3D velocity-density modeling and strong ground motion prediction in the Los Angeles basin: Collaborative research with Caltech and Harvard University 02HQGR0035

Annual Project Summary – 2002

John H. Shaw, Christiane Stidham
Department of Earth and Planetary Sciences, Harvard University
20 Oxford Street, Cambridge, MA 02138
Tel. (617) 495-2351; Fax (617) 496-0434;
shaw@eps.harvard.edu/stidham@rupture.harvard.edu

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

Summary

In this project, we have constructed a density model of the Los Angeles basin, with the same resolution as the earlier constructed velocity model (NEHRP 99HQGR0011; Suess and Shaw, 2002, JGR, in press), and based on more than 300 petroleum industry density logs. Preliminary versions of the density model incorporated information from bulk density logs at almost 200 wells; the most recent version of the density model is based on the initial 200 wells and density porosity logs from an additional 100 wells. Twenty-five of the density logs came from wells for which we also had access to sonic velocity logs; this allowed for derivation of the relationship between density and velocity for the Los Angeles basin. This relationship can be used to define density in areas beyond the central basin, where we have velocity information but no density logs. The density model was constructed using the statistical interpolation method kriging, in the 3D modeling program GOCAD. Both density and seismic velocity structure are necessary in any method of simulation of wave propagation; previous work in simulations used density models derived from the seismic velocity models used and theoretical relationships between density and velocity. This model represents a representation of density structure based on independent data that can be used in conjunction with velocity structure in earthquake simulation efforts.

Introduction

This year's efforts included assembly and processing of an industry database of density information in the Los Angeles basin, which consists of more than 300 bulk density and density porosity logs. Processing of the density information included scanning and digitization of all logs and combining of multiple log records from single wells. Interpolation of the well density data into a 3D density volume relied on previous evaluation of various interpolation schemes in the 3D volume analysis program GOCAD. As with construction of the velocity volume, we used a kriging approach to data interpolation that involves performing a variance analysis, defining the correlation ellipse, and using the ellipse parameters to guide interpolation. The density data are used to fill in the sedimentary volume of the Los Angeles basin, as defined by the topography and the sediment/basement interface; both these surfaces are the same surfaces used in constructing the velocity model. A newly compiled basement surface describes the base of the sedimentary layer (shown partially in Figure 1), and extends now farther north than in previous versions of the models, to include the San Fernando Valley basin. 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, and the subsurface basement interface was defined on the basis on previous oil industry studies and recent work with seismic reflection lines in the area.

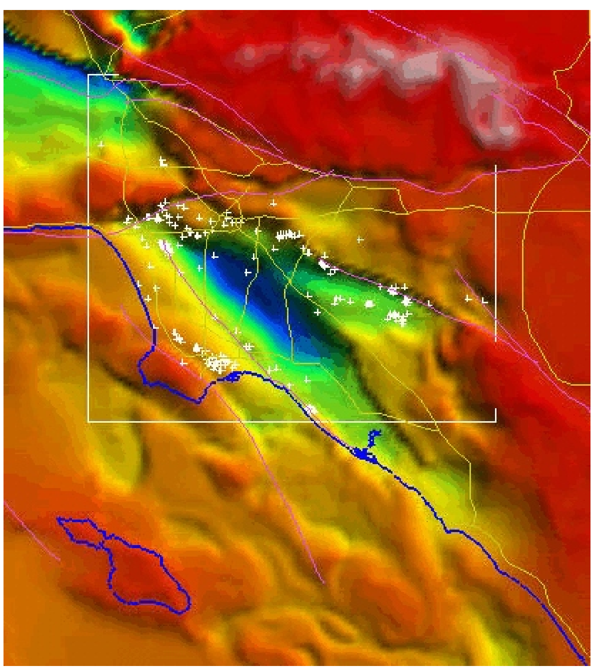

Figure 1. Construction of the density model. The basement surface is shown with depth corresponding to color (white=+2km; blue=-8km), and is the same surface used in construction of

the velocity model. The white crosses indicate locations of wells with density logs used in the density model, and the extent of the density model is indicated by the white rectangle.

The previously constructed velocity model contains modules with different spatial resolutions, with increasing resolution with decreasing volume. This construction was chosen because decreasing amounts of velocity information are available with increasing distance from the center of the basin. The density data, however, are fairly tightly clustered around the central Los Angeles basin, as shown in Figure 1, so the benefits of varying resolution models are eliminated; thus only one resolution density model was produced. The density model uses the same resolution as the final version of the velocity model, 1 km horizontally and 200m vertically. A representative depth-density relationship has been derived for the basin, and with 25 wells where both velocity and density logs were recorded, a depth-velocity relationship for the basin has also been derived. Both relationships from this region can be used to derive density models beyond this central model.

Data analysis

The density model is characterized by a heterogeneous, spatially varying density gradient with a range in densities from about 1.5 to 3.0 g/cm^3 in the sedimentary section. The bulk density in all the wells (313, including those with and without coincident sonic logs) has a mean value of 2.27 g/cm^3 (standard deviation 0.13 g/cm^3). In most of the wells, density increases fairly linearly with depth. The correlation coefficient between depth and density was found to be statistically significant (with less than a 5% probability of generating that correlation coefficient randomly with uncorrelated values) in 241 of the 313 wells, and the average of the statistically significant correlation coefficients between depth and density was -0.5. This indicates a moderate correlation of density to depth.

In analysis of the density data, one of our goals is to determine relationships of density to other parameters that can be used in areas where density is not known. The simplest correlations are of density to depth or velocity. Because our study area is confined to a sedimentary basin with relatively low densities and velocities, we expect slightly better correlations of density to depth and velocity than in most areas. However because density varies so little in the upper crust (usually about 2 to 3 g/cm^3), we should not expect exceptionally good correlation to either, but density should correlate better to velocity than to depth. We have density logs from 25 wells where we also have sonic velocity logs; figure 3 compares density and v_p in these wells. The bulk density varies from about 1.6 to 2.9 g/cm^3, with a mean of 2.3 g/cm^3 (standard deviation 0.11 g/cm^3).

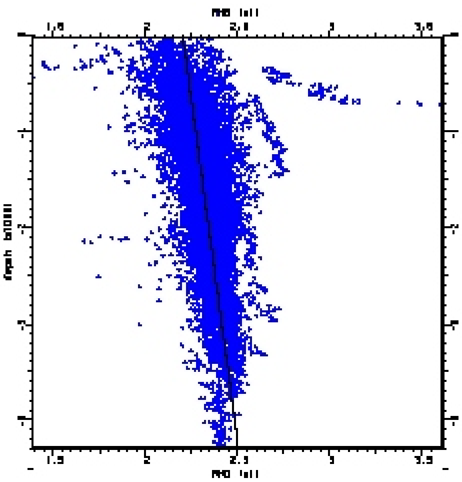

Figure 2. Relationship of density to depth in all 313 wells.

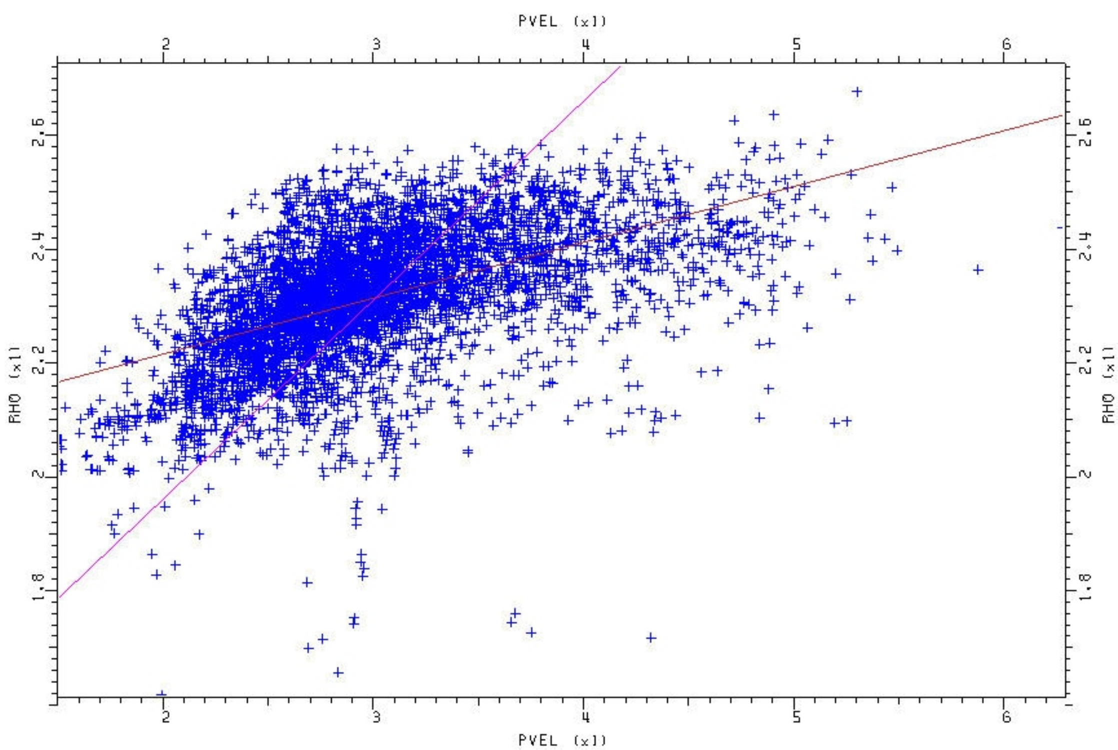

Figure 3. The distribution of density vs. sonic velocity for the 25 wells where both data exist is shown. Density is rho, in g/cm^3, and velocity is pvel, in km/s. The purple line is the rho on pvel regression and the red line is the pvel on rho regression.

The variation in correlation coefficients between density and velocity at the different wells is considerable: from -0.185 to -0.645, with a negative correlation, and from 0.0104 to 0.935, with a positive correlation. The average of the correlation coefficients for all 25 wells is 0.557. When three wells without statistically significant correlation between velocity and density are discounted, the extreme correlation coefficients are removed, and the range shrinks to only one negative correlation coefficient, -0.645, and positive correlation coefficients from 0.277 to 0.935. Of the remaining 22 wells, 14 have correlation coefficients between 0.7 and 0.9; the average of the correlation coefficients for the 22 wells is 0.63, with a standard deviation of 0.26. This reasonably good correlation of density to velocity means that velocity can be used as a proxy for density.

For both data sets (all 25 wells and the 22 statistically correlated wells) two types of average correlation coefficients are given: AVG, the mean of the individual wells' correlation coefficients, and ALL, the correlation coefficient of all the points in the listed wells, grouped together as one data set. In both cases, the correlation coefficient for ALL is lower than for AVG, since ALL measures the correlation of density values from one well to velocity values from other wells, and vice versa.

Well	# samples	Correlation coefficient	Regression: vp on rho slope	intercept	Regression: rho on vp slope	Intercept
ARSJ14	152	0.878	4.66669	-7.97447	0.165107	1.83847
ARSJ16	85	0.801	3.54559	-5.46117	0.181155	1.78382
ARSJ20	67	0.713	2.45859	-2.97972	0.206576	1.72447
ARSJ5	97	0.814	4.71694	-8.16517	0.140472	1.93683
ARSJ8	158	0.78	4.36955	-7.17901	0.139243	1.89255
CSRC1	409	0.861	5.18534	-8.48909	0.14292	1.81939
CUCL116	269	0.845	3.11977	-4.45997	0.228843	1.65615
OPWA1	196	0.568	4.42518	-7.28303	0.072896	2.11212
SOCHA1	299	0.756	2.4188	-2.90443	0.236573	1.65713
SOF1	497	0.508	2.33569	-2.27051	0.110601	1.98274
SOFRI1	363	0.714	4.5207	-7.61312	0.112628	2.01947
SOG4a	140	0.386	1.35199	0.559279	0.110029	2.00134
SOLO1	365	0.827	2.52065	-3.06595	0.271533	1.53698
SONT1	165	0.935	3.70738	-5.51629	0.235894	1.57357
SOP6	339	0.736	6.35635	-11.8333	0.085292	2.07951
SOSH278	230	0.688	4.57614	-7.35328	0.103447	2.07441
SOVC1	170	0.735	3.16465	-4.56977	0.170702	1.82611
SOWHI1	368	0.277	1.66618	-0.627443	0.046073	2.14311
SOYC1	210	0.779	2.63699	-3.14553	0.23018	1.59601
THCH1	12	-0.645	-1.7257	6.31343	-0.24086	2.87125
UOMG88	110	0.308	1.04862	0.900016	0.090471	2.05217
UOUSP1	175	0.552	2.28342	-1.93052	0.133607	1.93755
ARSJ11	215	-0.0464	-0.28645	3.43017	-0.00752	2.33056
ARWA1	101	0.0918	0.335602	1.93515	0.025085	1.99909
CCT2	92	0.0105	0.022037	3.65602	0.004966	2.42144
AVG 25		0.557				
ALL 25	6829	0.501	2.6274	-3.05645	0.095621	2.02173
AVG 22		0.63				
ALL 22	5531	0.53	2.85108	-3.59412	0.098426	2.02

Table 1: Coincident sonic velocity and density logs.

In Table 1, the statistics for the 25 wells with both velocity and density logs are shown. The # samples refers to the number of points (with 10m depth spacing) where both velocity and density information is available, and the correlation coefficient between velocity and density for those points is given for each well. The equations for both regressions are shown. The first 22 wells listed have statistically significant correlation between velocity and density for the number of data points available; the last three wells listed have statistically insignificant correlation (greater than 5% probability of generating that correlation coefficient randomly with uncorrelated values.)

Model construction

Inherent in any attempt to model the earth is the problem of how to fill in areas where data do not exist. The first step in reducing this problem is constraining the volume to be modeled to that where the bulk of the data is located. The dimensions of the initial density model and the locations of the wells used are shown in Figure 1. The volume to be filled in is also constrained by the surface defining the top of the basement and by the surface of the earth.

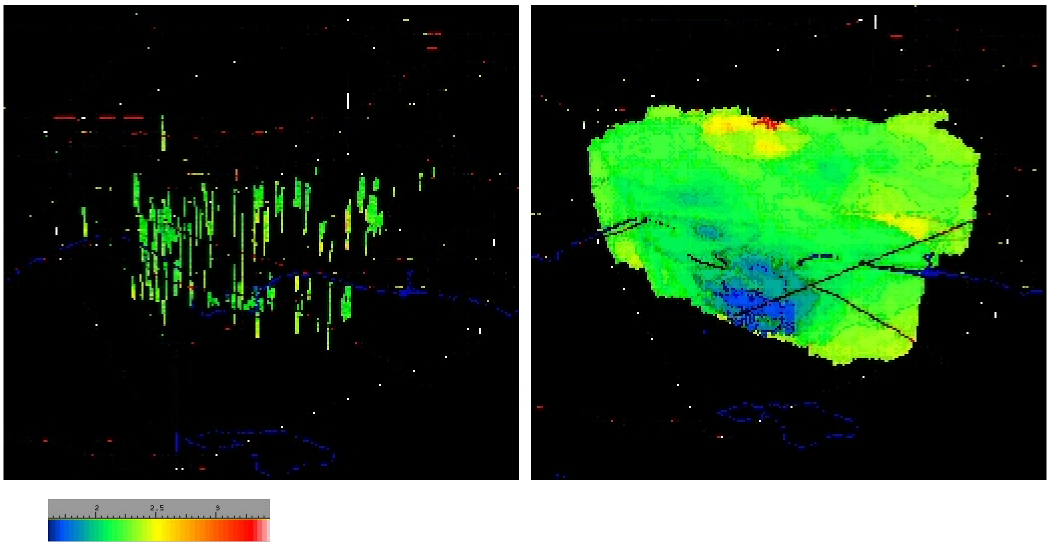

Figure 4. The figure on the left shows the distribution of wells with density information, with density shown in g/cm^3 according to the color scale. The bounding box of the density model is also shown. On the right, the volume to be filled in is shown (within the bounding box but constrained by the surface of the earth and top of the basement), with the exterior shaded by modeled density values, according to the same color scale.

Kriging is a commonly used statistical technique in model construction where interpolation of data values are necessary. Variograms that best fit the trends in the data in the vertical and horizontal directions are chosen, and the 3D modeling program GOCAD uses these variograms to prescribe density values throughout the rest of the model. With the kriging technique, scatter in the points used to define the variogram can lead to some uncertainty as to the best fitting variogram function but comparison of models derived using slightly different variograms indicated only slight differences in the calculated densities. Additional work will eliminate artifacts of the kriging technique, such as the artificially low velocities seen in the extreme southwest corner of the model at some depths. Alternate kriging techniques (such as kriging with trend, kriging with drift, and collocated co-kriging using velocity information and our velocity-density relationship) were tested but yielded no appreciable improvement in the derived density model.

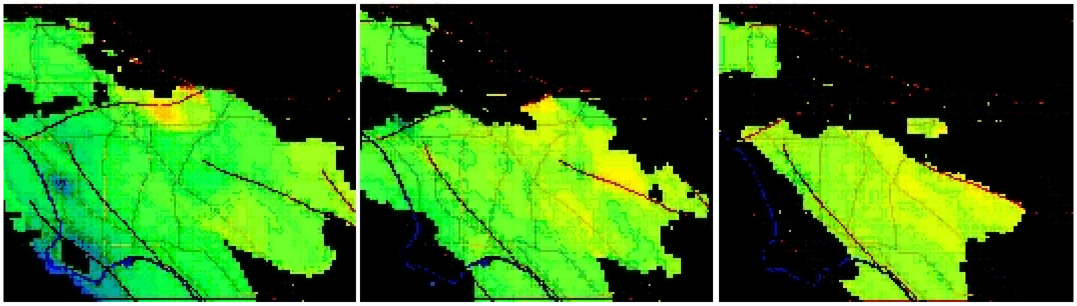

Figure 5. Depth slices of the density model at 200m, 1600m and 3000m below sea level. The density values are according to the same color scale used in Figure 4.

Figure 6. Cross sections of the density model, with bounding box shown and density according to the same color scale used in Figure 4.

The derived density model is shown in Figures 5 and 6. It is immediately apparent that the interpolation eliminates the possibility of any sharp contrasts but retains steep gradients. The bulk of the model has density values between 2 and 3 g/cm^3, as expected, but a few areas of the model are artificially influenced by a few very low or very high data points; methods such as kriging are susceptible to artifacts such as these at the edges of interpolated volumes.

Ongoing work continues to refine the density model. In addition to removing artifacts at the edges of the model, future work will establish a transitional zone to background densities, derived from the larger velocity model and from regional tomography models. A later version of the density model will also make values available at a higher resolution, 500m horizontally and 200m vertically. Gravity calculations and comparison of the gravity signal from the density model to recorded gravity data will allow for validation of the model, and if necessary, adjustments to the transition zone surrounding the model.

Publications

Stidham, C., M. P. Suess, J. H. Shaw, A New Density Model and Analysis of the Los Angeles Basin based on Oil Industry Data, 2002, in preparation.

Stidham, C., M. P. Suess, J. H. Shaw, D. Komatitsch and J. Tromp, 3D Velocity

and Density model of the LA Basin and Spectral Element Method Earthquake Simulations, 2001. SCEC Conference.
Stidham, C., M. P. Suess and J. H. Shaw, 3D Density and Velocity Model of the Los Angeles Basin, 2001. GSA Fall Conference.

Stidham, C., M. P. Suess, J. H. Shaw, D. Komatitsch and J. Tromp, 3D Velocity and Density Model of the LA Basin and Spectral Element Method Earthquake Simulations, 2001. AGU Fall Conference.

Online resources
Research summaries
http://www.seismology.harvard.edu/projects/waveprop/wavepropag.html
http://sger5.harvard.edu
Data Repository
http://structure.harvard.edu/SCEC/scec.html

3D velocity-density modeling and strong ground motion prediction in the Los Angeles basin: Collaborative research with Harvard University and CalTech 02HQGR0011

Non-Technical Project Summary – 2002

John H. Shaw, Christiane Stidham
Department of Earth and Planetary Sciences, Harvard University
20 Oxford Street, Cambridge, MA 02138
Tel. (617) 495-2351; Fax (617) 496-0434;
shaw@eps.harvard.edu/stidham@rupture.harvard.edu

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

This research presents a first attempt at construction of a density model for a sedimentary basin using only measured data points, rather than theoretical relationships to other parameters. The Los Angeles basin has been explored by the oil industry for the past several decades and thus a wealth of information exists for the area. This information includes several hundred wells where logs were made of the density of the surrounding rocks. Digitization of these logs and interpolation of the data from the logs yields a 3D model of the density of the Los Angeles basin. Analysis of the density data also allows us to derive relationships between density and depth, and between density and seismic velocity for the basin, relationships that can be used to derive density models in other areas without as much density data. The 3D density model can be used in conjunction with previously derived velocity models of the Los Angeles basin in computer simulations of earthquake wave propagation, which can be used to predict areas of intensified ground shaking in future earthquakes.