Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

ENGINEERING USES OF PHYSICS-BASED GROUND MOTION SIMULATIONS

Jack W. Baker[1], Nicolas Luco[2], Norman A. Abrahamson[3], Robert W. Graves[4], Philip J. Maechling[5], Kim B. Olsen[6]

ABSTRACT

This paper summarizes validation methodologies focused on enabling ground motion simulations to be used with confidence in engineering applications such as seismic hazard analysis and dynamic analysis of structural and geotechnical systems. Numerical simulation of ground motion from large earthquakes, utilizing physics-based models of earthquake rupture and wave propagation, is an area of active research in the earth science community. Refinement and validation of these models require collaboration between earthquake scientists and engineering users, and testing/rating methodologies for simulated ground motions to be used with confidence in engineering applications. This paper provides an introduction to this field and an overview of current research activities being coordinated by the Southern California Earthquake Center (SCEC). These activities are related both to advancing the science and computational infrastructure needed to produce ground motion simulations, as well as to engineering validation procedures. Current research areas and anticipated future achievements are also discussed.

---

[1] Stanford University, Stanford, CA 94305
[2] U.S. Geological Survey, Golden, CO 80401
[3] Pacific Gas & Electric, San Francisco, CA 94117
[4] U.S. Geological Survey, Pasadena, CA 91106
[5] University of Southern California, Los Angeles, CA 90089
[6] San Diego State University, San Diego, CA 92182

Baker, J. W., Luco, N., Abrahamson, N. A., Graves, R. W., Maechling, P. J., and Olsen, K. B. Engineering uses of physics-based ground motion simulations. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

Engineering uses of physics-based ground motion simulations

Jack W. Baker[1], Nicolas Luco[2], Norman A. Abrahamson[3], Robert W. Graves[4], Philip J. Maechling[5], Kim B. Olsen[6]

ABSTRACT

This paper summarizes validation methodologies focused on enabling ground motion simulations to be used with confidence in engineering applications such as seismic hazard analysis and dynamic analysis of structural and geotechnical systems. Numerical simulation of ground motion from large earthquakes, utilizing physics-based models of earthquake rupture and wave propagation, is an area of active research in the earth science community. Refinement and validation of these models require collaboration between earthquake scientists and engineering users, and testing/rating methodologies for simulated ground motions to be used with confidence in engineering applications. This paper provides an introduction to this field and an overview of current research activities being coordinated by the Southern California Earthquake Center (SCEC). These activities are related both to advancing the science and computational infrastructure needed to produce ground motion simulations, as well as to engineering validation procedures. Current research areas and anticipated future achievements are also discussed.

Introduction

Much of current earthquake engineering practice uses empirically calibrated ground motion prediction equations to quantify shaking intensity of future earthquakes, and recorded ground motions as input time series to dynamic engineering analyses. These approaches are relatively well understood and mature, but have limitations with regard to understanding conditions without significant observational evidence, such as shaking intensities from large crustal earthquakes, and the effects of deep sedimentary basins.

Numerically simulated ground motions have the potential to address these limitations. Ground motions can be simulated for arbitrary conditions, and conditions and model parameters can be varied systematically to understand sensitivities to input specifications. Benefitting from this great promise, however, requires simulation approaches utilizing current scientific knowledge of earthquake processes, computational infrastructure to produce and distribute simulations, and

---

[1] Stanford University, Stanford, CA 94305
[2] U.S. Geological Survey, Golden, CO 80401
[3] Pacific Gas & Electric, San Francisco, CA 94117
[4] U.S. Geological Survey, Pasadena, CA 91106
[5] University of Southern California, Los Angeles, CA 90089
[6] San Diego State University, San Diego, CA 92182

Baker, J. W., Luco, N., Abrahamson, N. A., Graves, R. W., Maechling, P. J., and Olsen, K. B. Engineering uses of physics-based ground motion simulations. *Proceedings of the 10th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Anchorage, AK, 2014.

procedures for validating simulations against real ground motions. The Southern California Earthquake Center (SCEC) is undertaking a number of activities in these areas to demonstrate the value of simulations for engineering analysis, and this paper discusses some of these activities and achievements.

It is notable that simulated ground motions already play an important role in seismic hazard analysis, as they are used to constrain empirical ground motion predictions in circumstances not well-constrained by observations, such as in sedimentary basins and on hanging walls (e.g. Abrahamson et al., 2013). Also, many building codes (e.g., ASCE, 2010) allow simulated time series to be used for response history analysis, though this approach is not widely adopted at present.

Simulation-based seismic hazard analysis using CyberShake

Numerical simulations of earthquake strong ground motions have improved to the point where it is worth investigating the predictive power of these physics-based methods in seismic hazard analysis. Researchers working through SCEC have developed community seismic velocity models (CVM-S and CVM-H) that describe seismic P- and S-wave velocities and densities throughout the southern California region and are comprised of basin structures embedded in tomographic crust and upper mantle models. The primary difference in the two models is the manner in which the basin velocities are prescribed. CVM-S uses a rule based approach relating depth and age of sediments to seismic velocities, whereas CVM-H utilizes an extensive set of seismic reflection data and borehole logs to constrain point estimates of the seismic velocities, which are then interpolated to a finer mesh covering the entire extent of the basins. In addition, CVM-H has a more extensive description of the basin structures in the offshore region. Numerical simulations of anelastic wave propagation through these three-dimensional (3D) structures have been tested against recorded ground motions (e.g., Graves and Aagaard, 2011; Olsen and Mayhew, 2010), and efforts are underway to improve the CVMs using the earthquake waveform data (Lee et al., 2013; Tape et al., 2010). The plate-boundary fault system has been well described in a Community Fault Model (CFM) (Plesch et al., 2007), and long-term earthquake rupture forecasts based on the CFM are now available (Field et al., 2009).

These developments have motivated considerable research on the prediction of strong ground motions from the large, as of yet unobserved fault ruptures that will someday occur. Empirical ground motion prediction equations (GMPEs) can potentially be improved by supplementing the direct observations of ground motions with simulation data that use the physics of wave propagation to extrapolate to unobserved conditions. The CyberShake project has a more ambitious goal: entirely replacing the GMPEs with simulation-based ground motion predictions (Graves et al., 2010). The computational platform for such a calculation must be able to efficiently simulate the ground motions at each site for an ensemble of rupture variations. The ensemble must be sufficiently large to characterize all sources in the earthquake rupture forecast. In particular, it must be large enough to properly represent the expected variability in the source parameters—e.g., hypocenter location, stress drop, and the slip heterogeneity. In the current CyberShake implementation, the ground motion time series at a given site are calculated using seismic reciprocity for an ensemble of kinematic rupture variations (Graves and Pitarka, 2010) that sample the Uniform California Earthquake Rupture Forecast, Version 2 (UCERF2) (Field et al., 2009). To date, time series have been simulated for approximately 415,000 rupture scenarios at each of nearly 300 sites in the Los Angeles region, for making ground shaking maps at periods of 2 seconds and longer. The computational process has been automated using scientific workflow tools developed within the SCEC Community Modeling Environment using TeraGrid and XSEDE high-performance computing facilities (Jordan and Maechling, 2003, Deelman et al., 2006, Callaghan et al., 2010).

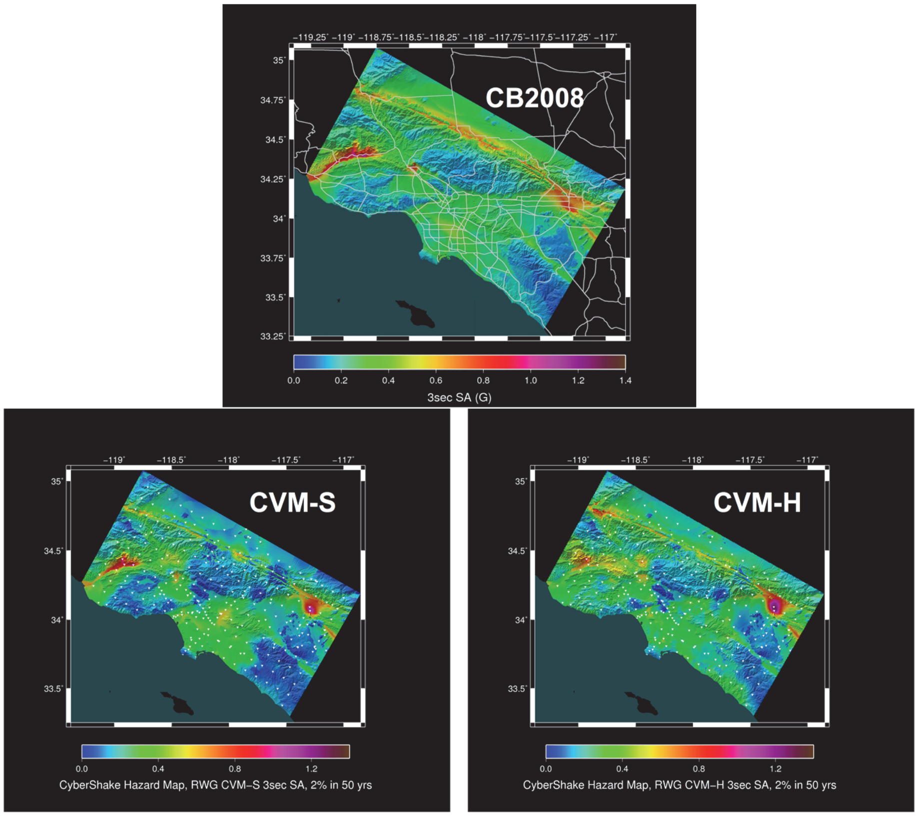

Figure 1: Los Angeles region probabilistic seismic hazard maps constructed with GMPE (top) and CyberShake Platform using CVM-S (bottom left) and CVM-H (bottom right).

We are currently able to construct a first generation CyberShake hazard map for the Los Angeles region. To produce a CyberShake hazard map, we first compute the residuals between the CyberShake predictions and those obtained from an empirical GMPE at each of the simulation sites. We then construct an interpolated version of this residual field that covers the entire region of interest. Finally, we construct the CyberShake map by adding the interpolated residuals to the original GMPE-based map. An example of this process is illustrated in Figure 1 using the GMPE of Campbell and Bozorgnia (2008), 3-second spectral acceleration and an exceedance probability of 2% in 50 years. The CyberShake maps show generally elevated hazard for many deep basin sites, and generally reduced hazard along the San Andreas fault, relative to the GMPE-based prediction. Additionally, it is clear that the map produced using CVM-S is not identical to the map produced using CVM-H, which represents the impact of epistemic uncertainty in the 3D velocity structure on the resulting hazard estimates. With further refinement of the velocity models, we expect these differences to diminish.

Beyond the direct product of region-specific hazard maps described above, the CyberShake database of simulated ground motions provides a valuable resource for investigation of other seismic hazard related problems. These include refinement of Earthquake Early Warning algorithms to include effects of rupture directivity and basin response on estimated shaking intensities (Boese et al., 2013) and statistical analyses of the relative importance of site, path, and source-complexity effects on the ground motion response throughout the Los Angeles region (Wang et al., 2013). Current efforts in the CyberShake project are aimed at 1) pushing the frequency limit of the deterministic computations to 1 Hz, for making ground shaking maps at periods of 1 seconds and longer, 2) increasing the density of sites, 3) expanding the region of coverage to other areas of California, and 4) transition to use of Version 3 of UCERF.

The SCEC Broadband Platform

The Broadband Platform (BBP) is an open-source software distribution that contains physics-based ground motion models capable of calculating earthquake ground motions at frequencies up to 10Hz across regional distances (http://scec.usc.edu/scecpedia/Broadband_Platform). In addition, the BBP provides software utilities that help users run large numbers of ground motion simulations and manage the simulation results (Somerville et al., 2011). The BBP also contains software tools for evaluating ground motion models and comparing simulation results against GMPEs and observed ground motion recordings. By integrating these capabilities, the BBP has developed into a computational platform capable of supporting scientific and engineering processes needed to assess ground motion models for use in engineering applications.

The BBP contains several physics-based ground motion simulation models as shown in Table 1. Ground motion models are computer software programs written in standard programming languages such as C and FORTRAN, and they may be implemented in one, or more, processing stages. Ground motion models must be able to input a simple earthquake description, and output acceleration ground motion time series at no less than 40 samples per second, with “broadband” ground motions from 0 to 10Hz or higher. Ground motion models are typically developed by individual researchers, or research groups, and then integrated into the BBP by the SCEC software development group.

Table 1: Ground motion model components implemented in the SCEC Broadband Platform.

Ground Motion Model	**Rupture Generator**	**0 to 1Hz Deterministic Motions**	**1 to 10Hz Stochastic Motions**	**Ground-Motion Post-Processing**	**Goodness of Fit Post-Processing**
GP (Graves and Pitarka, 2010)	Gen_Slip	JB_Sim	HF_Sim	RotD50	Bias Plot
SDSU (Mena et al., 2010)	Gen_Slip	JB_Sim	BB_Toolbox		
UCSB (Schmedes et al., 2012)	UCRMG	Syn1D			
EXSIM (Motazedian and Atkinson, 2005)	EXSIM				
CSM (Zeng et al., 1994)	Simula				

BBP ground motion models output ground motions as acceleration or velocity time series. Within the BBP, all further time series post-processing and analysis of results is done with common software utilities, so any differences in results can be attributed to the ground motion models themselves, and not the post-processing software. Both the ground motion simulation models, and the post-processing utilities, are distributed as open-source software to provide transparency to the scientific methods and algorithms implemented within the platform.

The BBP software group uses the phrase *ground motion model* to refer to any collection of programs that input standard earthquake parameters and output ground motion time series. We use the phrase *ground motion simulation* to describe a calculation that uses a specific ground motion model with a specific set of input parameters. Several BBP ground motion models are implemented in three processing stages: a rupture generator stage, a low frequency deterministic wave propagation stage, and stochastic high frequency stage. Other BBP ground motion models are implemented as a single computer program. Table 1 identifies the five ground-motion models in BBP version 13.9 and shows how each of these models is assembled from one or more processing stages. In some cases, different ground motion models (e.g. GP and SDSU) use the same programs in some of their processing stages.

The BBP software provides a way to define and run multi-stage computing processes in which the outputs from one computing stage are used as input in later stages, a type of computing model sometimes called a computational pipeline, or a scientific workflow. A data dependency is said to exist between processing stages when one stage produces outputs that are used as inputs by a following processing stage. Data dependencies impose a computational order into the processing, so the system must ensure that the producer stages complete successfully before the consumer stages are run.

The BBP implements its multi-stage computing capabilities using two main software elements. First, the BBP defines an XML workflow specification format to describe the input files and computer programs needed to run a ground motion simulation and any required post-processing stages. Second, the BBP provides a software framework that inputs these XML workflow specifications, and executes the given list of programs, with the given input files, in the correct order. With these two capabilities, the BBP can flexibly support multi-stage ground motion simulation calculations, making it easy to add or remove computational stages without changes to the BBP infrastructure. The BBP XML format workflow specification defines a BBP ground motion simulation calculation as a series of processing programs (called transformations), and input files and output files (called resources). BBP XML files are important metadata because they define the exact inputs and programs used to calculate a particular result. Given a working copy of the BBP software, and the required input files, a BBP XML workflow specification can be used to re-run a specific BBP ground motion simulation.

To help manage the output data, each BBP simulation is assigned a unique Simulation ID that is used to link simulation results with metadata for those results. BBP metadata for a given ground motion simulation includes the XML workflow specification, the input files and programs used, the BBP software version, and additional details about the computing environment.

The BBP is developed for use in Linux computing environments. Researchers can download the BBP distribution and build and run the software on any properly configured Linux computer. Ground motion validation activities may require running hundreds, or thousands, of different ground motion simulations for each ground motion model under evaluation, leading to output simulation data sets containing gigabytes of data. While the current BBP ground motion models are serial codes, the SCEC software group has been able to complete several large suites of BBP simulations using Linux-based computer clusters, showing that the BBP software can make use of HPC computer resources if available.

The BBP simulation platform has recently been used for a large-scale ground motion evaluation and validation project (Dreger et al., 2013), and results from that analysis are available at a SCEC web site (https://scec.usc.edu/it/Broadband_Study_13.6). For long-term storage of important BBP simulation results, we plan to migrate the required results to an appropriate seismological, or strong motion, data center.

The SCEC BBP software group is actively developing the BBP software using good software engineering practices that include use of widely supported programming languages, software version control, automated software tests, online documentation, software problem reporting system, and frequent public software releases. We recommend that users work with the most recent public release of the BBP software, which is distributed from a SCEC web site, because the ground motion models and computational infrastructure continue to improve rapidly. Future BBP developments will include integration of new ground motion models, integration of new analysis tools, and integration of new validation data sets.

Current directions in ground motion simulation

SCEC has, in recent years, increasingly prioritized bringing together seismologists and earthquake engineers, an effort aimed at more practical use of numerical simulations of earthquakes. This collaboration has strongly affected recent and current directions of the numerical simulations and their underlying methodology. Below, we summarize important trends in these and related developments.

While the BBP contains state-of-the-art tools to generate synthetic seismograms with frequencies in the range desired by earthquake engineers (so far in 1D models), SCEC is currently exploring the feasibility of using almost entirely physics-based, 3D deterministic methods (the 'High-F Project' http://scec.usc.edu/scecpedia/High-F). Recent deterministic simulations have been limited to relatively low frequencies (e.g., 0-0.5 Hz for TeraShake, Olsen et al., 2006; ShakeOut, Graves et al., 2008; Olsen et al., 2009; Bielak et al., 2010). However, more recent efforts have shown promise for High-F moving deterministic simulations up to 10 Hz within the next decade (e.g., 0-2 Hz for M8, Cui et al., 2011; 0-4 Hz for M5.4 Chino Hills, Taborda and Bielak, 2013; 0-10 Hz for M 7.2 scenario event, Shi and Day, 2013; Withers et al., 2013). In addition to advances in high-performance computing and efficient wave propagation methods (including GPU-based methods, see e.g., Cui et al., 2013), High-F will benefit from recent results in realistic characterization of earthquake source complexity (e.g., Shi and Day, 2013; Dunham et al., 2011), as well as statistical description of small-scale heterogeneities of the surrounding media (Savran and Olsen, 2013, see also Figure 2; Plesch et al., 2013).

The numerical methods leading the way for 3D simulations at higher frequencies include finite differences (FD), finite elements (FE), and spectral elements (SE), each with its own advantages and disadvantages. Higher-order methods (e.g., some FD and SE) require fewer points per wavelength, while FE and SE methods naturally lend themselves to modeling detailed mountain topography, an increasingly important feature at higher frequencies. Structured-mesh approaches (e.g., FD, some FE methods) excel at efficient mesh generation and parallel efficiency; however, they may require discontinuous mesh schemes, often unstable at long simulation times, to include the low near-surface velocities for the higher frequencies. Some of these methods can be combined into hybrid approaches (e.g., Moczo et al., 1997).

In the bandwidth below about ~1 Hz, frequency-independent attenuation is usually found to be in agreement with observations. This approach has been modeled in many simulations with good accuracy using the coarse-grained approach of Day (1998) for a 3D anelastic medium. As simulations reach higher frequencies, however, observations suggest that anelastic attenuation falls off. To account for this trend in simulations, Withers et al. (2013) propose a coarse-grained implementation of frequency-dependent Q in FD via a power-law function, $Q=Q_0f^n$, where Q is the quality factor, f is frequency, and Q_0 and n are constants that may vary regionally.

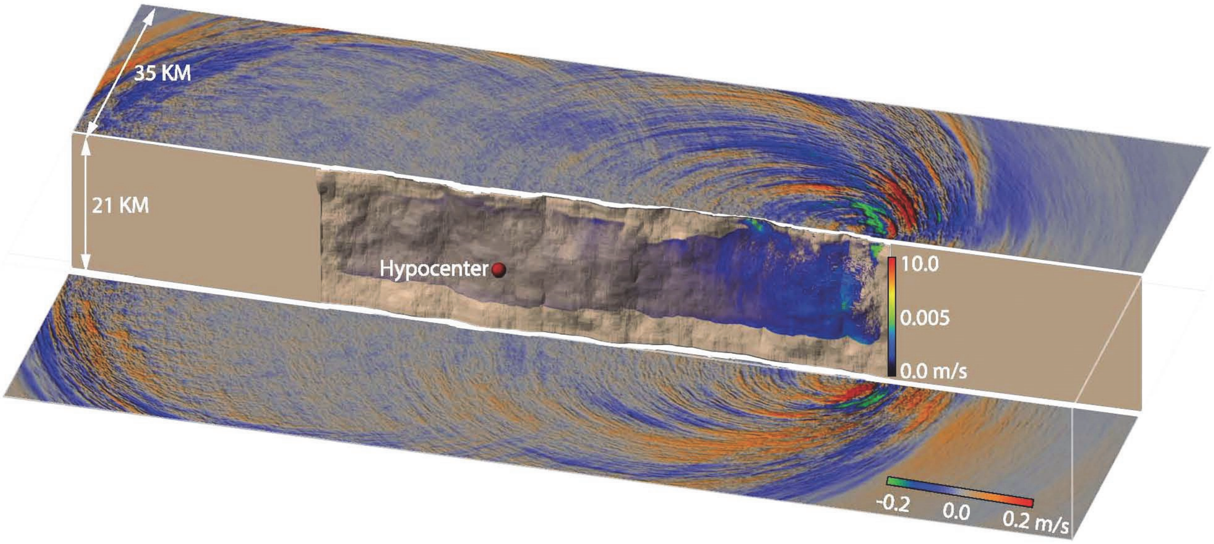

Figure 2: Snapshot of 0-10 Hz rupture propagation (slip rate) and surface wavefield (strike-parallel component) for a crustal model with a statistical model of small-scale heterogeneities. The displayed geometrical heterogeneities on the fault were included in the rupture simulation. The part of the crustal model in front of the fault has been lowered for a better view. Note the strongly scattered wavefield due to the small-scale heterogeneities. Visualization credit: Amit Chourasia, SDSC.

The recent large-scale 3D wave propagation efforts (e.g., TeraShake, ShakeOut, M8, Chino Hills) were carried out using linear schemes. It is generally believed that significant nonlinear effects are limited to higher frequencies (>~1Hz), at least when modeling near-vertically-incident SH waves, with increasing importance as frequencies grow in the simulations. However, the nonlinear effects of laterally propagating waves have not been studied in detail until recently. Roten et al. (2013) showed using an implementation of Drucker-Prager plasticity in 3D FD that nonlinear effects would significantly reduce (by up to 50%) the amplitude of long-period (>2s) Love waves propagating in the ShakeOut waveguide for a SE-NW propagating rupture on the southern San Andreas fault. Further analysis of the nonlinear effects on laterally propagating long-period waves is warranted in the future.

Technical Activity Group on validation of ground motion simulations

The SCEC Technical Activity Group (TAG) on Ground Motion Simulation Validation (GMSV) was established in 2010, with the objective to develop and implement, via collaboration between ground motion modelers and engineering users, testing/rating methodologies for simulated ground motions to be used in engineering applications. An initial planning workshop was held in January of 2011 to enumerate and prioritize work that should be conducted within the GMSV TAG, and four additional workshops have been held in 2012 and 2013 (Luco et al., 2013). Agendas, presentations and outcomes from these workshops are available at http://collaborate.scec.org/gmsv/.

Based in part on the recommendations from these workshops and resulting SCEC requests for proposals, six past and eight current GMSV-related projects have been funded. A number of these projects are funded by the SCEC Software Environment for Integrated Seismic Modeling (SEISM) project, while others have been funded through the annual SCEC request for proposals. Broadly speaking, the SEISM projects are focused on 1) GMSV for engineering analysis using simple and robust ground motion parameters (Burks and Baker, 2013), 2) GMSV for building-code nonlinear response history analysis, and 3) GMSV for application of simulated ground motions to duration-sensitive geotechnical systems. The projects are tightly coordinated so that comparisons of their results will reveal differences and similarities across the three types of GMSV. For example, all three projects are using the same reference ground motions from the Broadband Platform. Furthermore, the projects will compare results for three different types of validation tests, which each compare: 1) ground motion parameters or system responses (e.g., of a building or a slope) from simulated vs. recorded ground motions for historical earthquakes and their station locations, 2) system responses from simulated vs. recorded ground motions that have substantially similar elastic response spectra (or other ground motion parameters), and 3) ground motion parameters or simple system responses (e.g., slope displacements) from simulated ground motions vs. corresponding empirical prediction equations. To facilitate the implementation of these validation tests, calculation of additional ground motion parameters, such as significant duration, will be added to the SCEC Broadband Platform.

Conclusions

Numerical simulation of ground motions, and their validation for use in engineering applications, is a topic receiving significant attention within the Southern California Earthquake Center. Developments in simulation algorithms, computational infrastructure, and evaluation approaches have been discussed. These efforts are enabling simulation algorithm refinement to ensure that the simulations are useful for a number of engineering applications. The transparency of the infrastructure used to produce the simulations, and of the validation of the simulations, is aimed at facilitating the use of these simulations in engineering projects.

Acknowledgments

This work was supported in part by the Southern California Earthquake Center and the National Science Foundation under NSF grant number ACI 1148493. SCEC is funded by NSF Cooperative Agreement EAR-0529922 and USGS Cooperative Agreement 07HQAG0008. The SCEC contribution number for this paper is 1815. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors. Thanks to Lynne Burks and Sanaz Rezaeian for helpful feedback on this paper.

References

Abrahamson, N. A., Silva, W. J., and Kamai, R. (2013). *Update of the AS08 Ground-Motion Prediction Equations Based on the NGA-West2 Data Set*. PEER Report 2013/04, Berkeley, California. 144p.

ASCE. (2010). *Minimum Design Loads for Buildings and Other Structures, ASCE 7-10*. American Society of Civil Engineers/Structural Engineering Institute.

Bielak, J., R.W. Graves, K.B. Olsen, R. Taborda, L. Ramirez-Guzman, S.M. Day, G.P. Ely, D. Roten, T.H. Jordan, P.J. Maechling, J. Urbanic, Y. Cui, and G. Juve (2010). The ShakeOut earthquake scenario: Verification of three simulation sets, *Geophysical Journal International* 180, 375-404.

Boese, M., R. Graves, D. Gill, S. Callaghan, P. Maechling (2014). CyberShake-Derived Ground-Motion Prediction Models for the Los Angeles Region with Application to Earthquake Early Warning*, Bull*

Seism. Soc. Am. (submitted).

Burks, L. S., and Baker, J. W. (2013). “Validation of ground motion simulations through simple proxies for the response of engineered systems.” *Bulletin of the Seismological Society of America*, (in review).

Callaghan, Scott, Ewa Deelman, Dan Gunter, Gideon Juve, Philip Maechling, Christopher Brooks, Karan Vahi, Kevin Milner, Robert Graves, Edward Field, David Okaya, Thomas Jordan (2010), Scaling up workflow-based applications, Journal of Computer and System Sciences, 76:6, pp. 428-446.

Campbell, K.W. and Bozorgnia, Y. (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5%-damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthquake Spectra* 24(S1), 139–172.

Cui, Y., E. Poyraz, K.B. Olsen, J. Zhou, K. Withers, S. Callaghan, J. Larkin, C. Guest, A. Chourasia, Z. Shi, S. M. Day, P. Maechling, and T.H. Jordan (2013). Physics-based seismic hazard analysison petascale, Gordon Bell Prize finalist, and in Procs. Supercomputing Conference, New Orleans, November 2010.

Cui, Y., K.B. Olsen, D. Choi, T. H. Jordan, K. Lee, J. Zhou, P. Small, D. Roten, G. Ely, D.K. Panda, A. Chourasia, J. Levesque, S. M. Day, P. Maechling (2010). Scalable earthquake simulation on petascale heterogeneous supercomputers, in Procs. Supercomputing Conference, Denver, November 2013.

Day, S.M. (1998). Efficient simulation of constant Q using coarse-grained memory variables, Bull. Seis. Soc. Am. 88, 1051-1062.

Deelman, E., S. Callaghan, E. Field, H. Francoeur, R. Graves, N. Gupta, V. Gupta, T. H. Jordan, C. Kesselman, P. Maechling, J. Mehringer, G. Mehta, D. Okaya, K. Vahi, Li. Zhao (2006). Managing Large-Scale Workflow Execution from Resource Provisioning to Provenance tracking: The CyberShake Example, *2nd International Conference on e-Science and Grid Computing*, Amsterdam.

Dreger, D., Beroza, G. C., Day, S. M., Goulet, C. A., Jordan, T. H., Spudich, P., and Stewart, J. P. (2013). *Evaluation of SCEC Broadband Platform Phase 1 Ground Motion Simulation Results*. Southern California Earthquake Center Report, Los Angeles, California, USA.

Dunham, E. M., D. Belanger, L. Cong, and J. E. Kozdon (2011). Earthquake ruptures on rough faults, in Multiscale and Multiphysics Processes in Geomechanics (results of workshop at Stanford Univ., June, 2010), Springer Series in Geomechanics and Geoengineering, edited by Ronaldo I. Borja, ISBN 978-3-642-19629-4, pp. 145-148.

Field, E.H., T.E. Dawson, K.R. Felzer, A.D. Frankel, V. Gupta, T. H. Jordan, T. Parsons, M.D. Petersen, R.S. Stein, R.J. Weldon II and C.J. Wills (2009). Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2), *Bull. Seismol. Soc. Am.*, 99, 2053-2107, doi:10.1785/0120080049.

Graves, R. W., and A. Pitarka (2010). Broadband ground motion simulation using a hybrid approach*, Bull Seism. Soc. Am.*, 100, doi: 10.1785/0120100057.

Graves, R. W., and B. T. Aagaard (2011). Testing Long-Period Ground-Motion Simulations of Scenario Earthquakes Using the Mw 7.2 El Mayor-Cucapah Mainshock: Evaluation of Finite-Fault Rupture Characterization and 3D Seismic Velocity Models*, Bull Seism. Soc. Am.*, 101.

Graves, R. W., B. Aagaard, K. Hudnut, L. Star, J. Stewart, and T. H. Jordan (2008), Broadband simulations for Mw 7.8 southern San Andreas earthquakes: Ground motion sensitivity to rupture speed, Geophys. Res. Lett., 35.

Graves, R., S. Callaghan, E. Deelman, E. Field, T. H. Jordan, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, K. Vahi (2010). CyberShake: Full Waveform Physics-Based Probabilistic Seismic Hazard Calculations for Southern California, *PAGEOPH,* DOI 10.1007/s00024-010-0161-6.

Jordan, T. H., and P. Maechling, (2003). The SCEC Community Modeling Environment—an information infrastructure for system-level earthquake science, *Seismol. Res. Lett.*, 74, 324-328.

Lee, E., P. Chen, T. H. Jordan, P. J. Maechling, M. Denolle, and G. C. Beroza (2013). Full-3D waveform tomography of Southern California crustal structure by using earthquake recordings and ambient noise Green’s functions based on adjoint and scattering-integral methods, SCEC Annual Mtg, Poster 198.

Luco N., Jordan T.H. & Rezaeian, S. (2013). Progress of the Southern California Earthquake Center Technical Activity Group on Ground Motion Simulation Validation. Seismological Research Letters, 84(2).

Mena, B., Mai, P. M., Olsen, K. B., Purvance, M. D., and Brune, J. N. (2010). “Hybrid broadband ground-motion simulation using scattering Green’s functions: Application to large-magnitude events.” *Bulletin of the Seismological Society of America*, 100(5A), 2143–2162.

Moczo, P., J. Kristek, J.M. Carcione, and M. Bouchon (1997). Hybrid modeling of P-SV seismic motion at inhomogeneous viscoelastic topographic structures, Bull. Seis. Soc. Am. 87, 1305-1323.

Motazedian, D., and Atkinson, G. M. (2005). "Stochastic finite-fault modeling based on a dynamic corner frequency." Bulletin of the Seismological Society of America, 95(3), 995–1010.

Olsen, K. B., and J. E. Mayhew (2010), Goodness-of-fit criteria for broadband synthetic seismograms, with application to the 2008 Mw 5.4 Chino Hills, CA, earthquake, *Seis. Res. Lett.* 81, 715-723.

Olsen, K. B., S. M. Day, J. B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling, and T. Jordan (2006). Strong shaking in Los Angeles expected from southern San Andreas earthquake, *Geophysical Research Letters*, 33, L07305, doi:10.1029/2005GL025472.

Olsen, K. B., S. M. Day, L. Dalguer, J. Mayhew, Y. Cui, J. Zhu, V.M. Cruz-Atienza, D. Roten, P. Maechling, T.H. Jordan, and A. Chourasia (2009). ShakeOut-D: Ground Motion Estimates Using an Ensemble of Large Earthquakes on the Southern San Andreas Fault With Spontaneous Rupture Propagation, *Geophysical Research Letters* 36 L04303, doi:10.1029/2008GL036832.

Olsen, K.B., and B.H. Jacobsen (2011). Spatial variability of ground motion amplification from low-velocity sediments including fractal inhomogeneities with special references to the southern California basins, Effects of Surface Geology on Seismic Motion, 4th IASPEI/IAEE International Symposium, UCSB.

Olsen, K.B., S. M. Day, J. B. Minster, Y. Cui, A Chouasia, R. Moore, P. Maechling, T. Jordan (2008), TeraShake2: simulation of Mw7.7 earthquakes on the southern San Andreas fault with spontaneous rupture description, *Bull. Seismol. Soc. Am.* 98, 1162-1185, doi: 10.1785/0120070148.

Plesch, A., J. H. Shaw, C. Benson, W. A. Bryant, S. Carena, M. Cooke, J. Dolan, G. Fuis, E. Gath, L. Grant, E. Hauksson, T. H. Jordan, M. Kamerling, M. Legg, S. Lindvall, H. Magistrale, C. Nicholson, N. Niemi, M. Oskin, S. Perry, G. Planansky, T. Rockwell, P. Shearer, C. Sorlien, M. P. Süss, J. Suppe, J. Treiman, and R. Yeats (2007). Community Fault Model (CFM) for Southern California, *Bull. Seismol. Soc. Am.*, 97, 1793-1802, doi 10.1785/0120050211.

Rezaeian, S., Zareian, F. & Zong, P. (2013). Validation of Simulated Ground Motions Based on Evolution of Intensity and Frequency Content. Southern California Earthquake Center Annual Meeting,.

Roten, D., K.B. Olsen, S.M. Day and D. Fäh (2013). The Shakeout earthquake scenario with plasticity, SCEC Annual Mtg Procs, Poster 217, Palm Springs.

Savran, W.H., K.B. Olsen, and B.H. Jacobsen (2013). Statistics of velocity structure in the Los Angeles Area, SCEC Annual Mtg Procs, Poster 218, Palm Springs.

Schmedes, J., Archuleta, R. J., and Lavallée, D. (2013). "A kinematic rupture model generator incorporating spatial interdependency of earthquake source parameters." *Geophysical Journal International*, 192(3), 1116–1131.

Shaw, J.H., A. Plesch and T.H. Jordan (2013). Stochastic Descriptions of Basin Velocity Structure from Analyses of Sonic Logs and the SCEC Community Velocity Model (CVM-H), SCEC Annual Mtg Procs, Poster 124.

Shi, Z., and S.M. Day (2013). Rupture dynamics and ground motion from 3-D rough-fault simulations, Journal of Geophysical Research: Solid Earth 118(3), p 1122–1141, DOI: 10.1002/jgrb.50094.

Somerville, P. G., Callaghan, S., Maechling, P., Graves, R. W., Collins, N., Olsen, K. B., Imperatori, W., Jones, M., Archuleta, R., Schmedes, J., And Jordan, T.H. (2011). The SCEC Broadband Ground Motion Simulation Platform, SRL, 82(2), p. 275, 10.1785/gssrl.82.2.273..

Taborda, R., and J. Bielak (2013). Groun-Motion Simulation and Validation of the 2008 Chino Hills, California, Earthquake, Bulletin of the Seismological Society of America, February 2013, v. 103, p. 131-156.

Tape, C., Q. Liu, A. Maggi and J. Tromp (2010). Seismic tomography of the southern California crust based on spectral-element and adjoint methods, *Geophys. J. Int.* (2010) 180, 433–462.

Wang, F., T. H. Jordan, S. Callaghan, R. Graves, K. B. Olsen, and P. Maechling (2013). Using the Averaging-Based Factorization to Assess CyberShake Hazard Models, SCEC Annual Mtg Procs, Poster 214, Palm Springs.

Withers, K.B., K.B. Olsen, and S.M. Day (2013). Deterministic high-frequency ground motion using dynamic rupture along rough faults, small-scale media heterogeneities, and frequency-dependent attenuation, SCEC Annual Mtg Procs, Poster 85, Palm Springs.

Zeng, Y., J. G. Anderson and G. Yu (1994). A composite source model for computing realistic synthetic strong ground motions, *Geophysical Research Letters* 21, 725-728.