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THE SCIENCE, ENGINEERING APPLICATIONS, AND POLICY IMPLICATIONS OF SIMULATION-BASED PSHA

M. P. Moschetti[1], S. Chang[2], C.B. Crouse[3], A. Frankel[4], R. Graves[5], H. Puangnak[6], N. Luco[7], C. Goulet[8], S. Rezaeian[7], A. Shumway[7], P. M. Powers[7], M. D. Petersen[7], S. Callaghan[8], T. H. Jordan[8,9], K. Milner[8]

ABSTRACT

We summarize scientific methods for developing probabilistic seismic hazard assessments from 3-D earthquake ground motion simulations, describe current use of simulated ground motions for engineering applications, and discuss on-going efforts to incorporate these effects in the U.S. national seismic hazard model. The 3-D simulations provide important, additional information about earthquake ground-shaking, which is critical to proper characterization of potential ground motions. Example uses of these simulations for engineering applications provide alternative approaches to introducing the effects of deep basins on long-period ground motions into design requirements. In Seattle, Washington tall building design includes requirements for accounting for the effect of the Seattle basin, and one method for including this effect relies upon local 3-D simulations. In Los Angeles, California a working group of scientists and engineers is advancing the use of local 3-D simulations for local building codes. In light of the benefit to ground motion characterization from the use of 3-D simulations, similar efforts are underway for national-scale seismic hazard analyses, which seek to make use of the extensive work applied from local efforts; current methods for incorporating these effects on a national-scale are presented.

[1]U.S. Geological Survey, Denver, CO (mmoschetti@usgs.gov)
[2]City of Seattle Department of Construction and Inspections, Seattle, WA
[3]AECOM, Seattle, WA
[4]U.S. Geological Survey, Seattle, WA
[5]U.S. Geological Survey, Pasadena, CA
[6]GeoEngineers, Inc., Redmond, Washington
[7]U.S. Geological Survey, Denver, CO
[8]Southern California Earthquake Center, Los Angeles, CA
[9]University of Southern California, Los Angeles, CA

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We summarize the scientific methods for developing probabilistic seismic hazard assessments from 3-D earthquake ground motion simulations, describe current use of simulated ground motions for engineering applications, and discuss on-going efforts to incorporate these effects in the U.S. national seismic hazard model. The 3-D simulations provide important, additional information about earthquake ground-shaking, which is critical to proper characterization of potential ground motions. Example uses of these simulations for engineering applications provide alternative approaches to introducing the effects of deep basins on long-period ground motions into design requirements. In Seattle, Washington tall building design includes requirements for accounting for the effect of the Seattle basin, and one method for including this effect relies upon local 3-D simulations. In Los Angeles, California a working group of scientists and engineers is advancing the use of local 3-D simulations for local building codes. In light of the benefit to ground motion characterization from the use of 3-D simulations, similar efforts are underway for national-scale seismic hazard analyses, which seek to make use of the extensive work applied from local efforts; current methods for incorporating these effects on a national-scale are presented.

Introduction

Probabilistic seismic hazard analysis (PSHA) requires a characterization of the expected ground motion distribution from all considered seismic sources ([1]). Modern seismic hazard analyses typically employ ground motion models (GMMs) that assume log-normal ground motion distributions and provide means and standard-deviations for a given set of explanatory variables (e.g., magnitude, distance metrics, faulting mechanism). Empirical GMMs, such as those from the NGA-West-2 Project (e.g., [2]), are developed from regressions to ground motion recordings and

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[1]U.S. Geological Survey, Denver, CO (mmoschetti@usgs.gov)
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[7]U.S. Geological Survey, Denver, CO
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achieve significant variance reductions.

Seismological observations, however, indicate that there are cases where earthquake ground motions can greatly differ from the predictions of empirical GMMs. For example, ground motions within sedimentary basins can be greatly complicated by interaction between different phases, development of strong surface waves, and scattering. Modeling these features may require the use of numerical simulations because of the enormous complexity and interplay between seismic waves and earth structure.

The past decade has seen significant improvements in 3-D simulations of earthquake ground motions. This is especially true for long-period ($T \geq 1\ s$) ground motions, where there is a greater level of knowledge about the earth structure and earthquake rupture process, which are required for accurate simulations. Given the increasing consensus on the validity of earthquake simulations, multiple efforts to incorporate simulated ground motions into seismic hazard analyses—ultimately, for engineering applications—have emerged.

Efforts in Seattle, Washington and Los Angeles (LA), California have already employed the use of 3-D simulations in PSHA (e.g., [3,4]), and similar efforts are underway in other regions within the western U.S. (e.g., [5–8]). In this paper, we highlight the efforts from Seattle and LA, as well as on-going national-scale efforts to incorporate 3-D simulations into PSHA for engineering applications. We summarize the 3-D simulation methods, the ways in which the results are being employed for engineering design and by local building officials, and recent efforts to incorporate features of these simulations into national-scale seismic hazard analyses, for future consideration in U.S. building codes.

3-D Simulations of Earthquake Ground Motions

Earthquake simulations in Seattle and LA share many common features. Seismic velocities vary in three dimensions and include data from multiple geophysical measurements and studies, such as data from borehole logging, shallow surface seismic, local and regional tomography, and gravity inversions. Because of the contributions of many researchers to these models, they are often referred to as "community velocity models" (CVMs). Earthquake ruptures are modeled on faults and for a set of seismic sources that are consistent with long-term earthquake recurrence (e.g., [9,10]). Ruptures are implemented by kinematic descriptions of the timing and amount of slip on fault surfaces, and the ruptures conform to observations and reproduce the average features of recorded ground motions (e.g., [11,12]). The 3-D anelastic wave-propagation and workflow calculations employ substantial supercomputing requirements. There are subtle differences in the methodologies applied in Seattle and LA, though the ultimate products are synthetic seismograms corresponding to all seismic sources. Ground motion intensities (e.g., pseudo-spectral accelerations) from the synthetic seismograms provide the basis for computing seismic hazard curves from earthquake recurrence, with the Seattle and LA simulations employing differing methods for defining the ground motion distributions.

3-D Simulations for the Seattle Region

Researchers from the U.S Geological Survey (USGS) produced probabilistic seismic hazard maps for Seattle using the results of 541 3-D simulations of ground motions for earthquakes on the Seattle fault, Southern Whidbey Island fault (SWIF), Cascadia subduction zone, and for background (deep and shallow crustal) earthquakes ([3]). The maps incorporate the 3-D amplification of the Seattle basin and rupture directivity effects for earthquakes on the Seattle fault and SWIF. In addition, empirical site factors were applied to account for nonlinear amplification of soft soils. The maps depict 1-Hz response spectral accelerations for various probabilities of exceedance. Approximately 7200 sites with a spacing of 280 m were used.

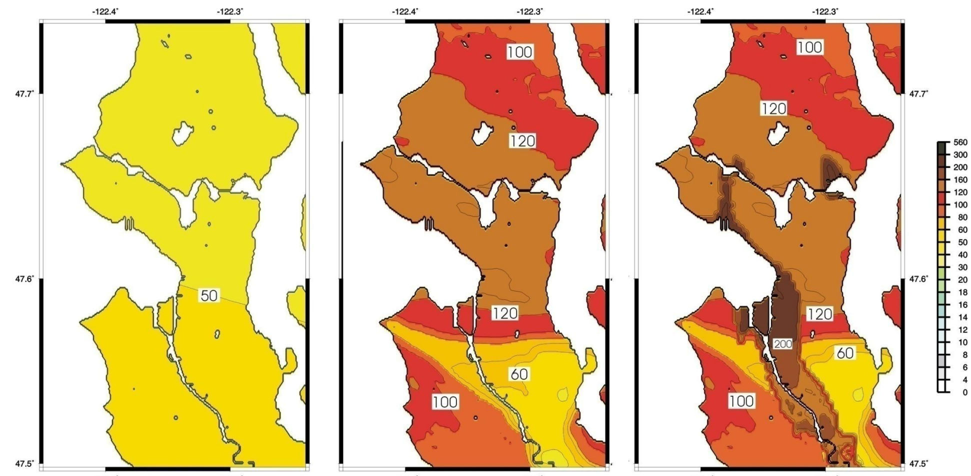

Figure 1. 1 Hz spectral accelerations for Seattle area with 2% probability of exceedance in 50 years. (left) From 2002 national seismic hazard maps with a firm-rock site condition. (middle) seismic hazard map based on 3D simulations that incorporate amplification from Seattle basin and rupture directivity of earthquakes on the Seattle fault. (right) also including non-linear response of soft soils. (from Frankel et al. [3]).

Synthetic seismograms from the 3-D simulations were used to calculate basin amplification factors that depended on the location of each source and, for the finite-fault simulations, the slip distribution and hypocenter. These basin amplification factors were applied to the GMMs used in the 2002 NSHM and used the variability of the empirical GMMs and the earthquake recurrence from the 2002 NSHM ([9]). This methodology was designed so that the hazard for firm-rock sites outside of the Seattle basin was equivalent to that in the 2002 NSHM.

The Seattle maps provide spatial detail on the seismic hazard in Seattle. The highest hazard is found for sites on artificial fill or alluvium located in the Seattle basin. The next highest hazard is for sites on stiff soils located in the Seattle basin and soft-soil sites outside the basin. The lowest hazard at this period is for sites on shallow bedrock south of the Seattle basin.

The 3-D model of the Seattle basin was validated by modeling the observed waveforms and amplifications of a set of local earthquakes, including the 2001 M6.8 Nisqually earthquake ([13]), and the model continues to be updated to include recent tomographic models and results from shallow seismic studies ([14]). Updated scenarios for M9 earthquakes in the Cascadia subduction zone have also recently been completed, to include new observations from recent large subduction zone earthquakes that greatly affect strong ground motion generation ([15]).

3-D simulations for the Los Angeles region

Researchers working together through the Southern California Earthquake Center (SCEC) have developed CVMs that include detailed representations of sedimentary basins and other near-surface structures. Numerical simulations have been tested against recorded ground motions, and efforts are underway to improve the CVMs using earthquake waveform data.

The SCEC CyberShake project leads the effort to produce 3-D-simulation-based seismic hazard maps for southern California and continues to advance knowledge about seismic velocity structure and earthquake rupture for future updates (Jordan et al., [16]). First generation CyberShake hazard maps were produced from long-period ($T \geq 2\ s$) 3-D ground motion simulations for all fault-based seismic sources (M ≥ 6) in the long-term California earthquake rate forecast ([4,10]). The methodology employed a reciprocity-based approach that permitted the calculation of over 400,000 rupture variations of seismic sources, hypocenters, and slip distributions. For the more than 350 sites of interest in the LA region, all ruptures within 200 km were considered. CyberShake directly samples the ground motion variability at each site over many earthquake cycles (i.e., rupture scenarios), resulting in non-ergodic ground motion distributions that are directly obtained from the simulations ([17]).

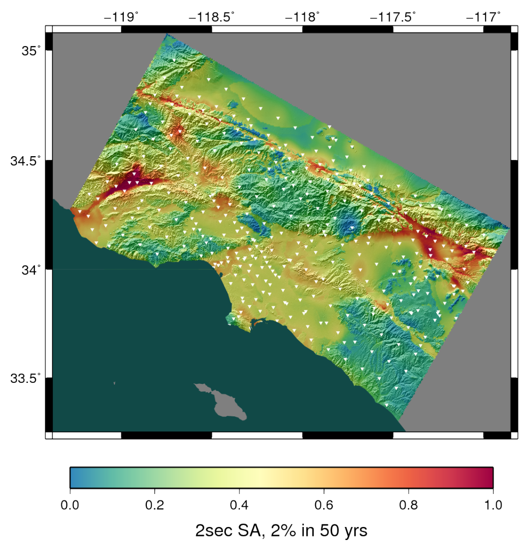

Figure 2. 2-s spectral accelerations for the Los Angeles region with 2% probability of exceedance in 50 years. The map is based on interpolated hazard values computed at 336 individual sites (white triangles) from CyberShake (study 15.4) ([16]).

The simulations indicated that the combination of rupture directivity and basin response effects led to increased hazard level for some sites, relative to that given by empirical GMMs. Recent refinements to the rupture generators lead to a decrease in the strength of directivity effects with increasing source complexity. Additionally, though epistemic uncertainties in the source representation remain substantial (and the focus of continuing research), the overall variance of the directivity effect in the most recent CyberShake models is consistent with observational studies ([18]). CyberShake simulations with several of the SCEC Community Velocity Models show how the site and path effects vary with differences in upper crustal structure, and they are particularly instructive about epistemic uncertainties in the modeling of basin effects, which are not well parameterized by the depth to particular iso-velocity surface.

Incorporating 3-D simulations into local and national building codes

Incorporation of Basin Response in the Design of Tall Buildings in the City of Seattle

For performance-based design of tall buildings, the City of Seattle requires that the design team account for basin effects due to the Seattle Basin, including the use of recent 3-D simulations in the region. Accounting for basin response is unique in Seattle, partly because of the lack of empirical data and the presence of multiple seismic sources. While the empirical GMMs for crustal sources include factors that account for basin effects, the GMMs for subduction sources do not.

In 2013, the City of Seattle and the USGS hosted a workshop to develop recommendations for incorporation of basin response in ground motion estimation. The results of that workshop are summarized by Chang et al. ([19]). In summary, the workshop participants recommended that until basin amplification factors are developed for subduction zone sources, the basin factors from crustal, empirical GMMs could be applied to the uniform hazard spectrum after site effects are considered.

Since the publication of this report ([19]), typical practice in Seattle includes evaluation of basin amplification factors using one of two methods:

Method 1: Basin factors are calculated from several sources including, (1) using depths to seismic shear-wave velocities of 2.5 km/s (Z2.5) and an empirical GMM [20]; (2) using depths to seismic shear-wave velocities of 1 km/s (Z1) for empirical GMMs [21–23]; (3) the average of basin factors computed from recorded motions from the M6.8 Nisqually and M6.4 Vancouver Island earthquakes at Seattle Urban Seismic Array stations located in downtown Seattle; and (4) an average of the low and high basin amplification factors calculated from 3-D simulations of M9 subduction interface events (written comm. A. Frankel, 2015; [15]). For each spectral period, the basin factors from each method are weighted based on the seismic hazard deaggregation (e.g., Figure 3, left).

Method 2: Using a weighted average of the basin amplification factors from [20] (0.5 weight); [21–23] (0.1667 weight, each). The basin factors from Campbell and Bozorgnia ([20]) are given higher proportional weight because they are considered more appropriate for the seismic velocity structure of the Seattle basin ([19]).

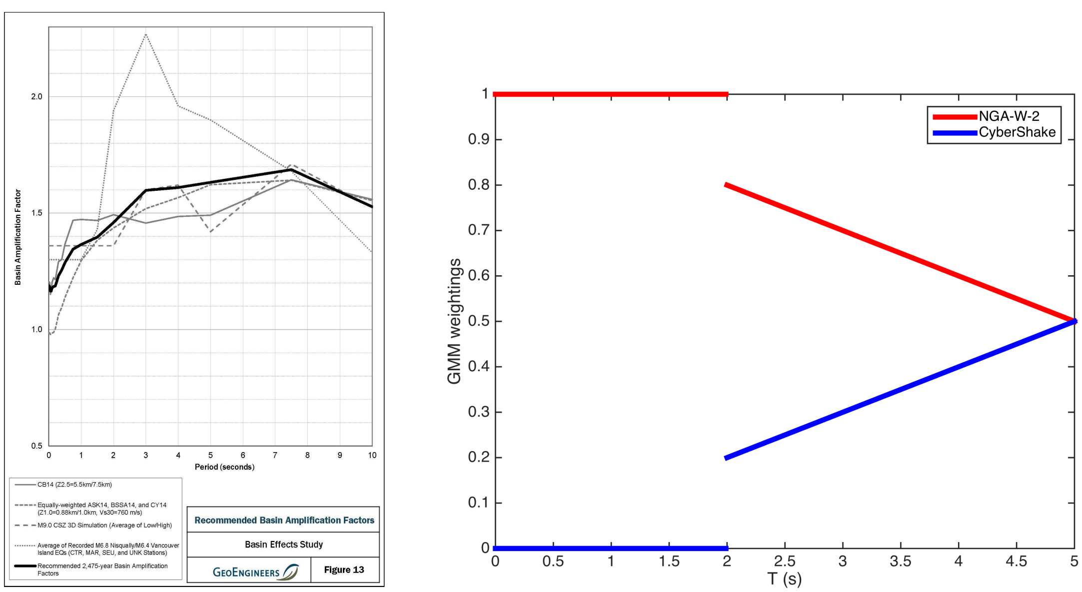

Figure 3. (left) Example basin factors for Seattle, *Method 1*. Recommended basin factors for 2,475-year return period ground motions basin factors for a site in downtown Seattle. (right) Weights for MCE_R response spectral accelerations for Los Angeles.

With the publication of ASCE 7-16, the use of conditional mean spectra is becoming more common for the design of tall buildings in Seattle. The approaches described above may be used for uniform hazard spectra or conditional mean spectra.

Ground-Motion Maps for Los Angeles based on 3-D Simulations and Empirical GMMs

The Utilization of Ground Motion Simulation (UGMS) committee of SCEC has developed risk-targeted Maximum Considered Earthquake (MCE_R) spectral acceleration maps for the LA region ([24]). The long period ($T \geq 2\ s$) values for these maps are based on a weighted average of MCE_R spectral accelerations derived from (1) the CyberShake simulations, and (2) empirical GMMs from NGA-West-2 ([2]) that use regional estimates of the travel-time-averaged shear-velocity in the top 30 m (Vs30), Z1, and Z2.5. For both the simulated and GMM-based motions, the corresponding MCE_R spectral accelerations for each site were computed following the site-specific procedures in Chapter 21 of the ASCE 7-10 standard. The final MCE_R response spectra were obtained as the weighted geometric average of the two sets of spectra. UGMS developed a period-dependent weighting scheme that introduces the effects of the simulations at the periods for which they are valid (Figure 3, right). For periods less than 2 s, the MCE_R response spectra were computed solely from the empirical GMPEs. For sites and periods where the MCE_R spectral accelerations from empirical GMPEs are higher than those from the simulations, the empirical GMMs define a floor value, thereby providing a conservatism to introduction of the simulated ground motions.

A web-based lookup tool has been developed so users can obtain the MCE_R response spectrum for a specified latitude and longitude and for a specified site class or Vs30. The acceleration ordinates of the MCE_R response spectrum are provided at 21 natural periods (0–10 s); values of S_{DS} and S_{D1}, per the requirements in Section 21.4 of ASCE 7-16, are also listed. The MCE_R multi-period response spectra, and associated values of S_{DS} and S_{D1}, are considered site specific and thus are an alternative to the S_{DS} and S_{D1} values obtained from Chapter 11 in ASCE 7-16 edition.

Incorporating 3-D Simulations into the U.S. National Seismic Hazard Model

Given the increasing accuracy of earthquake ground motion simulations, their availability in multiple regions, and their importance for assessing seismic hazards, the USGS is currently working to incorporate features of 3-D simulations in the U.S. National Seismic Hazard Model (NSHM; e.g., [25]). A recent publication from an internal-USGS working group included recommendations for the NSHM to include local-scale information from the types of simulation-based seismic hazard assessments that have been carried out in Seattle and LA ([26]). Although alternative seismic hazard analyses are already permitted by the site-specific option in U.S. building codes, a primary motivation for this effort is the desire to simplify the use of seismic hazard assessments for practicing engineers.

For incorporation of 3-D simulations into the NSHM, the USGS working group highlighted important differences in the development of local- and national-scale hazard models that are required to maintain the uniform NSHM methodology that is expected by its users. In particular, it was recognized that only those features of the 3-D simulations that have been sufficiently well validated should be included into the NSHM.

Based on these recommendations, as well as input from an external steering and advisory committees to the NSHM and the USGS, the USGS is currently pursuing methods for incorporating the effects of basin amplification from 3-D simulations into the NSHM. The approach aims to minimize or exclude the effects of rupture directivity, attenuation along different source-receiver paths (path effects), and the absolute ground motions from the 3-D simulations (including their inferred variability). Although these are important features that are recognized to contribute to hazard and should be part of a long-term strategy for improving seismic hazard assessments, basin effects were judged to have the greatest acceptance by the community for initial efforts.

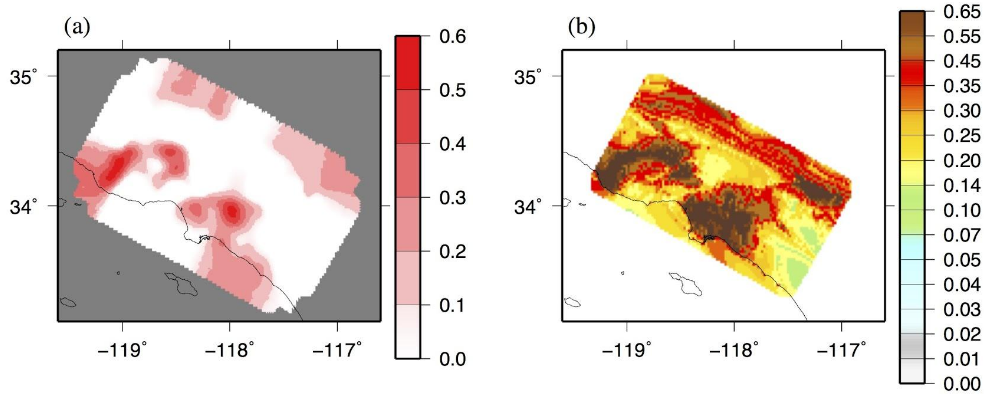

Figure 4. (a) Positive log-amplifications from the basin effects from the CyberShake simulations, relative to Abrahamson et al. (2014), as indicated by averaging-based factorization ([18]). (b) Trial 3-s spectral accelerations with 2 % probability of exceedance in 50 years, employing an empirical GMM ([21]), but with the basin effects specified by 3-D CyberShake simulations.

Isolating basin effects from other seismologic effects (e.g., directivity), which may not be as well validated, has been the focus of recent research (e.g., [3, 18]). USGS is currently investigating the averaging-based factorization method of Wang and Jordan ([18]), as applied to 3-D simulations from LA and to recent empirical GMMs. In a collaboration between the USGS and SCEC, SCEC researchers have extracted basin effects from the CyberShake simulations. This approach allows for the basin effects from the GMMs to be replaced with those from the 3-D simulations but maintains the absolute ground motion level of the GMMs, including their magnitude-, distance- and Vs30-dependent features (Figure 4).

Conclusions

Seismic hazard assessments based on 3-D simulations have been developed and used for engineering design in Seattle and Los Angeles, and efforts are underway to implement the important ground motion features arising from basin effects in these, and other, regions. The Seattle and LA simulations employed similar—though not identical—methodologies for modeling the effects of the deep sedimentary basins and the controlling seismic sources in those regions.

Approaches to incorporating 3-D simulations in both Seattle and LA were developed by independent groups. In both cases, the ground motions from 3-D simulations were combined with ground motions predicted from empirical GMPEs, and in Seattle, only, from recorded ground motions. On-going efforts to include these effects into national-scale hazard assessments are being focused on isolating the basin effects from the simulations, because these effects are most widely accepted by seismologists and best supported by validation work.

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