NGA-West2 Research Project

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The NGA-West2 project is a large multidisciplinary, multi-year research program on the Next Generation Attenuation (NGA) models for shallow crustal earthquakes in active tectonic regions. The research project has been coordinated by the Pacific Earthquake Engineering Research Center (PEER), with extensive technical interactions among many individuals and organizations. NGA-West2 addresses several key issues in ground-motion seismic hazard, including updating the NGA database for a magnitude range of 3.0–7.9; updating NGA ground-motion prediction equations (GMPEs) for the "average" horizontal component;

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Earthquake Spectra, Volume 30, No. 3, pages 973–987, August 2014; © 2014, Earthquake Engineering Research Institute

scaling response spectra for damping values other than 5%; quantifying the effects of directivity and directionality for horizontal ground motion; resolving discrepancies between the NGA and the National Earthquake Hazards Reduction Program (NEHRP) site amplification factors; analysis of epistemic uncertainty for NGA GMPEs; and developing GMPEs for vertical ground motion. This paper presents an overview of the NGA-West2 research program and its sub-projects. [DOI: 10.1193/072113EQS209M]

INTRODUCTION

In 2003, the Pacific Earthquake Engineering research Center (PEER) initiated a large research program to develop next generation attenuation relationships for shallow crustal earthquakes in active tectonic regions ("NGA," now called NGA-West1). The project concluded in 2008 with several important products, including a comprehensive database of ground motions recorded worldwide and a set of peer-reviewed ground-motion prediction equations (GMPEs) for horizontal motion (Power et al. 2008). Many researchers, practitioners, and organizations throughout the world are now using the NGA-West1 database and models for a wide range of applications, from research to seismic design codes, site-specific earthquake design and evaluation, and financial loss estimation. As successful as the original NGA-West1 program was, there were some important ground-motion issues and supporting research projects that were not addressed. Additionally, a number of well-recorded events have occurred worldwide that needed to be added to the database and analyzed. The goal of the follow-up study, NGA-West2, is to address the following topics:

- Expand the NGA-West1 database for small-, moderate-, and large-magnitude data.
- Update NGA-West1 GMPEs for the horizontal component of ground motion.
- Develop damping models to scale response spectra predicted by GMPEs to damping values other than the reference 5% value.
- Evaluate directivity models and their effects on horizontal ground motion.
- Quantify directionality (polarization) of horizontal ground motion.
- Evaluate epistemic uncertainty for NGA-West2 GMPEs.
- Further develop empirical and simulation-based site response models, and resolve discrepancies between the site factors from the NGA GMPEs and the NEHRP Provisions.
- Develop GMPEs for vertical ground motion.

The above main tasks or sub-projects were also supported by other research projects, such as the reclassification of main shocks and aftershocks for the purpose of developing GMPEs, detailed modeling of hanging-wall effects employing ground-motion simulations, and further investigation of simulation-based nonlinear site response.

The NGA research programs, including the NGA-West2 project, are large, complex multidisciplinary efforts; therefore, coordinated interactions among interns, students, postdoctoral fellows, faculty members, practitioners, end users, and internal and external reviewers are essential to producing successful outcomes that are both scientifically sound and that can address important technical issues in earthquake engineering. Such interactions become even more essential considering that the database, findings, and models of the NGA research programs are quickly adopted by the earthquake community in a wide spectrum of applications, ranging from research, national seismic hazard maps, seismic design codes, earthquake financial loss modeling, and site-specific seismic hazard evaluations for important facilities (e.g., power plants, dams, tall buildings, etc.).

This paper has 32 co-authors, reflecting the strong teamwork among researchers and practitioners involved in the NGA-West2 project. Due to space limitations, unfortunately, we could not list numerous part-time student interns who helped with the project over the last five years in the signal processing of recorded ground motions for the NGA-West2 database.

In the following sections, we present an overview of the NGA-West2 research program and its sub-projects.

NGA-WEST2 DATABASE

Thousands of ground motions recorded worldwide since 2003 have been uniformly processed and added to the NGA-West1 database. The latest version of the NGA-West2 database includes 21,332 (mostly) three-component recordings, after excluding the recordings with missing important metadata (e.g., magnitude) and/or missing ground-motion data (e.g., PGA). The new NGA-West2 database is larger than the NGA-West1 database by about a factor of six. The NGA-West2 database includes events with moment magnitude (**M**) ranging from 3.0 to 7.9. Figure 1 shows the magnitude–distance distribution of the database and its evolution since the formal establishment of PEER in 1997. The largest-magnitude events in the database are the 2002 Denali, Alaska, and 2008 Wenchuan, China, earthquakes, both with **M** 7.9. The oldest event in the database is the 1935 Helena, Montana, earthquake (**M** 6.0), and other recent moderate-to-large magnitude events in the database include the 2003 Bam, Iran (**M** 6.6); 2004 Parkfield, California (**M** 6.0); 2009 L'Aquila, Italy (**M** 6.3); 2010 El Mayor-Cucapah, Mexico (**M** 7.2); 2010 Darfield, New Zealand (**M** 7.0); and 2011 Christchurch, New Zealand (**M** 6.2), events. The distance range of the recordings in the NGA-West2 database is from 0.05 km to 1,533 km, in terms of the shortest distance from the recording site to the rupture plane, although the database is well-populated only to about 400 km.

In the NGA-West2 project, we added a large number of recordings from small-magnitude events. The database includes 10,706 recordings associated with events with $3.0 \leq \mathbf{M} \leq 4.5$. Small-magnitude data was added to the database because (a) NGA-West1 GMPEs were found to have misfits (generally overprediction) of small-magnitude observations (e.g., Campbell 2008, Atkinson and Morrison 2009, Chiou et al. 2010, Atkinson and Boore 2011), thus requiring an enhanced small **M** data set to improve predictions in NGA-West2; (b) the future development of "single-station sigma" will require multiple-events recorded at the same site (e.g., Al Atik et al. 2010, Lin et al. 2011), which practically can only be achieved from smaller magnitude data; and (c) to provide data needed to extend directivity models to smaller magnitudes.

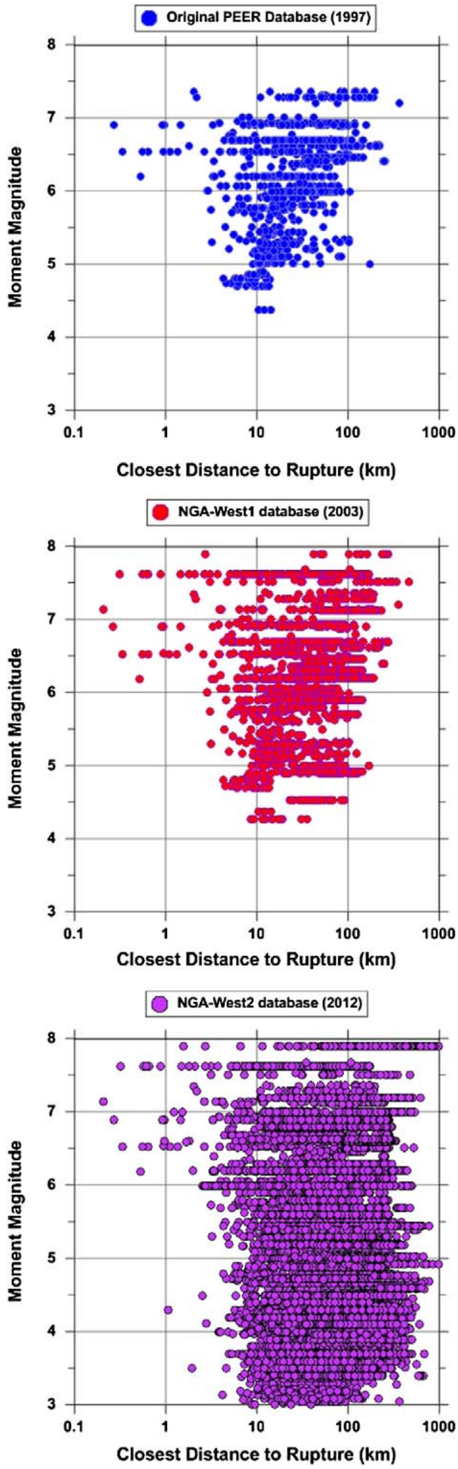

Figure 1. Distribution of recordings of the 1997 PEER, NGA-West1 and NGA-West2 ground motion databases with magnitude and distance.

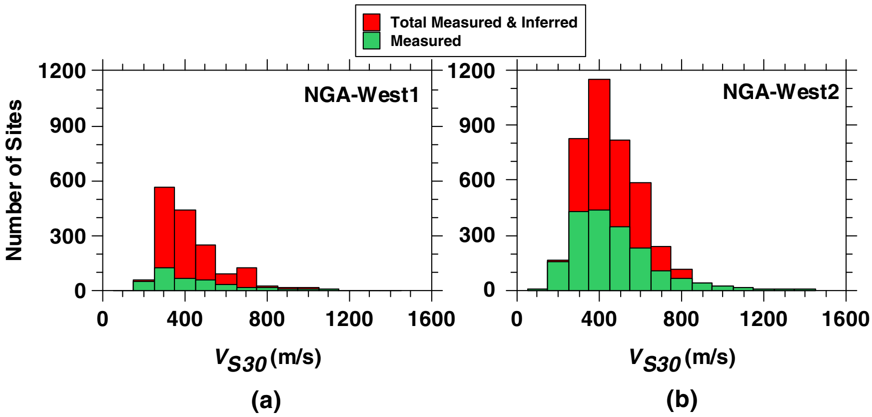

Figure 2. Distribution of V_{S30} in (a) NGA-West1 and (b) NGA-West2 databases (adapted from Seyhan and Stewart 2014). A site is considered as "measured" if there is a measured shear-wave velocity in the top 10 m (or deeper) of soil or rock.

Figure 2 shows the distribution of V_{S30} in the NGA-West1 versus the NGA-West2 databases, where V_{S30} is the time-averaged shear-wave velocity in the top 30 m of the site. It is evident that the number and percentage of the measured V_{S30} sites in the NGA-West2 database have significantly increased compared to those in the NGA-West1 database (Seyhan and Stewart 2014). This has important implications for site amplification, especially for rock sites where the database has been substantially enhanced.

As a consequence of adding well-recorded events in China, Italy, and Japan, the concept of the regionalization of ground-motion attributes has been examined in NGA-West2, including anelastic attenuation, site response, and within-event standard deviation.

Another aspect of the development of the NGA-West2 database was a major effort to reprocess the NGA-West1 recordings to widen the useable bandwidth at long periods. Many "pass-through" records in the NGA-West1 database were reprocessed from the "Volume 1" (uncorrected) data. Figure 3 shows the effect of this reprocessing effort. For example, at a period of 10 s the number of recordings with reliable data increased from 603 (originally processed in NGA-West1) to 1,527 (after the reprocessing), that is, an increase by a factor of 2.5.

In the tradition of transparency in the NGA program, the flatfiles of the NGA-West2 database used in the development of the GMPEs are made publicly available at the PEER website at http://peer.berkeley.edu/ngawest2/databases/. More details on the NGA-West2 database can be found in Ancheta et al. (2013, 2014).

NGA-WEST2 GMPEs FOR HORIZONTAL GROUND MOTION

In the NGA-West2 program, the process of database development and checking was carried out in parallel with the development and formulation of the GMPEs. While the large database was being finalized and checked, the NGA-West2 GMPE developers were

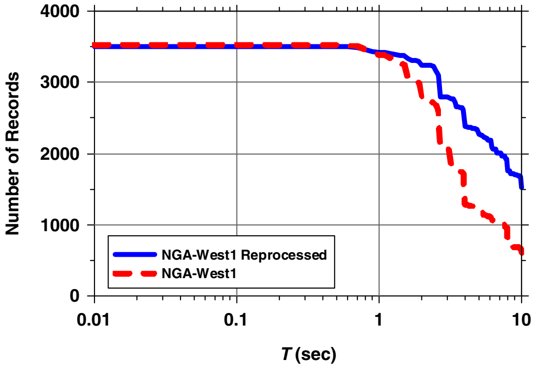

Figure 3. Effect of reprocessing of NGA-West1 records and widening the useable bandwidth (adapted from Ancheta et al. 2013).

examining the data and providing important technical input and feedback to the database team. This interactive process also helped the GMPE developers to observe some trends and issues in the data. The five horizontal GMPE developer teams are listed below alphabetically:

- Abrahamson, Silva, and Kamai (ASK)
- Boore, Stewart, Seyhan, and Atkinson (BSSA)
- Campbell and Bozorgnia (CB)
- Chiou and Youngs (CY)
- Idriss (I)

It should be noted that for vertical ground motion, the compositions of the GMPE developer teams are somewhat different from the above list (PEER 2013). The details of these new horizontal GMPEs can be found in Abrahamson et al. (2013, 2014), Boore et al. (2013, 2014), Campbell and Bozorgnia (2013, 2014), Chiou and Youngs (2013, 2014), and Idriss (2013, 2014).

The intensity measure (IM) used in the development of the horizontal GMPEs is RotD50, which is the 50th percentile of the rotated orientation-independent, period-dependent combined horizontal components defined by Boore (2010). Overall, for the purpose of GMPE development, the difference between RotD50 (in NGA-West2) and GMRotI50 (the IM used in NGA-West1) is relatively small (Boore 2010). One advantage of RotD50 is that it is in the same IM "family" as RotD100, which is the maximum rotated horizontal ground motion adopted by the U.S. building code after the completion of the NGA-West1 models (details can be found in Stewart et al. 2011).

The GMPE developers had the flexibility to select a subset of the NGA-West2 database for their analysis, provided they documented their specific data-selection criteria.

Similar to the NGA-West1 project, the horizontal GMPEs address: horizontal components of peak ground acceleration (PGA), peak ground velocity (PGV), and pseudo-absolute response spectral acceleration (PSA) for at least 21 oscillator periods (T) ranging from 0.01 s to 10 s. The 21 spectral periods are 0.01 s, 0.02 s, 0.03 s, 0.05 s, 0.075 s, 0.1 s, 0.15 s, 0.2 s, 0.25 s, 0.3 s, 0.4 s, 0.5 s, 0.75 s, 1 s, 1.5 s, 2 s, 3 s, 4 s, 5 s, 7.5 s, and 10 s. The NGA-West2 collective decision was to exclude peak ground displacement (PGD) due to its sensitivity to frequency-filtering parameters and record processing. The general applicable limits of the NGA-West2 GMPEs are $\mathbf{M} \leq 8.5$ for strike-slip faults, $\mathbf{M} \leq 8.0$ for reverse faults, and $\mathbf{M} \leq 7.5$ for normal faults, as well as rupture distance—R_{RUP}, or Joyner & Boore distance, R_{JB}—ranging from 0–300 km. The GMPE developers could justify their modifications (if any) of these ranges.

Examples of comparisons of the NGA-West2 GMPEs are provided in Figure 4 for distance scaling of a **M** 7.0 strike-slip earthquake for $V_{S30} = 760$ m/s for PGA and T = 1.0 s. Another example comparison showing magnitude scaling of the GMPEs is presented in Figure 5 for a strike-slip fault at 30 km and for $V_{S30} = 760$ m/s for PGA and T = 1.0 s.

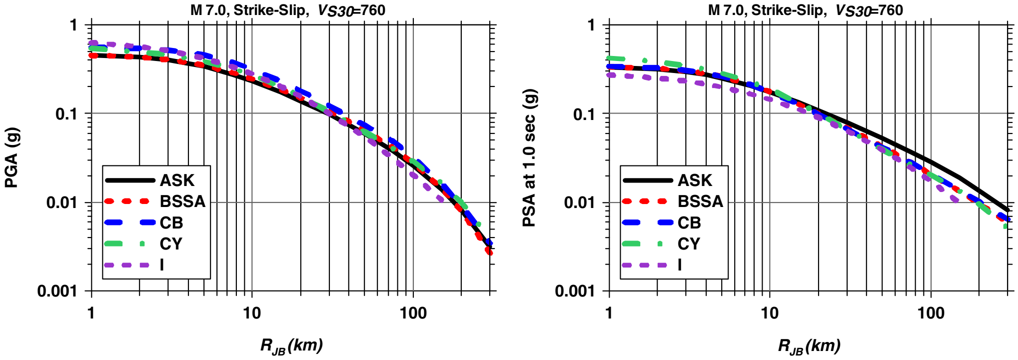

Figure 4. Examples of distance scaling of NGA-West2 GMPEs for PGA and PSA, for magnitude 7.0 strike-slip earthquakes and for $V_{S30} = 760$ m/s (adapted from Gregor et al. 2014).

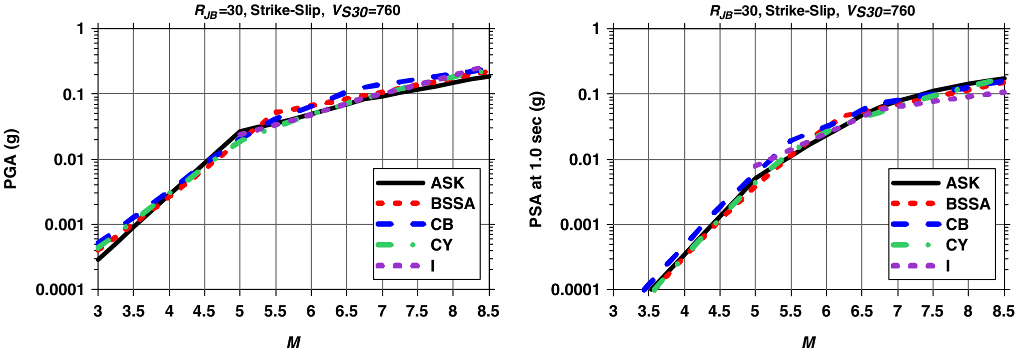

Figure 5. Examples of magnitude scaling of NGA-West2 GMPEs for PGA and PSA, strike-slip earthquakes, and a distance of $R_{JB} = 30$ km for $V_{S30} = 760$ m/s (adapted from Gregor et al. 2014).

As shown in the various GMPE papers in this volume, the enhancement of the database at small **M** has resolved the over-prediction issue that was present for the NGA-West1 GMPEs. Detailed comparisons of the NGA-West2 GMPEs for a combination of input parameters are presented in Gregor et al. (2014).

DEVELOPMENT OF DAMPING MODELS

The NGA-West1 and NGA-West2 spectral acceleration ground-motion models were developed for a reference damping ratio of 5%. In reality, however, structural and nonstructural systems can have damping ratios other than 5%, depending on the construction material, structural and nonstructural systems, and the intensity of input ground motions (e.g., Bozorgnia and Campbell 2004a). Widely used guidelines to map the 5% damped smooth elastic spectrum to other damping values pre-date the NGA data and are generally outdated. As part of the NGA-West2 project, PEER researchers developed a new damping model that can be used to adjust the 5% damped GMPEs for damping values ranging from 0.5% to 30% (Rezaeian et al. 2014a, 2014b). The new damping model was developed directly from the NGA-West2 database and is independent of any specific GMPE. Figure 6 presents the result of scaling 5% damped NGA-West1 response spectra for a range of damping values (Rezaeian et al. 2014a). Damping models were developed for the horizontal and vertical components of ground motion (Rezaeian et al. 2014a and 2014b, respectively).

DIRECTIVITY EFFECTS

In the NGA-West2 project, four directivity models were developed based on data from the NGA-West2 database and numerical simulations of large strike-slip and reverse-slip earthquakes (Spudich et al. 2013). All but one of the directivity models are explicitly “narrow-band” models (in which the effect of directivity is maximum at a specific period,

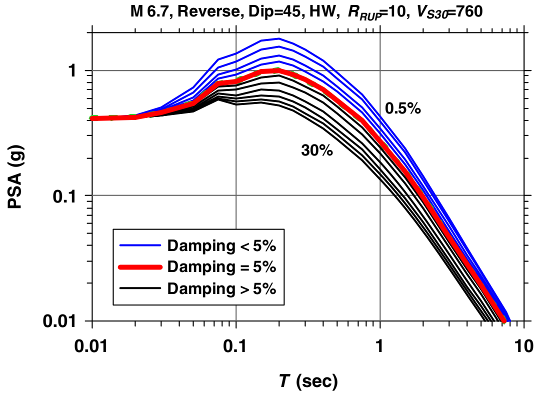

Figure 6. Scaling of the geometric mean of the five NGA-West1 GMPEs for 5% damping (middle curve in red color) for damping ratios: 0.5%, 1%, 2%, 3%, 5%, 7%, 10%, 15%, 20%, 25%, and 30%. Assumptions: **M** 6.7, reverse fault, dip = 45°, hanging wall, fault rupture width = 15 km, $R_{JB} = 0$ km, $R_X = 7$ km (adapted from Rezaeian et al. 2014a).

which is a function of **M**). Functional forms and preliminary coefficients of the models are presented in Spudich et al. (2013). A comparison of the directivity models suggests that the directivity model predictions are strongly influenced by the assumptions used to develop them, and more than one model should be used for site-specific studies of directivity for ruptures dipping below about 65 degrees (Spudich et al. 2013). For this reason, except for the Chiou and Youngs team, the NGA-West2 GMPE developer teams decided not to adopt any specific directivity model until the models are more extensively compared and interpreted. Therefore, the research work of the NGA-West2 directivity working group will continue.

DIRECTIONALITY OF HORIZONTAL GROUND MOTION

The direction (azimuth) and relative amplitudes of the maximum and minimum horizontal ground motions at a site located close to an active fault are important in determining the damage and/or loss to structures. As mentioned previously, the NGA-West2 GMPEs are based on the RotD50 horizontal component. Using the NGA-West2 database, empirical models for orientation-dependent spectra were developed (Shahi and Baker 2013, 2014). A model for the ratio RotD100/RotD50 and its aleatory variability was developed, which can be used to estimate RotD100 spectra from RotD50 spectral ordinates.

An interesting finding of this task is that only for the cases in which the site is within 5 km of the fault and the spectral period is longer than 0.5 s is the orientation of RotD100 more likely to be closer to the strike-normal than the strike-parallel direction. Beyond these ranges, the azimuth of RotD100 is random (Shahi and Baker 2013, 2014).

EPISTEMIC UNCERTAINTY FOR NGA-WEST2 GMPEs

A major strength of the NGA research programs has been the strong interaction and collaboration among the NGA GMPE developers and researchers. This interaction has resulted in a major improvement in the quality of the database and research outcomes. However, this interaction may have resulted in a lower epistemic uncertainty among the NGA GMPEs than would have occurred had the investigators worked separately without interacting. Recognizing this, the NGA-West2 GMPE developers recommended that a minimum level of epistemic uncertainty be incorporated into the median ground-motion estimation when applying the NGA-West2 models. Accordingly, a minimum additional epistemic uncertainty model is proposed based on statistical estimates of the uncertainty in the median predictions of each NGA-West2 GMPE. The details of the proposed additional minimum epistemic uncertainty model are presented in Al Atik and Youngs (2013, 2014).

SITE RESPONSE IN GMPEs AND BUILDING CODES

Both the NGA-West1 and NGA-West2 GMPEs include terms for local site amplification, and all five NGA-West2 GMPEs use V_{S30} as the site parameter. We are aware that site parameters other than V_{S30} have been proposed for use in predicting site response (such as site period or average velocities over different depth ranges). Stewart et al. (2013) undertook a review of site parameters used in GMPEs for all major tectonic domains world-wide as part of the Global Earthquake Model (GEM) project. The result of that review is that alternative single-value site parameters have not generally been shown to perform better than V_{S30}.

One such parameter is site period, which has been used to classify sites in a manner similar to V_{S30}, suggesting that it could be used as a replacement, but its benefits relative to V_{S30} are unclear. As such, a decision was made early in the project to continue the use of V_{S30} for NGA-West2. Additional reasons for doing this are that (1) V_{S30} data (measurements and proxy-based analysis) are much more widely available than the alternative site parameters, and (2) V_{S30} is the site parameter used in a number of building codes.

It is a common practice in engineering applications to use the site-amplification factors recommended by the NEHRP Provisions (e.g., BSSC 2009) and adopted in seismic codes worldwide. However, the NEHRP site factors are not entirely consistent with the site amplifications obtained from the NGA-West models (Stewart and Seyhan 2013). Therefore it is inconsistent to use NGA-West1 or NGA-West2 GMPEs with the current NEHRP site factors, as many users do to be consistent with the building code. To correct this problem, the discrepancy between the NEHRP site factors and those predicted by the NGA-West1 GMPEs was investigated, which demonstrated the cause of misfit as being principally due to differences in the reference velocity (i.e., where the amplification is unity) and differences in the level of site nonlinearity. Accordingly, an updated site-amplification model was developed from the NGA-West2 database and used to derive a new set of site factors for potential use in future NEHRP provisions and seismic codes (Stewart and Seyhan 2013, Seyhan and Stewart 2014).

DEVELOPMENT OF GMPEs FOR VERTICAL GROUND MOTIONS

Some structural and nonstructural elements are sensitive to the vertical component of ground motion, especially at near-source distances. It is also established that deriving vertical response spectra by scaling the horizontal spectra by a factor of two thirds is potentially in error (see Bozorgnia and Campbell 2004a, 2004b, Gülerce and Abrahamson 2011). The 2009 NEHRP Provisions (BSSC 2009) introduced recommendations for constructing vertical design spectra, which are generally consistent with the simplified vertical design spectra recommended by Bozorgnia and Campbell (2004b). These models predate the extensive NGA-West2 database, and the models have been updated as part of the NGA-West2 project. The scope of this special issue of *Earthquake Spectra*, however, is only on results and findings for horizontal motions. The NGA-West2 ground-motion models for the vertical component have been published separately (PEER 2013).

OTHER SUPPORTING RESEARCH PROJECTS

CLASSIFICATION OF “MAIN SHOCKS” VERSUS “AFTERSHOCKS”

Previous studies have shown that that median ground motions from aftershocks are systematically lower than median ground motions from main shocks, especially at short spectral periods, possibly due to different stress drops in the main shocks and aftershocks (e.g., Abrahamson and Silva 2008, Wooddell and Abrahamson 2012). The classical categorization of main shock versus aftershock—for example, based on the Gardner and Knopoff (1974) algorithm—has shortcomings, especially as related to the use of epicentral distance, which is a poor distance metric for events with an extended fault rupture. In the NGA-West2 project, an improved method of classification of “main shocks” and “aftershocks” was developed using the Joyner and Boore distance metric, R_{JB} (Joyner and Boore 1981), rather than the epicentral distance (Wooddell and Abrahamson 2012, 2014). Due to these differences, these events are referred to as “Class 1” and “Class 2” earthquakes. The new classification was employed in the NGA-West2 database, and the GMPE developers used this classification in their data selection and modeling.

DETAILED MODELING OF HANGING-WALL EFFECTS

Sites located on the hanging-wall (HW) of a dipping fault generally experience higher ground motions than sites on the footwall (FW), especially at short spectral periods. In order to capture HW effects, a relatively dense network of recording sites located on both the HW and FW is needed for a number of events with different values of magnitude, distance, dip angle, and depth to the top of the rupture plane. Such an empirical data set does not exist at this time; therefore, the NGA-West2 project utilized a series of finite-fault simulations to model HW effects (Donahue and Abrahamson 2014). Two NGA-West2 ground-motion modelers adopted this specific simulation-based HW model; however, to ensure consistency with the existing empirical data, they modified and calibrated the HW model empirically (Abrahamson et al. 2013, 2014; Campbell and Bozorgnia 2013, 2014).

SIMULATION-BASED NONLINEAR SITE RESPONSE

In the NGA-West1 project, Walling et al. (2008) developed a nonlinear site response model for horizontal ground motion that was employed by two of the GMPEs (Abrahamson and Silva 2008, Campbell and Bozorgnia 2008). Under the NGA-West2 project, the nonlinear soil amplification models developed by Walling et al. (2008) were revisited with an expanded simulation database (Kamai et al. 2013, 2014). The nonlinear soil amplification model was also generalized to have both PGA and PSA as input shaking parameters. This specific model was adopted by Abrahamson et al. (2013, 2014). Other GMPE developers either used the Walling et al. (2008) model or developed their own site amplification models. Seyhan and Stewart (2014) compared the nonlinearity from the Kamai et al. (2013, 2014) simulations to those identified from the NGA-West2 data and developed a hybrid amplification model.

CONCLUDING REMARKS

The NGA-West2 project is a comprehensive and coordinated multidisciplinary research program that addresses several key issues in ground-motion hazard for active crustal regions. The empirical database includes one of the largest sets of ground motions and associated metadata available globally. Various components of the database—including the instrument correction, spectral-filters, estimated V_{S30} values, distance measures, source characteristics, and spectral ordinates—were repeatedly reviewed and checked by various individuals and teams. However, it is still possible that there are errors in this very large database, and we welcome feedback from users.

Five GMPEs for the horizontal component of ground motion have been developed in the NGA-West2 program, and they supersede the 2008 (NGA-West1) versions. Supporting research projects helped to shed light on issues such as classification of “main shock” versus “aftershock,” hanging-wall effects, nonlinear site response, and quantification of minimum epistemic uncertainty. The NGA-West2 GMPEs have been adopted by the USGS for developing the 2014 U.S. National Seismic Hazard Maps (Rezaeian et al. 2014c). Therefore, similar to its previous version, the NGA-West2 database and models will impact seismic design, analysis, evaluation, and financial loss estimation in the western United States. Their worldwide applications and implementations are also expected to be widespread.

ACKNOWLEDGMENTS

The NGA-West2 research program was sponsored by the Pacific Earthquake Engineering Research Center (PEER) and was funded by the California Earthquake Authority, the California Department of Transportation, and the Pacific Gas & Electric Company. Partial support was also provided by Southern California Edison and Los Alamos National Labs. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsoring agencies. Members of the project oversight committee and external review committee: John Anderson, Roger Borcherdt, Silvia Mazzoni, Farzad Naeim, Mark Petersen, Chris Poland, and Chris Wills are gratefully acknowledged for their constructive feedback. Over several years, numerous students assisted in the signal processing of the recorded ground motion data; their efforts are greatly appreciated. We thank John Douglas and Steve Kramer for their efforts as Guest Editors of this special issue of *Earthquake Spectra*. We are grateful to Ruth Harris, *Jack Boatwright, and two anonymous reviewers* for their constructive comments.

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(Received 21 July 2013; accepted 17 October 2013)