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The SCEC Broadband Platform Validation Exercise: Methodology for Code Validation in the Context of Seismic-Hazard Analyses

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Online Material: Source geometry files and 1D crustal velocity models for parts A and B validation scenarios.

INTRODUCTION: PURPOSE AND SCOPE

As part of the design process, most engineering applications require a response spectrum or earthquake time series as input to structural models to simulate their response. In the last few decades, the number of recordings from large earthquakes has exponentially increased, and seismic records are constantly being compiled and updated. However, there is still a limited number of records available for large magnitude events ($\mathbf{M} > 7$) recorded at close distances (within 10–20 km). Other source-site configurations, such as those leading to hanging-wall or rupture directivity effects, may also not have been widely captured by recorded events. There is a growing recognition that simulated ground motions from validated codes may be used to overcome these shortcomings as a complement to recorded motions. Consequently, the need for carefully validated ground-motion simulation procedures is becoming highly desirable.

The concept of ground-motion simulation validation itself is not new and appeared in the literature following the pioneering simulation work from Hartzell (1978) and Irikura (1978). The topic continued to grow and became part of special sessions at conferences (e.g., Abrahamson *et al.*, 1990) and part of guidelines for ground-motion characterization (Electric Power Research Institute [EPRI], 1993). Researchers continued to publish on individual simulation methods and validation exercises (e.g., Beresnev and Atkinson, 1998; Hartzell *et al.*, 1999; Boore, 2001; Star *et al.*, 2011) as larger coordinated efforts emerged, such as documented in the Multidisciplinary Center for Earthquake Engineering Research (MCEER) report on simulation methodologies (Abrahamson and Becker, 1999) and in the Pacific Earthquake Engineering Research Center (PEER)-Lifelines Task 1 project reports (Silva *et al.*, 2002; Zeng and Anderson, 2002; Collins *et al.*, 2006). The validation exercise described in this article largely benefited from the experience of past efforts, such as those listed above. The current validation exercise is the product of a collaborative effort between the Southern California Earthquake Center (SCEC) and PEER, involving a large number of participants (see list of authors in the Focus Section of this volume and the Acknowledgments section in each article). The validation is coordinated around the SCEC Broadband Platform (BBP), and it was designed to improve the transparency of validation efforts. The exercise led to the improvement of tools on the BBP and to strong interaction between the modelers, who were encouraged to further develop their methodology throughout the process.

This first article describes the process and objectives for validating numerical ground-motion simulation models and modules implemented on the BBP (see Maechling *et al.*, 2015). The current validation exercise is part of a larger, longer-term, and broader plan for the validation of simulated ground motions for engineering applications. The project, referred to as the Broadband Platform Validation Exercise for Pseudospectral Acceleration, has the limited scope of assessing the ability of different simulation methods to reproduce reasonable average pseudospectral acceleration (PSA) values only. It is understood that many other metrics would be necessary to fully assess the simulations methods' ability to produce reasonable ground motions as a whole. These will not be addressed here. On the other hand, because the focus of this article is on the design of a validation exercise conducted for a specific application, the key elements described here are portable to other metrics and applications.

Motivation and Validation Metric

This validation exercise was driven by the needs of two main ground-motion hazard projects: (1) the southwestern United States utilities project and (2) the PEER Next Generation Attenuation (NGA) project for the central and eastern North America (CENA) region (NGA-East). These projects involve

doi: 10.1785/0220140104

the development of new ground-motion prediction equations (GMPEs) and/or new ground motion characterization models (logic trees of various GMPEs). The two projects have different specific needs, but they share a similar interest in the simulations: to fill the gap in recorded datasets for PSA. The validation evaluation, described in detail in Dreger *et al.* (2015), is based on the performance of the different methodologies in matching the PSA of recorded ground motions and empirical relations for a set of earthquake scenarios and stations. The target validation metric is the RotD50 5%-damped PSA for spectral periods in the 0.01–10 s range. RotD50 is the median value PSA of the resultant of two horizontal components of ground motions as computed over each degree of rotation from 1° to 180° (Boore, 2010). RotD50 is computed independently for each spectral period and is, by definition, independent of the original sensor orientation.

The validation exercise described below has the following main objectives and desired outcomes:

- To develop a set of robust quantitative evaluation criteria and to assess the ability of existing methods to produce ground motions that are consistent with observations for specific frequency, magnitude, and distance ranges.
- To develop clear rules based on the validation parameters for generating forward simulations of earthquake scenarios for which no observations exist. Specifically, the exercise is designed to allow model parameters to be optimized on a region-specific basis before a final evaluation is completed by a review panel.
- To further improve the BBP with the addition of new modules, evaluation products, and workflow processes.

Following the validation exercise, end users can make a decision regarding which models to use for their forward simulations. The validation is carried out for cases in which data are available, but the intended use is for extrapolated cases (e.g., considering larger magnitude, closer distance, hanging wall, or directivity effects). The validation results can be quantified by the goodness of fit (GOF) of results with observed ground motions and aggregated so that an objective set of criteria is used for the evaluation (Dreger *et al.*, 2015). The confidence in using methods beyond the tested limits must also be assessed in light of the science behind each method. For this validation exercise, each modeler provided the technical documentation of their method and a self-assessment of the expected performance for cases for which no data are available. The review panel's role was to review the quantitative results, the documentation, and the modelers' assessment to provide final recommendations. The software additions to the BBP, including the evaluation tools, are described in Maechling *et al.* (2015), and the results of the review panel's assessment are summarized in Dreger *et al.* (2015). Papers describing the individual simulation methods complete this Focus Section.

VALIDATION EXERCISE DESIGN AND IMPOSED CONSTRAINTS

A validation exercise similar in scope to this one was attempted as part of NGA-East in 2011 (PEER, 2011). Valuable lessons were learned from that exercise that led to the incorporation of different constraints on the validation process and also in the input parameters used by the different modelers. The BBP validation project officially started in 2012 with the design and constraints all motivated by at least one of the following objectives:

1. to improve the transparency of the validation process;
2. to make the validation process consistent with the definition of forward simulations;
3. to ensure the results are technically defensible and reproducible; and
4. to focus on clear objectives with the scope adapted to the specific application.

Key constraints imposed as part of the validation exercise are summarized below.

Validate Methods for Median PSA

The current validation exercise only focused on median PSA values, not on their aleatory variability (dispersion). Some of the products from this exercise include different measures of dispersion, but these are provided as additional information and are not formally part of the evaluation. The variability of ground motions is a very important problem that will need to be addressed in subsequent work.

Have the Computations Performed by an Independent Operator, and Tie the Validation Results to a Specific Version of the BBP

Having all the simulations run by an independent entity on the BBP ensures that all the events' parameters are consistent and lead to reproducible results. Moreover, all the results must be associated with a specific version of the BBP release for which the results are reproducible. The current Focus Section documents the validation results for BBP version 14.3. This is the second version of the BBP evaluated as part of this project (see Dreger *et al.*, 2013, for the evaluation of version 13.6).

Process the Data, and Generate Products in a Uniform Fashion

Past validations sometimes led to different metrics of performance that were often inconsistent, both in their computation (different codes) and in their presentation (e.g., different plot scales). To address this issue, several new postprocessing and plotting tools have been incorporated into the BBP (Maechling *et al.*, 2015). A RotD50 code was implemented on the BBP and used to compute PSA for both the records and simulations, enabling a direct comparisons of results.

Specify Source and Path Input Parameters So They Are Consistent between Methods (Whenever Possible)

A single fault-plane geometry with an associated moment magnitude (or an equivalent seismic moment) and a fixed hypocenter location was specified for each event and used by all the modelers. By constraining the basic input parameters, all the modelers are trying to solve the same problem and the results can be directly compared. The geometry was defined by consensus to make sure it was globally appropriate to all modelers and technically defensible.

The simulations are also performed for 1D crustal structures. The motivation for this simplified approach was to start with a well-understood, simple path model that also allowed the direct evaluation of source effects. Three-dimensional effects are to be considered in subsequent exercises. A group composed of the modelers and various stakeholders agreed on the appropriate 1D layered crustal model to be used for each set of simulations. Ⓔ The source models and velocity structures used in the current validation exercise are available in the electronic supplement to this article.

Perform Simulations for a Large Number of Source Realizations instead of Using an Inverted Source Model

There is a potential for circularity if the source model used in the validation process comes from the inversion of recorded data. Fortunately, all the models considered in the current validation exercise include a source generator that defines the kinematics of the source (e.g., amount of slip, slip velocity, rise time) based on internal rules. These source generators were used to generate 50 realizations of the source, avoiding the circularity described above. The validation is then performed on the average results from those 50 realizations. Because the specific kinematic features of a future rupture are not known, the forward simulations are also done for numerous realizations and the average is used to define the predicted ground motion.

Perform the Simulations for a Single Site Condition, as Characterized by V_{S30}

The simulation methods are generally based on seismological and geophysical properties and do not tend to focus much on near-surface effects such as those coming from a nonlinear site response. In previous validation exercises, there was no consistency in how near-surface site effects were modeled for different recording stations, if they were modeled at all. The intent of the validation exercise was never to put the burden of a geotechnical engineering problem on the shoulders of seismological modelers. We therefore use empirical site models (linear and nonlinear) to correct the data to a stiff site condition in which nonlinear site effects are expected to be small. A single generic site profile with a V_{S30} of 863 m/s was used in combination with the basic 1D crustal model to define the full model for all the scenarios outside of CENA. A similar surface profile for the CENA scenarios was defined with a V_{S30} of 1000 m/s. Empirical site corrections were applied to the PSA of the recorded data instead of correcting the simulations to the as-recorded site conditions. For the CENA events, amplification factors developed by the NGA-East Geotechincal Working Group (Stewart *et al.*, 2012) were applied, and recordings for all the other events were corrected using an interim version of the Boore *et al.* (2014) site effects model in combination with the basin effects model from Chiou and Youngs (2008). Ⓔ The corrected PSA values for all the events and stations are available in the electronic supplement.

Consider a Large Number of Past Events Spanning Different Regions, Rupture Mechanisms, and Magnitudes

Using a large number of scenarios within a given tectonic region allows for a regional optimization of parameters. Although this may lead to a variable degree of fit across multiple events, because no single event is perfectly matched, this approach has the advantage of being consistent with forward simulations, for which it is impossible to know the specific source parameters *a priori*.

Compare Simulations with Empirical Models in which They are Well Constrained by Data (Model Centering)

The comparison with empirical models (GMPEs) is complementary to the validation for specific events in that it inherently aggregates data from multiple events. This type of validation can therefore compensate for using only a limited number of recorded earthquake scenarios and was first proposed by Frankel (2009). More importantly as part of this project, it enabled the testing of the process, applying rules in a consistent fashion as they are expected to be used for forward simulations.

Have All the Modelers Use the Validation Process to Define Regional Rules for Input Parameters

The definition of fully documented rules, developed by each modeler through the validation exercise, is critical for using the models in a forward sense. Examples of such rules include the specification of the rupture velocity or the definition of stress drop (or parameter) to use for simulations in a given tectonic or geographical region. The use of these rules in the validation, instead of event-specific optimized parameters, aims to demonstrate that the models can generate reasonable ground motions for events we have not yet observed.

Require the Modelers to Provide a Clear Documentation of the Principles behind Their Model and to Justify the Results They Obtain

This is a critical part of the methods' evaluation as it provides insight into how the models are expected to perform if the magnitude and/or distance range is extrapolated relative to the validation scenarios.

VALIDATION EXERCISES

Two groups of validation exercises were conducted as part of this project: Part A, against recorded ground motions and Part B, against relevant GMPEs.

Part A: Validation against Recorded Ground Motions

Twenty-five different earthquake scenarios were selected based on their relevance to the two driving projects. The selection aimed to cover several tectonic regions and to span a wide range of rupture events and magnitudes. Events that were well recorded (more than 40 stations) were also favored. Table 1 lists the scenarios and the number of selected records for the 12 events simulated in the validation of BBP version 14.3. This

Table 1 Selected Events for Part A Validation							
Region*	Event Name	Year	M	Mechanism†	Number of Records <200 km	Number of Selected Records	Note on Selection
WUS	Chino Hills	2008	5.39	REV-OBL	40	40	NA
WUS	Alum Rock	2007	5.45	SS	40	40	NA
WUS	Whittier Narrows	1987	5.89	REV-OBL	95	40	Only stations within 40 km
WUS	North Palm Springs	1986	6.12	REV-OBL	32	32	NA
WUS	Northridge	1994	6.73	REV	124	40	All stations within 10 km selected
WUS	Loma Prieta	1989	6.94	REV-OBL	59	40	NA
WUS	Landers	1992	7.22	SS	69	40	Only stations within 100 km selected
Japan	Tottori	2000	6.59	SS	171	40	NA
Japan	Niigata	2004	6.65	REV	246	40	NA
CENA	Rivière-du-Loup	2005	4.60	REV	21	21	NA
CENA	Mineral	2011	5.68	REV	10‡	10	NA
CENA	Saguenay	1988	5.81	REV-OBL	11	11	NA

*WUS, western United States; CENA, central and eastern United States.
†Mechanisms: REV-OBL, reverse oblique; SS, strike slip; REV, reverse; NA, Not applicable.
‡Number of records less than 300 km.

initial set was selected because either the fault geometry was simple (without bends or splays), or it could reasonably be reduced to a single plane. Complex rupture capabilities are currently being developed for the different rupture generators. Other events (Table 2) will be addressed in subsequent exercises but are listed to provide insight into the range covered.

After the validation events were selected, the number of records per event was limited to a maximum of 40 stations.

Table 2 Additional Events for Part A Validation					
Region	Event Name	Year	M	Mechanism	Number of Records <200 km
WUS	Coalinga	1983	6.36	REV	27
WUS	Big Bear	1992	6.46	SS	42
WUS	Parkfield	2004	6.50	SS	78
WUS	San Simeon	2003	6.50	REV	21
WUS	Hector Mine	1999	7.13	SS	103
WUS	El Mayor Cucapah	2010	7.20	SS	134
Turkey	Kocaeli	1999	7.51	SS	14
Taiwan	Chi-Chi	1999	7.62	REV-OBL	257
New Zealand	Christchurch	2011	6.20	REV-OBL	26
New Zealand	Darfield	2010	7.00	SS	24
Japan	Chuetsu-Oki	2007	6.80	REV	286
Japan	Iwate	2008	6.90	REV	186
Italy	L'Aquila	2009	6.30	NML	40

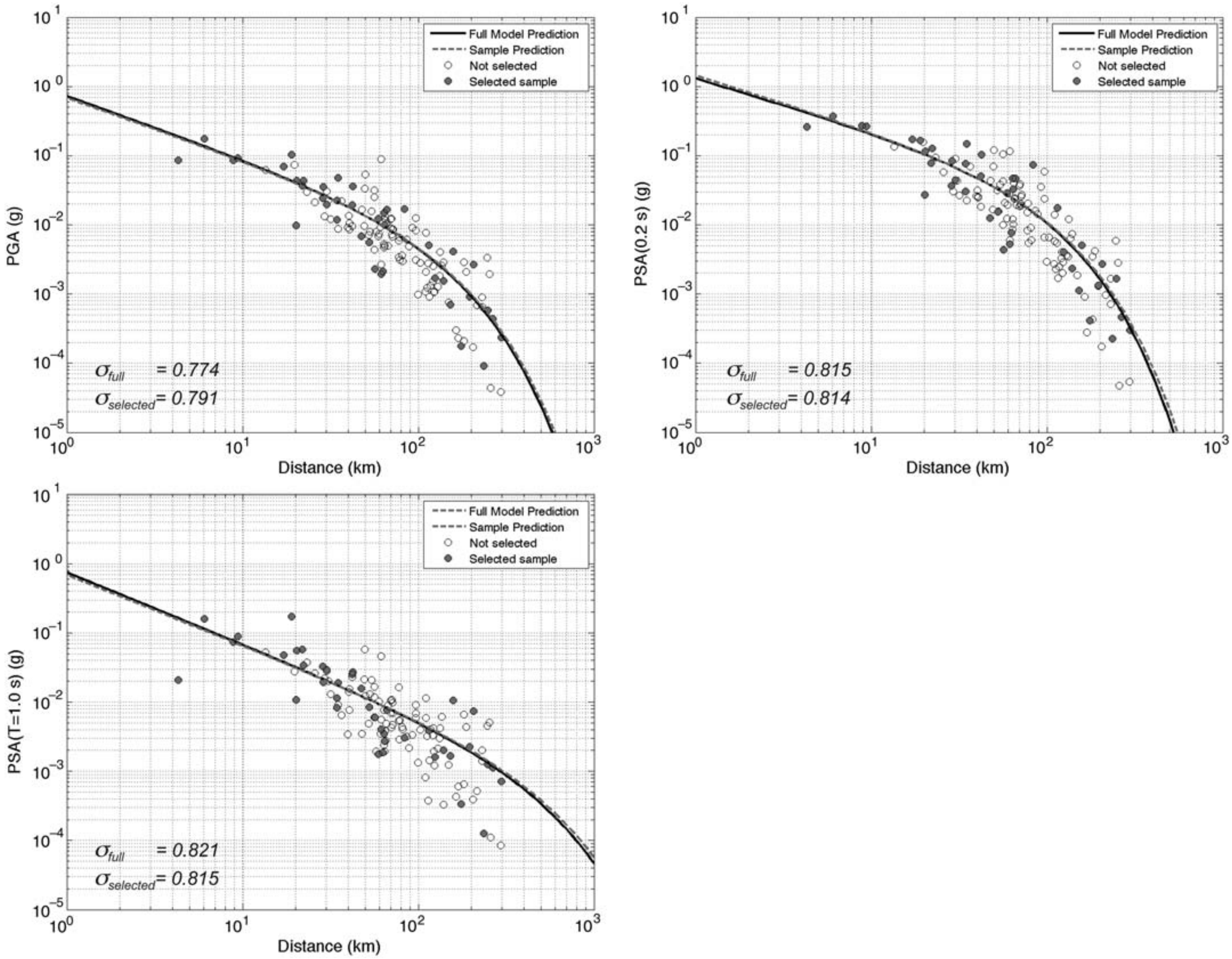
Abbreviations are as for Table 1.

The ground-motion data for each event came from preliminary versions of the NGA-East database (Goulet *et al.*, 2014) for the CENA events and from the NGA-West2 database (Ancheta *et al.*, 2014) for all the other events. A computer code was created to select a subset of stations that was unbiased in terms of the mean and standard deviations of three ground-motion intensity measures (peak ground acceleration and PSA at 0.2 and 1 s, respectively), relative to those of all the available stations. The process is illustrated in Figure 1. For all the scenarios (except for CENA), an additional restriction was applied to retain only stations with $V_{S30} > 300$ m/s, and stations were selected within a range of 200 km. Additional distance constraints were imposed to sample a subset of stations from four predefined distance bins. The distance restriction ensured that important near-fault effects were captured whenever possible. Exceptions to these rules are listed in Table 1. Ⓔ The lists of stations for each event are provided, with their coordinates and the corresponding corrected PSA values, in the electronic supplement.

Part B: Validation against Relevant Ground-Motion Prediction Equations

The intent of the validation against GMPEs is to verify whether the different simulation models are relatively centered for cases in which a lot of recorded data are available. For this part of the exercise, four of the original PEER NGA-West1 GMPEs were used:

- Abrahamson and Silva (2008)
- Boore and Atkinson (2008)
- Campbell and Bozorgnia (2008)
- Chiou and Youngs (2008)



▲ **Figure 1.** Illustration of the station selection process using the Alum Rock event. The circles represent recordings for the event. A simple regression model (function of magnitude, distance, and V_{S30}) was developed for the whole dataset (open and gray circles) for the RotD50 peak ground acceleration and 5% damped PSA at 0.2 and 1.0 s. The solid black line is the mean model regression considering all the records. The algorithm finds the sample of stations (filled gray circles) with the closest match to the mean and standard deviation from the full set for all three ground-motion measures simultaneously.

Data mining of the NGA-West1 database allowed the identification of the mechanism, magnitude, and distance ranges for which most data were available. These were grouped into scenarios for which the GMPEs are considered to be well constrained:

- **M** 5.5, 45°-dipping reverse, $Z_{tor} = 6$ km
- **M** 6.2, vertical strike slip, $Z_{tor} = 4$ km
- **M** 6.6, vertical strike slip with a surface rupture
- **M** 6.6, 45°-dipping reverse, $Z_{tor} = 3$ km

in which **M** is the moment magnitude and Z_{tor} is the depth to the top of rupture. For each of the scenarios, most of the available data were centered at rupture distances of 20 and 50 km. For each of these two distances, 40 stations were randomly located at different azimuths on the footwall side of the fault.

RESULTS AND INTERMEDIATE EVALUATION PRODUCTS

The validation evaluation is based on the performance of the different methodologies in their ability to match PSA from recorded ground motions (part A) and GMPE predictions (part B). Different summary plots and tables are generated throughout the validation exercise to provide direct feedback on the performance of the various models. The plots introduced below are all produced directly by the BBP and are part of new features added to the software (Maechling *et al.*, 2015). The purpose of the data products described below is to help the modelers better understand systematic trends in their simulations, and to allow adjustments to the parameters or methods. These plots, along with additional metrics developed by the review panel, are then evaluated as described in Dreger *et al.* (2015).

Part A: Validation against Recorded Ground Motions

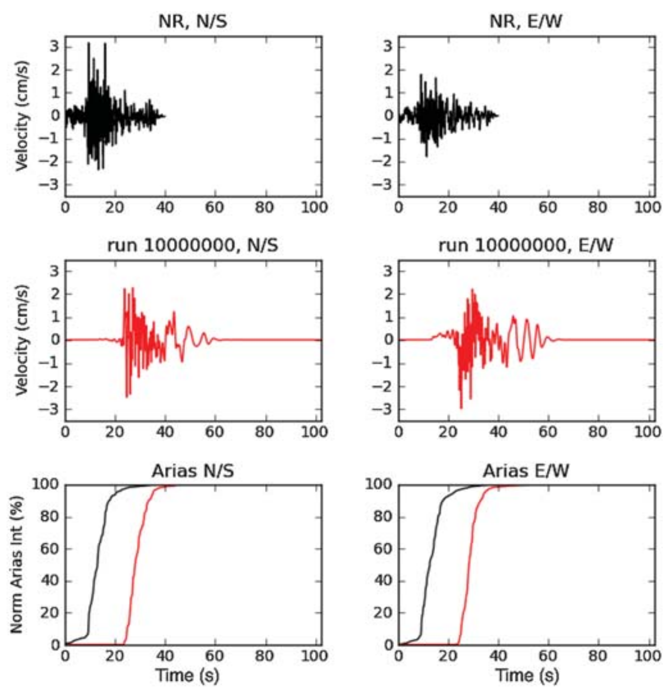
Time Series and Husid Plots

For each source realization and each station, plots comparing the recorded and simulated time series are produced (Fig. 2). Because the recorded data include site effects and the simulations are completed for fixed stiff site conditions, a direct comparison of the waveform is not possible. Also, the recorded time series do not include the full travel time, whereas the simulations do. These plots were generated to make sure that the waveforms otherwise looked reasonable. Husid plots are also produced to allow a visual assessment of the energy release with time. Although plots such as Figure 2 are not formally part of the evaluation assessment, they were generated to provide a first-order verification that the simulated time series were reasonable.

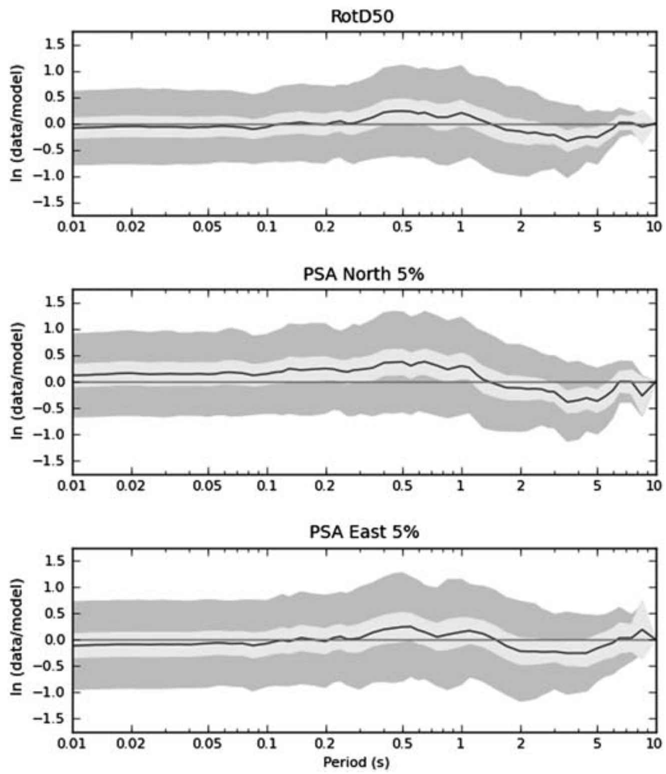
Plot of GOF with Spectral Period

As mentioned earlier, the main parameter considered for the evaluation is PSA. Most of the plots therefore are produced for the logarithmic residuals of PSA from the simulations relative to recorded motions. This metric, referred to as the "goodness-of-fit" (GOF), is computed for each spectral period. A key plot generated by the BBP is the GOF with spectral period. There is a plot for each realization (Fig. 3) and a plot that combines all the realizations for a given method and scenario (Fig. 4). For all the plots similar to Figure 3, the solid line corresponds to the mean GOF over all stations specified for the scenario (usually 40). The wide band limits correspond to the standard deviation, and the narrow band represents the 90% confidence interval of the mean. The narrow band tends to increase in width with spectral period, usually above 2 or 3 s, reflecting a smaller number of records available due to processing of data from different instruments and various signal-to-noise attributes. The increasing width of the narrow band indicates the mean is less well constrained by data. The GOF is shown for RotD50, as well as for the two uniform component orientations for verification. Figure 4 shows an example of results aggregated over all the realizations for a given method and scenario. The data used to generate Figure 4 is the main source of information used in the evaluation.

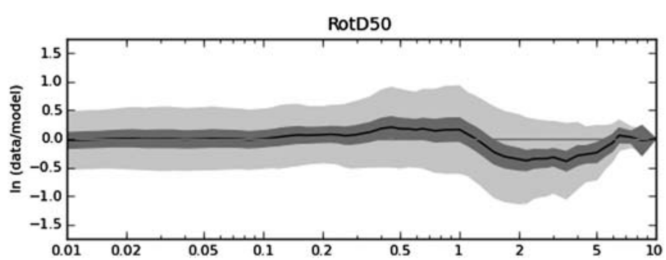
The platform produces a third GOF plot that allows the comparison of recorded ground motions to GMPE predictions (Fig. 5). There is a similar set of plots generated for each Part A scenario, with sub-plots corresponding to a specific NGA-West1 GMPE. This type of plot is useful for a first-order comparison of performance between simulations and GMPE predictions. We expect that a full finite-fault representation of a rupture would lead to a better performance than a GMPE that aggregates data from various events, and for which the fault



▲ **Figure 2.** Example of velocity time series and Husid plots for a single realization of ground-motion simulations. Black lines correspond to records and red lines are for simulated data. For this specific station (Northridge, ACI), the site conditions of the recorded data are for $V_{S30} = 822$ m/s, and the simulations are completed for $V_{S30} = 863$ m/s.



▲ **Figure 3.** Example of GOF with period for a single realization (best fit of Loma Prieta from a specific method); the statistics are for data from all the stations. The solid line is the mean, the narrow band is the 90% confidence interval of the mean, and the wide band shows the standard deviation centered around the mean.

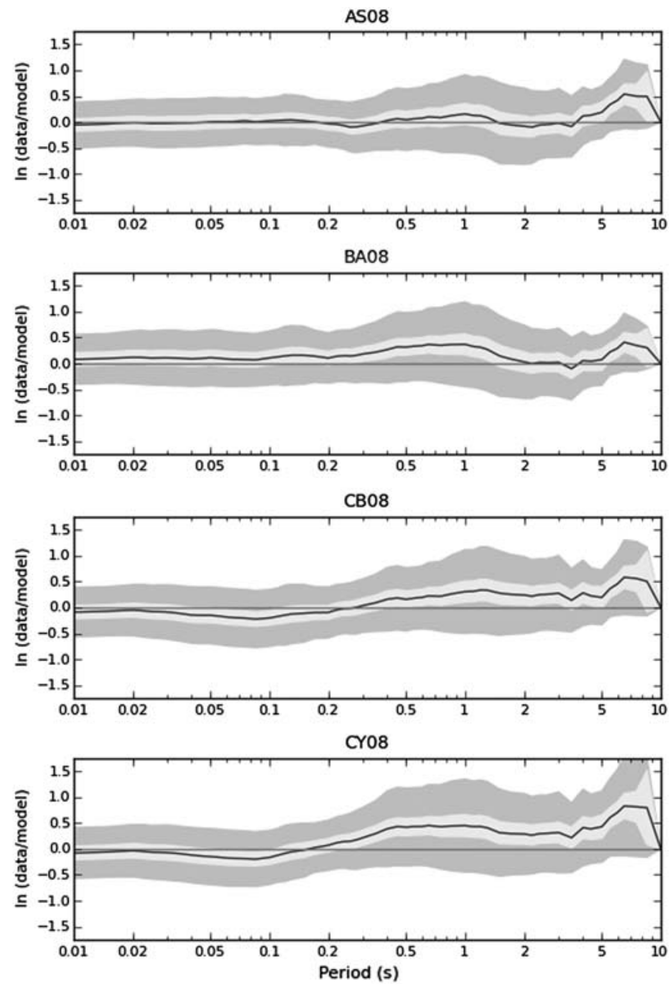


▲ **Figure 4.** Example of GOF with period, combining all the realizations for a given scenario (Loma Prieta); the statistics are for data from all the stations (average of all realizations). The solid line is the mean, the narrow band is the 90% confidence interval of the mean, and the wide band shows the standard deviation centered around the mean.

geometry is parameterized only through a set of site-source distance metrics. The overall trends in the GMPE plots are generally similar to those observed in the simulations, and the deviation from neutral GOF can be interpreted as an event term (more details provided in Dreger *et al.*, 2015).

Plot of GOF with Distance for a Subset of Spectral Periods

Additional plots aggregating the GOF with distance are also generated. The plots are produced for each realization, as well as for the aggregates of the 50 realizations for a subset of eight

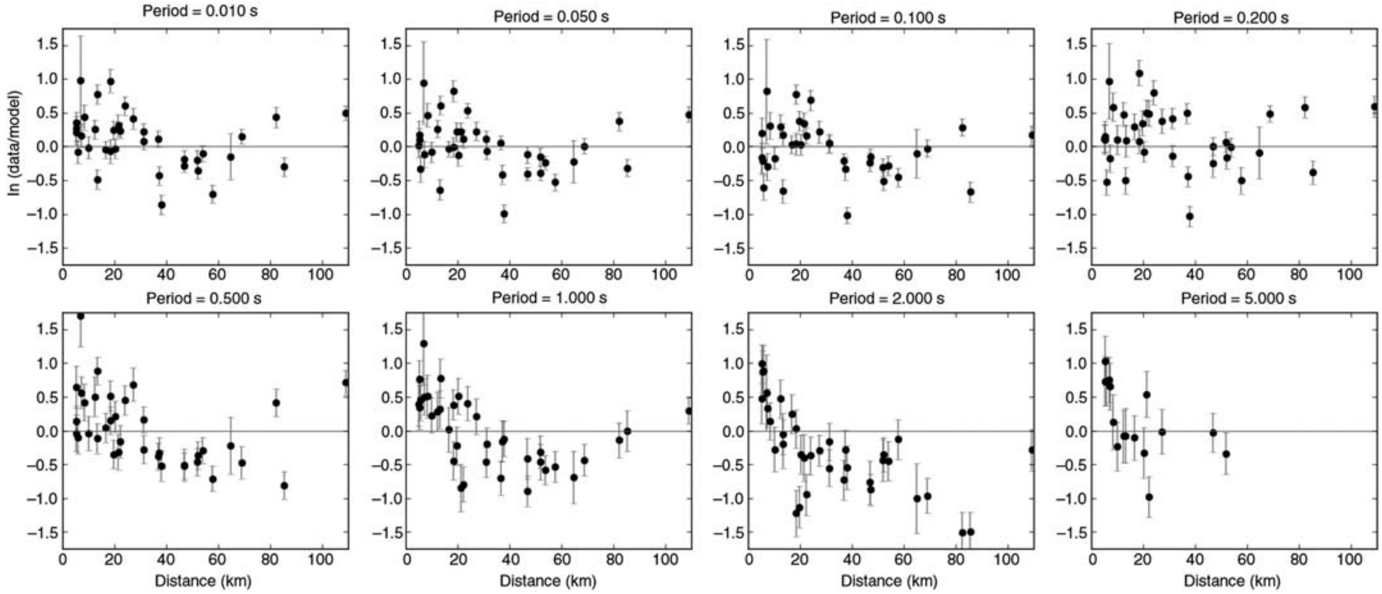


▲ **Figure 5.** Example of GOF with period considering four NGA-West1 GMPEs for a given scenario (Loma Prieta). The statistics are for data from all the stations. The solid line is the mean, the narrow band is the 90% confidence interval of the mean, and the wide band shows the standard deviation centered around the mean. (AS08, Abrahamson and Silva, 2008; BA08, Boore and Atkinson, 2008; CB08, Campbell and Bozorgnia, 2008; and CY08, Chiou and Youngs, 2008)

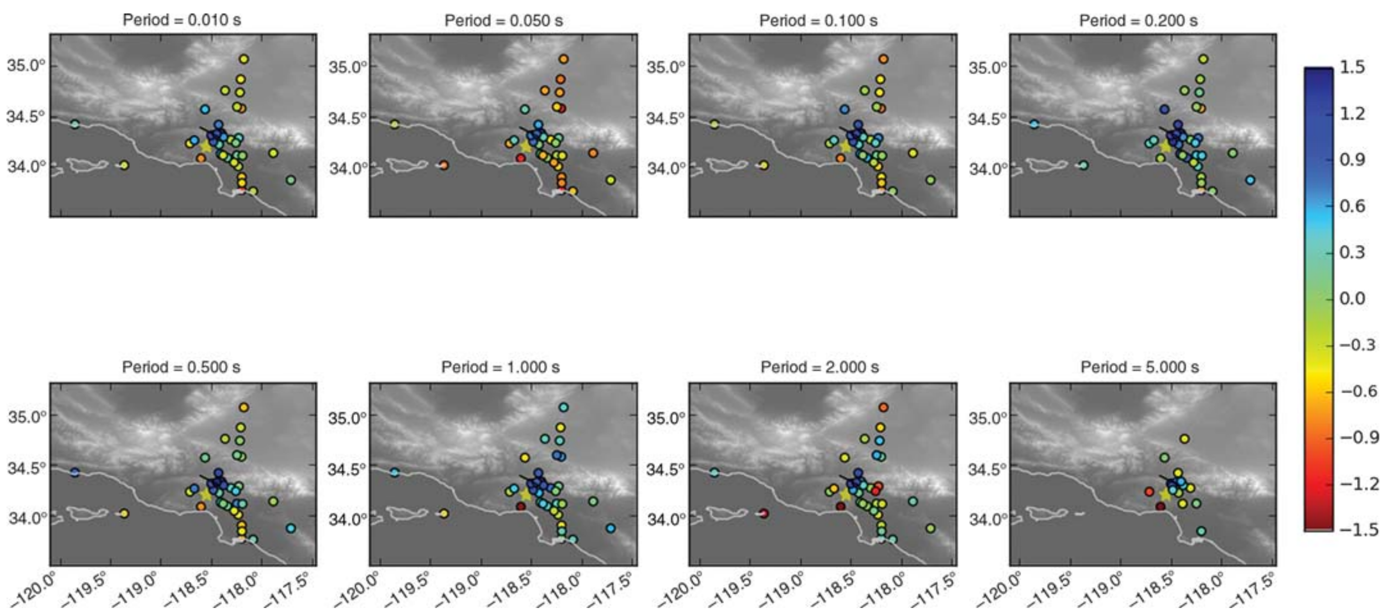
spectral periods using a linear (Fig. 6) and a logarithmic distance axis (not shown). The purpose of these plots is to perform a visual inspection of potential nonzero trends of attenuation with distance. The distance metric is the closest distance to the rupture plane (R_{rup}).

Mapped GOF for a Subset of Spectral Periods

The last type of GOF plot is a color-coded map representation of the data from Figure 6. The fault trace is shown with the GOF values anchored at the station locations (Fig. 7). This type of figure is again generated both for each realization and for the combined 50 realizations. This representation allows verification of whether or not there is a systematic directionality in the GOF values (e.g., the over- or underprediction trends of the simulations relative to recorded data). Figures 6 and 7 are



▲ **Figure 6.** Example of GOF with distance for a subset of periods for a given scenario (Northridge). The circle represents the mean of all the realizations, and the whiskers show the extrema. Similar plots with a logarithmic scale for distance are also produced. The presence of trends with distance indicates a mismatch between the attenuation of the recorded data and how it is modeled in the simulations.



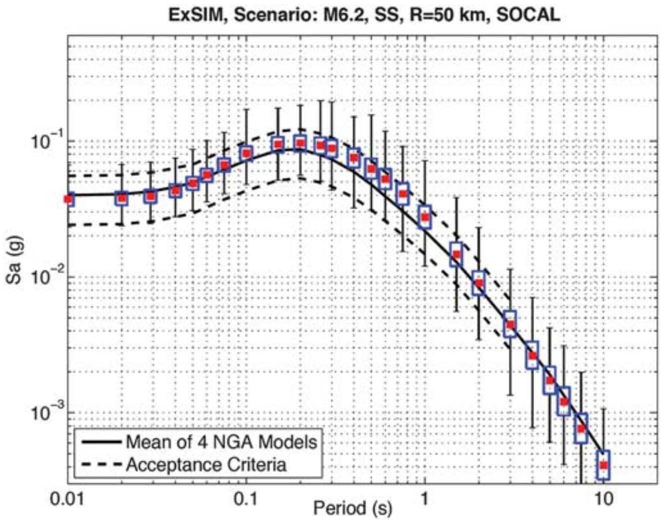
▲ **Figure 7.** Example of color-coded GOF map for a subset of periods. The projection of the fault trace is shown by the thick black line (partially hidden by colored circles). The example from above is for all the realizations of Northridge for a simulation method.

complementary and can be used together to detect systematic trends in simulation results.

Part B: Validation against GMPEs

Summary Response Spectrum Plot

The main evaluation tool for part B is a single plot for each scenario and crustal model combination, generated in response spectral space (Fig. 8). The solid black line shows the average of the median prediction from the four NGA-West1 GMPEs. The box plots represent the 50 realizations of the simulations, the red squares are the medians, the blue boxes represent plus or minus one standard deviation, and the whiskers are extended to the extrema. The evaluation criterion (dashed black lines) was established so as to be wide enough to limit a pass/fail grade for each scenario considered. The dashed lines were obtained by considering the upper and lower bounds of the



▲ **Figure 8.** Example plot for the evaluation against GMPEs (part B). See description in text. (SOCAL, southern California model)

GMPE predictions for the four models and the upper and lower bounds of the preliminary PEER NGA-West2 (Bozorgnia *et al.*, 2014) models in development as of 16 January 2013. A reference point was first specified by taking the largest GMPE prediction from all the models considered at any period, to which 15% was added (this number was selected based on judgment to increase the allowable range). The upper-bound spectrum then was defined by applying the ratio of the upper-bound reference point to the average spectrum. The same process was applied for the lower-bound spectrum criterion. This resulted in criterion limits capturing the GMPEs' range of ground motions and beyond. Because the criteria are defined on the extreme excursion from the mean at any period but applied equally at all the periods, the range is considered to be wide. Departure from that range is a definite sign that the model is not consistent with our current dataset and is a sign of potential issues with the simulations. There is no GMPE constraint for periods above 3 s, because the data are fairly sparse and cannot provide a reliable constraint.

DISCUSSION

This article summarized the design of the BBP validation exercise as a robust approach for validating simulation methods. Through this process, which involved weekly phone calls and regular in-person meetings of over a dozen of regular participants and many other contributors, we have truly capitalized on the value of collaborative effort. End users were part of the process to ensure the engineering perspective and objectives remained on track; modelers had an opportunity to be part of the development but also learned from each other through regular interactions; SCEC software developers implementing the methods and developing new postprocessing tools were part of the whole process as well. Through this, we developed a framework for validations that is driven by the needs of end users. Additional work is necessary to further validate simulated ground motions in terms of other applications and/or metrics. We will be building on the same four key objectives listed above to address new problems in increasing levels of difficulty (e.g., looking at duration and time series properties). In the future of the BBP development related to validation, we foresee addressing the validation of ground-motion variability and epistemic uncertainty, the implementation of new modeling methods, the implementation of site effects models, and the inclusion of more realistic models for faults (multisegment ruptures) and for the propagation media (include plasticity and 3D computations of the domain). ■

ACKNOWLEDGMENTS

This study was supported by funding and resources from four main entities: (1) the Pacific Gas and Electric Company; (2) the Southern California Edison Company; (3) the Pacific Earthquake Engineering Research Center (PEER) as part of Next Generation Attenuation-East, a project funded by the U.S. Nuclear Regulatory Commission, the U.S. Department of Energy, and the Electric Power Research Institute, with the participation of the U.S. Geological Survey (USGS); and (4) the Southern California Earthquake Center (SCEC), which is funded by the National Science Foundation and the USGS. Recorded earthquake data used in the validation were provided by PEER. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the organizations listed above. We are especially thankful to Fabio Silva, Phil Maechling, and Tran Hyun from SCEC. We thank all the Broadband Platform (BBP) participants and contributors for their time and efforts. Beyond those coauthoring articles in the current volume, we acknowledge Ronnie Kamai, Jeff Bayless, and Feng Wang, who were also instrumental in supporting the project.

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Published Online 17 December 2014