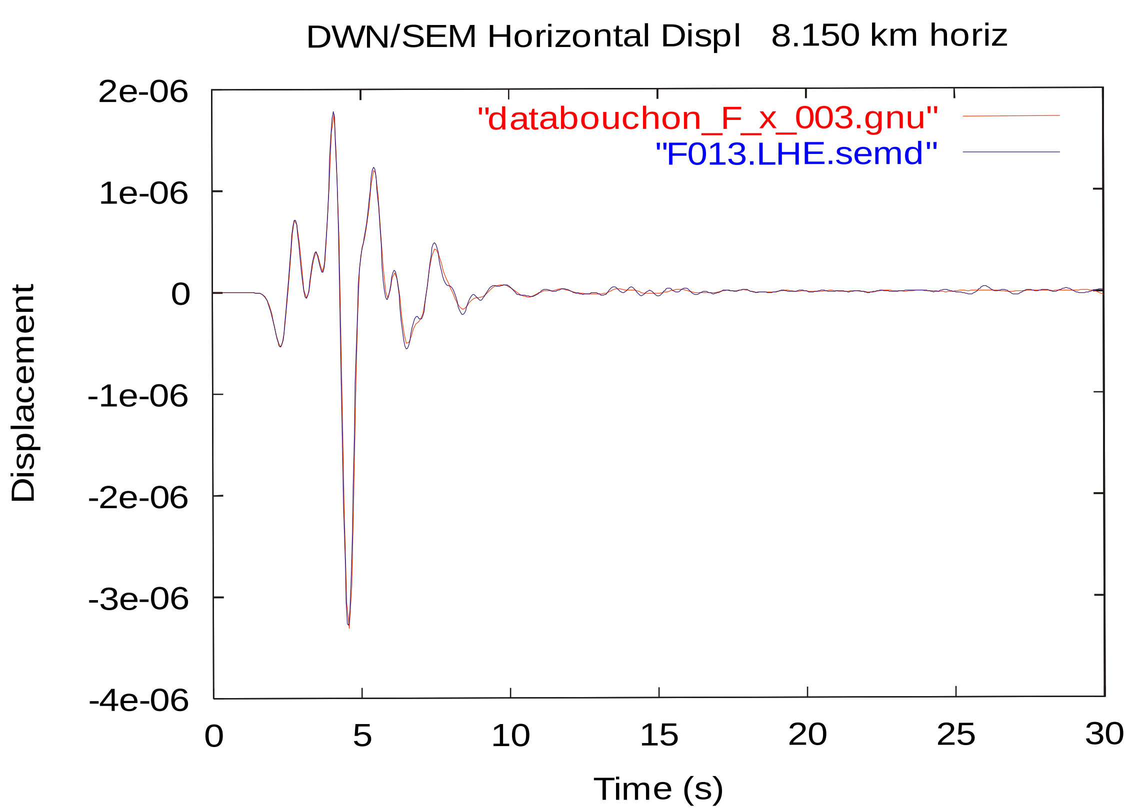


Figure 5. Vertical and horizontal displacements for the SEM and DWN

calculations using a representative 1D velocity model. Both are 8.15 km laterally from the source.

Further refinement of the boundary conditions should result in even better agreement to the DWN results at the later time steps. Current work involves the implementation of PML absorbing conditions in the SEM, which should provide a marked improvement over result using Clayton and Engquist boundary conditions. Current work also involves the conversion of the velocity model surfaces (topography and basement top) into the element mesh used by the SEM, for initial simulations using the 3D velocity model. Initial simulations will use a January 1998 M 4.3 event that occurred under the Los Angeles basin, in order to avoid inclusion of source complexity. This should allow for more accurate iterative improvements to the velocity model, before simulations of more important events such as 1987 Whittier Narrows and 1994 Northridge.

Publications

Komatitsch, D., and Tromp, J., 1999. Introduction to the spectral element method for three-dimensional seismic wave propagation, Geophys. J. Int., 139, 3, 806-822.

Komatitsch, D., Barnes, C., and Tromp, J., 2000. Wave propagation near a fluid-solid interface: A spectral element approach, Geophysics, 65, 2, 623-631.

Online resources

Research summaries

http://www.seismology.harvard.edu/projects/waveprop/wavepropag.html

http://tectonics.harvard.edu/SGAT.html

Data Repository

http://structure.harvard.edu/SCEC/scec.html

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Non-Technical Project Summary – 2000

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Komatitsch's SEM is one of the most recent methods for computer simulation of earthquakes and improves the accuracy with which we can predict where maximum ground shaking will occur in an earthquake. With an improved velocity model of the Los Angeles basin, based on oil industry measurements, we have the ability to improve our understanding of the greatest damage risks in the Los Angeles area. At this stage our work concentrates on testing of SEM and development of the model; future work will involve simulations of recorded earthquakes (small events and significant events such as 1987 Whittier Narrows and 1994 Northridge) and simulations of hypothetical large earthquakes (such as M7.5 on the San Andreas Fault.)