An Overview of the Project of Next Generation of Ground Motion Attenuation Models for Shallow Crustal Earthquakes in Active Tectonic Regions

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ABSTRACT

The "Next Generation of Ground Motion Attenuation Models" (NGA) project is a partnered research program conducted by Pacific Earthquake Engineering Research Center-Lifelines Program (PEER-LL), U.S. Geological Survey (USGS), and Southern California Earthquake Center (SCEC). The project has the objective of developing updated ground motion attenuation relationships through a comprehensive and highly interactive research program. Five sets of updated attenuation relationships are developed by teams working independently but interacting throughout the development process. The main technical issues being addressed by the NGA teams include magnitude scaling at close-in distances, directivity effects, polarization of near-field motion (fault-strike-normal component vs. fault-strike-parallel component), nonlinear amplification by shallow soil, and sedimentary basin amplification. The attenuation relationships development is also facilitated by the development of an updated and expanded database of recorded ground motions; conduct of supporting research projects to provide constraints on the selected functional forms of the attenuation relationships; and a program of interactions throughout the development process to provide input and reviews from both the scientific research community and the engineering user community. An overview of the NGA project components, process, and products developed by the project is presented in this paper.

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INTRODUCTION

The objective of the “Next Generation of Ground Motion Attenuation Models” (NGA) project is to develop updated ground motion attenuation relationships for shallow crustal earthquakes in the western U.S. through a comprehensive and highly interactive research program that involves the following components: (1) development of separate sets of attenuation relationships by five teams (the “Developers”); (2) development of an updated and expanded PEER ground motion database to provide the recorded ground motion data and the supporting metadata on the causative earthquakes, source-to-site travel paths, and local site conditions needed by the Developers for their empirical regression analyses; (3) a number of supporting research projects, including theoretical simulations of rock motions, soil site response, and basin response, to provide an improved scientific basis for evaluating the functional forms of and constraints on the attenuation relationships; and (4) a series of workshops, working group meetings, Developer meetings, and external review that provides input into and review of the project results by both the scientific research community and the engineering user community. These project components are described in subsequent sections of the paper.

The NGA Project is being jointly conducted by the Lifelines Program of the Pacific Earthquake Engineering Research Center (PEER-LL), the U.S. Geological Survey (USGS), and the Southern California Earthquake Center (SCEC). This collaboration framework provides a unique opportunity for the community of strong-motion seismologists and geotechnical engineers to work together and make a significant step forward in the prediction of strong-ground motions for shallow crustal earthquakes in active tectonic regions.

ATTENUATION RELATIONSHIP DEVELOPMENT

Developers of five pre-existing and widely used attenuation relationships are participating in the concurrent development of NGA relationships. The Developers are listed below with references to their pre-existing attenuation models shown in parentheses:

- Norman Abrahamson and Walter Silva (Abrahamson and Silva, 1997).
- David Boore and Gail Atkinson (Boore, et al., 1997).
- Kenneth Campbell and Yousef Bozorgnia (Campbell, 1997; Campbell and Bozorgnia, 2003).
- Brian Chiou and Robert Youngs, representing the model of Sadigh et al. (Sadigh, et al., 1993; 1997).
- I.M. Idriss (Idriss, 1991).

To meet the needs of earthquake engineering design practice, all NGA models are required to be applicable to:

- Ground motion parameters of peak ground acceleration and velocity (PGA, PGV), and 5%-damped elastic response spectral accelerations in the period range of 0 seconds (PGA) to 10 seconds.
- Average horizontal motion, as well as motion in the fault-strike-normal and fault-strike-parallel directions.

- Shallow crustal earthquakes (strike slip, reverse, and normal earthquakes) in the western U.S.
- Moment magnitude range of 5 to 8.5.
- Distance range of 0 to 200 km.
- Commonly used site classification schemes, including the NEHRP classification scheme.

The following are the main technical issues being addressed in the NGA relationship development and in the supporting research.

- Considerations of the following effects on ground motions:
  - Rupture directivity
  - Polarization of near-field motion (fault-strike-normal component vs. fault-strike-parallel component)
  - Footwall vs. hanging wall for dipping faults
  - Style of faulting (strike-slip, reverse, normal)
  - Depth to faulting (e.g., buried vs. surface rupture)
  - Static stress drop (or rupture area)
  - Site amplification effects relative to a reference "rock" condition
  - 3-D sedimentary basin amplification (depth to basement rock)
- Considerations of the following features in the statistical analysis of data:
  - Uncertainties in predictor variables (e.g. uncertainty in the magnitude of an earthquake)
  - Missing values of predictor variables (e.g. the NEHRP category of a recording site)
  - Dependencies of standard errors on magnitude, distance, and soil type

DATABASE DEVELOPMENT

To provide a common database of recorded ground motions and supporting metadata for the Developers, the NGA project conducted an extensive update and expansion of the PEER database. Each Developer team is required to use the database developed during the NGA project as the source of ground motion data and supporting information (metadata) on the causative earthquakes, source-to-site travel path, and local site conditions of the recording stations. However, the Developers select their own data sets to use in regression analyses from within the common database.

Fig. 1 shows the magnitude (M) – distance (R) distribution of the new earthquake data that have been added to the PEER database superimposed on the pre-existing data. The new earthquakes include the 1999 Hector Mine earthquake in California, the 1999 Kocaeli and Duzce events in Turkey, the 1999 Chi-Chi earthquake and five major aftershocks from Taiwan, several well-recorded moderate events in California, the 2003 Nenana Mountain and Denali earthquakes in Alaska, and several earthquakes from extensional tectonic regimes. The expanded data set includes 173 earthquakes, 1400 recording stations, and about 3500 multi-component recordings.

A process was undertaken to evaluate the techniques used in processing the recorded data with respect to the accuracy of the peak parameters and response spectral values of the processed data.

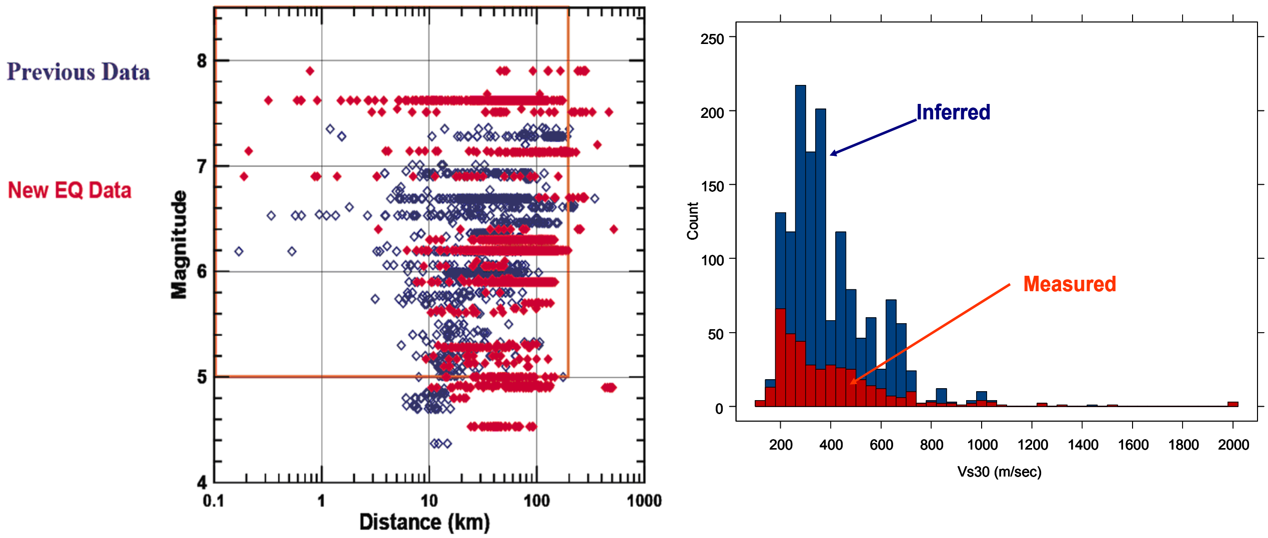

Figure 1. (Left). Magnitude and distance distribution of recorded ground motion data in previous PEER database and data added for NGA project ; (Right). Histogram of Vs30 values at the recording staiotns.

The useable frequency range for each record has also been evaluated. All records have been rotated to fault-strike-normal (FN) and fault-strike-parallel directions (FP) so that attenuation relationships can be developed for each as well as for the average horizontal component. A method was developed and implemented for records in the data set that uniquely defines the average horizontal component independent of the orientation of the horizontal components (Boore et al., 2006).

An extensive effort has been made to compile, evaluate, and extend the metadata on earthquake sources, travel paths, and local site recording conditions. A few of the significant accomplishments include: characterizations of site conditions of recording stations using different parameters and classification systems, such as Vs30 (average shear wave velocity to 30 meter depth), NEHRP classification, surface geology classification, and Geomatrix classification; estimation via correlations of Vs30 values at stations not having measured Vs30 values (Fig.1b shows about 30% of the recording stations have measured Vs30); systematic and consistent evaluation of earthquake magnitudes, type of faulting, fault rupture geometry, classification of stations for hanging wall and footwall conditions, rupture directivity parameters using both Somerville et al. (1997) and Spudich et al. (2004) parameterizations, source-to-site distances using different distance measures; and depth to earthquake rupture.

The strong-motion data and supporting metadata are now available for public use at PEER's web site **http://peer.berkeley.edu/nga/**. For easy access of the entire dataset, a flatfile, along with documentation of each data column, is also available at the same web site.

SUPPORTING RESEARCH

Supporting research has been carried out by the project partners, PEER-LL, USGS, and SCEC, to provide an improved scientific basis for evaluating the functional forms and constraints for NGA relationships. This research includes: simulations of rock motions; simulations of shallow site response; simulations of 3-dimenional basin response amplification of ground motion; development

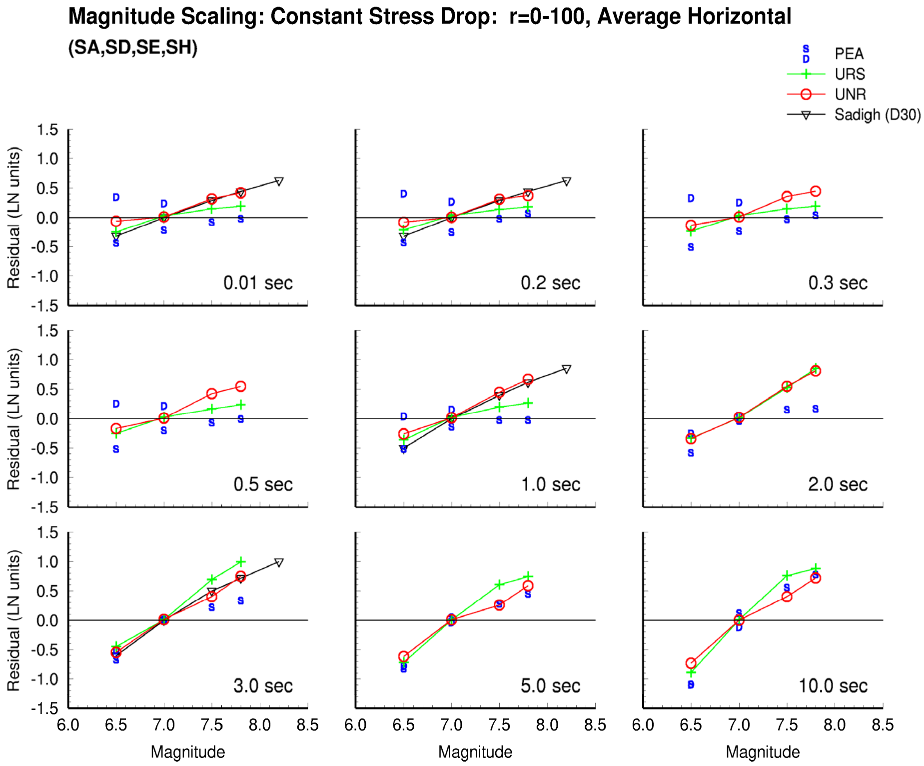

Figure 2. Magnitude scaling of spectral acceleration for strike-slip earthquakes from 1D rock motion simulations using constant stress drop model, normalized at M7 (Somerville et al., 2006).

of a new formulation for directivity using the isochrone theory; and others. Brief descriptions of the listed studies are given below.

Simulations of Rock Motions

Simulations of rock motions were carried out by three groups to provide theoretical guidance to the NGA Developers on the scaling of ground motion response spectra with magnitude, distance, and rupture area, and on effects of rupture directivity, hanging wall vs. foot wall, and buried vs. shallow faulting. The simulation procedures by URS Corporation (URS), Pacific Engineering and Analysis (PEA), and University of Nevada, Reno (UNR) are described by Graves and Pitarka (2004), Silva et al. (2002), and Zeng and Anderson (1994) and Zeng (2002), respectively. The three sets of results are compared and discussed by Somerville, et al. (2006). The simulations provided some constraints on the scaling of ground motions with various source parameters, but differences among the simulations were significant in some cases (Somerville, et al., 2006). An example of results obtained by the three groups—effects of magnitude on response spectral values at several periods normalized to values for magnitude 7 is shown in Fig. 2. The magnitude scaling shown in Fig. 2 is for constant stress drop, and results for another source model are also given in Somerville et al. (2006).

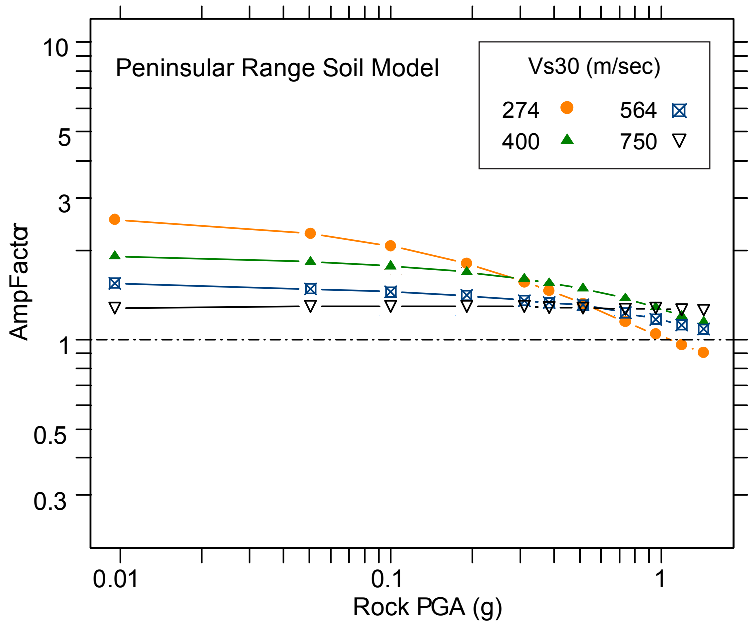

Figure 3. Amplifications of peak ground acceleration (PGA) from site response simulations using Peninsular Range soil model (Silva, 2005; Silva et al.; 1999, 2000).

Simulations of Shallow Site Response

A set of parametric site response analyses were conducted by Silva et al. (1999, 2000) and Silva (2005) for shear wave velocity profiles representative of different NEHRP soil categories and geologies. The analyses included two different soil models (i.e., different relationships for variation of shear modulus and damping with shear strain) and variations in profile depth. Fig. 3 illustrates the average amplification of peak ground acceleration (PGA) relative to reference rock for soil and rock profiles of different shear wave velocities as a function of reference rock PGA (Vs30 for reference rock =1130 m/sec) for the "Peninsular Range" soil model. The Vs30 values of 1130 m/sec, 564 m/sec, and 274 m/sec correspond approximately to mid-range values for NEHRP site classes B, C, and D, and the Vs30 value of 750 m/sec is approximately the NEHRP B/C boundary. The curves shown represent average results for profiles ranging in depth from 30 to 300 m.

Results similar in form to those in Fig. 3 were developed for a second soil model ("EPRI" model), which gave greater reduction in amplification with increase in rock PGA than the "Peninsular Range" model (i.e., greater nonlinearity). The results included amplifications of spectral accelerations from 0- to 10-second period and a wider range of shear wave velocities, Vs30, than shown in Fig. 3. Using these simulation results, Walling and Abrahamson (2006) derived two theoretical models (one for each soil model) of nonlinear soil amplification as a function of reference rock PGA. Some NGA Developers utilized these theoretical results to constrain the nonlinear soil response, while others used the site response simulations merely to aid in developing their functional forms for modeling site response.

In addition to the parametric site response analyses, the NGA project conducted a review of recent empirical site amplification studies (Power et al., 2004). Results of these studies were compared with the site response simulations to provide additional resource information for NGA model development.

3D Basin Response Simulations

Day et al. (2006) carried out a comprehensive series of 3D basin response simulations for sedimentary basins in southern California. Fault geometries are based on the SCEC Community Fault Model and the 3D velocity structure based on the SCEC Community Velocity Model. Response spectral accelerations from the simulations were normalized to those from simulations for reference hard-rock models. Fig. 4 shows source-averaged basin amplifications for different periods as a function of depth to the 1.5 km/sec shear wave velocity interface. Day et al. (2006) developed a function to characterize these amplifications. For use in developing and incorporating a basin depth effect in attenuation relations, it is necessary to assess how the average rock site departs from the idealized reference model and how basin depth may correlate with other predictor variables affecting amplification, such as Vs30 of the basin soils.

Directivity Formulation Using Isochrone Theory

Spudich et al. (2004) introduced a directivity parameter as an alternative to the parameterization developed by Somerville et al. (1997). The parameter is an approximation to the isochrone velocity developed by Spudich and Frazer (1984). The approximation is made by assuming the finite fault is a line source extending from the hypocenter to the point on the fault closest to the site where a predicted motion is desired. To calculate the S-wave polarization, Spudich et al. (2004) also approximated the radiation pattern from a finite fault by those from two point sources on the fault. The optimal locations of these point sources were determined by Spudich et al. (in preparation) to be the hypocenter and a point approximately midway between the hypocenter and the closest point. This optimal two-point-source solution together with the approximate isochrone velocity allow a uniform approach (applicable to all types of faulting) to be formulated to predict amplitudes of the fault-strike-normal and fault-strike-parallel component of horizontal motions close to the fault.

PROJECT INTERACTIONS AND REVIEW

The NGA models development process has occurred over a period of three-plus years. Several activities were an integral part of that process to obtain frequent input and reviews of the NGA relations development, database, and supporting research. These are briefly summarized below.

Workshops

Eight one-to-two day workshops, each attended by 40 to 80 scientists and engineers, have been conducted through 2005 and at least one additional workshop is planned before project completion. The workshops provided for systematic presentations by NGA Developers, researchers, and working groups of project results being developed, and review of those results by the scientific community and the engineering user community.

Working Groups

Six working groups, comprised of scientists and engineers having expertise in the respective working group areas of activity and including project Developers, researchers, and many other project participants, were formed and met frequently to review specific results being developed by the project and discuss key issues. Table 1 shows the interrelationships between the working groups and the project technical tasks. The working groups made significant contributions to the project, and results of their deliberations were reported at the workshops. As an example, Working Group #5, Site Effects, examined different potential site classes and parameters that could be used as predictor variables for site amplification in developing NGA models, and their work influenced the decisions of most of the Developer teams to adopt Vs30 as the preferred site characterization parameter/predictor variable.

TABLE I. TECHNICAL TASKS AND RELATED WORKING GROUPS FOR NGA PROJECT

Tasks	Working Group(s)
Task 1: Dataset Development, Validation of Record Processing, and Evaluation of Fling Step Removal Procedures	WG#1a Record Processing WG#1b Fling Step Removal Procedure WG#2 Ground Motion Dataset WG#4 Source/Path Effects WG#5 Site Effects
Task 2: 1-D Rock Simulations and Validation of Simulation Procedures	WG#3 Validation of 1-D Rock Simulation Procedures WG#4 Source/Path Effects
Task 3: 3-D Simulations of Basin Effects	WG#4 Source/Path Effects WG#5 Site Effects
Task 4: Evaluation of Alternative Source/Path Predictor Variables	WG#4 Source/Path Effects
Task 5: Evaluation of Site Classification Schemes and Site Effects	WG#5 Site Effects
Task 6: Evaluation of Site Response Analysis Procedures and Development of Site Amplification Factors	WG#5 Site Effects
Task 7: Development of Statistical Methods and Tools for NGA Applications	WG#6 Statistical Modeling of Data

Developers Interaction Meetings

Numerous meetings were held by the five NGA Developer teams to exchange views on technical issues and compare in-progress development of the NGA relations. This process was invaluable in providing knowledge to all the Developers of viewpoints held by the teams and the breadth and details of modeling approaches being used. Each Developer team made decisions and independently developed their attenuation model, but because of the interactions, decisions resulted in some of the models being similar in several respects.

External Review

The USGS, led by the Golden, Colorado office and working cooperatively with the California Geological Survey (CGS), conducted a review of the preliminary NGA models. The review was focused on the potential use of the NGA models in the next round of national ground motion hazard mapping. The review, which is continuing, has been very useful in further focusing attention on key issues and stimulating additional development of the models. The external review of NGA models for the average horizontal component is expected to be completed by the fall of 2006, and final report published by the end of the year.

CONCLUSIONS

An overview of the development of next generation ground motion attenuation models (NGA) has been presented in this paper. The development of these updated attenuation models has benefited greatly from supporting components of the development process. These components have included a comprehensive updating and expansion of the PEER ground motion database; supporting research to aid the Developers in selecting functional forms for the relations; and a program of project interactions including workshops, working group meetings, Developers interaction meetings, and external review to provide input and review from the scientific research community and the engineering user community.

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REFERENCES

Abrahamson, N.A. and Silva, W.J., (1997), "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes," *Seismological Research Letters,* Vol. 68, pp. 94-127.

Boore, D. M., Joyner, W.B., and Fumal, T. E., (1997), "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work," *Seismological Research Letters,* Vol. 68, pp. 128-153.

Boore, D.M., Watson-Lamprey, J., and Abrahamson, N., (2006), "Orientation Independent Measures of Ground Motion," *Bulletin of the Seismological Society of America,* accepted for publication.

Campbell, K.W., (1997), "Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra," *Seismological Research Letters,* Vol. 68, pp. 154-179.

Campbell, K. W., and Bozorgnia, Y., (2003), "Updated Near-Source Ground-Motion (Attenuation) Relations for the Horizontal and Vertical Components of Peak Ground Acceleration and Acceleration Response Spectra," *Bulletin of the Seismological Society of America,* Vol. 93 (1), pp. 314-331.

Day, S. M., Bielak, J., Dreger, D., Graves, R., Larsen, S., Olsen, K.B., Pitarka, A., and Ramirez, L., (2006), "Numerical Simulation of Basin Effects on Long-Period Ground Motion," Proceedings of the Eighth National Conference on Earthquake Engineering, San Francisco, CA.

Graves, R. W., and Pitarka, A. (2004), "Broadband Time History Simulation Using a Hybrid Approach," Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, Paper No. 1098.

Idriss, I. M., (1991), "Selection of Earthquake Ground Motions at Rock Sites," Report prepared for the Structures Division, Building and Fire Research Laboratory, National Institute of Standards and Technology, Department of Civil Engineering, University of California, Davis.

Power, M., Borcherdt, R., and Stewart, J., (2004), "Site Amplification from Empirical Studies," NGA project report, Working Group #5.

Sadigh, K., Chang, C.-Y., Abrahamson, N.A., Chiou, S.J., and Power, M.S., (1993), “Specification of Long-Period Ground Motions: Updated Attenuation Relationships for Rock Site Conditions and Adjustment Factors for Near-Fault Effects,” Proceedings of the ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control, San Francisco, CA, 59-70.

Sadigh, K., Chang, C.-Y., Egan, J. A., Makdisi, F., and Youngs, R.R., (1997), “Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data,” *Seismological Research Letters,* Vol. 68, pp.180-189.

Silva, W. J., (2005), “Site Response Simulations for the NGA Project,” Draft report to PEER.

Silva, W., Darragh, R., Gregor, N., Martin, G., Abrahamson, N., and Kircher, C., (2000), “Reassessment of Site Coefficients and Near-Fault Factors for Building Code Provisions,” USGS NEHRP Program Report 9-HQ-GR-1010.

Silva, W., Gregor, N., and Darragh, R. (2002), “Validation of 1-D Numerical Simulation Procedures,” final report to PEER-Lifelines Project, available at http://peer.berkeley.edu/lifelines/LL-CEC/notes/topic1.html.

Silva, W. J., Sylvia, L., Darragh, B. R., and Gregor, N., (1999), “Surface Geology Based Strong Motion Amplification Factors for the San Francisco Bay and Los Angeles Areas,”, PEER Task 5B.

Somerville, P., Collins, N., Graves, R., Pitarka, A., Silva, W., and Zeng, Y., (2006), “Simulation of Ground Motion Scaling Characteristics for the NGA-E Project,” Proceedings of the Eighth National Conference on Earthquake Engineering, San Francisco, CA.

Somerville, P., Smith, N., Graves, R., and Abrahamson, N., (1997), “Modification of Empirical Strong Ground Motion Attenuation Relations to Include the Amplitude and Duration Effects of Rupture Directivity,” *Seismological Research Letters,* Vol. 68 (1), pp. 199-222.

Spudich, P., Chiou, B. S.-J., Graves, R., Collins, N. and Somerville, P. (2006), “A Formulation of Directivity for Earthquake Sources Using Isochrone Theory,” *U.S. Geological Survey Open File Report 2004-1263,* available at http://pubs.usgs.gov/of/2004/1268 /

Spudich, P., Chiou, B. S.-J., Graves, R., Collins, N. and Somerville, P. (2006), “Simple Functions for Mapping Ground Motion Polarization and Directivity Amplification Around a Fault”, in preparation.

Spudich, P., and Frazer, L. N., (1984), “Use of Ray Theory to Calculate High Frequency Radiation from Earthquake Sources Having Spatially Variable Rupture Velocity and Stress Drop,” *Bulletin of the Seismological Society of America*, Vol. 74, pp. 2061-2082.

Walling, M. and Abrahamson, N. (2006), “Non-linear Soil Response Model,” Proceedings of the Eighth National Conference on Earthquake Engineering, San Francisco, CA.

Zeng, Y., (2002), “Final Technical Report on Validation of 1-D Numerical Simulation Procedures,” PEER Project 1C02, Task 1: Earthquake Ground Motion, Seismological Lab, University of Nevada – Reno.

Zeng, Y., Anderson, J. G., and G. Yu, (1994), “A Composite Source Model for Computing Realistic Synthetic Strong Ground Motions,” *Geophysical Research Letters*, Vol. 21, pp. 725-728.