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Abstract

This article summarizes the Next Generation Attenuation (NGA) Subduction (NGA-Sub) project, a major research program to develop a database and ground motion models (GMMs) for subduction regions. A comprehensive database of subduction earthquakes recorded worldwide was developed. The database includes a total of 214,020 individual records from 1,880 subduction events, which is by far the largest database of all the NGA programs. As part of the NGA-Sub program, four GMMs were developed. Three of them are global subduction GMMs with adjustment factors for up to seven worldwide regions: Alaska, Cascadia, Central America and Mexico, Japan, New Zealand, South America, and Taiwan. The fourth GMM is a new Japan-specific model. The GMMs provide median predictions, and the associated aleatory variability, of RotD50 horizontal components of peak ground acceleration, peak ground velocity, and 5%-damped pseudo-spectral acceleration (PSA) at oscillator periods ranging from 0.01 to 10 s. Three GMMs also quantified "within-model" epistemic uncertainty of the median prediction, which is important in regions with sparse

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ground motion data, such as Cascadia. In addition, a damping scaling model was developed to scale the predicted 5%-damped PSA of horizontal components to other damping ratios ranging from 0.5% to 30%. The NGA-Sub flatfile, which was used for the development of the NGA-Sub GMMs, and the NGA-Sub GMMs coded on various software platforms, have been posted for public use.

Keywords

Ground motion models, subduction earthquakes, NGA, Next Generation Attenuation for Subduction, attenuation, seismic hazard

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Introduction

Ground motion models (GMMs) are a key element of both probabilistic and deterministic seismic hazard analyses. Next Generation Attenuation (NGA) research programs have a goal of developing databases and GMMs for different tectonic regimes. To achieve that goal, the NGA programs have also supported various research projects. The NGA programs were initiated in October 2003. The first was called "NGA-West" (subsequently changed to "NGA-West1") and focused on shallow crustal earthquakes in active tectonic regions ("crustal" earthquakes). NGA-West1 was successfully completed in 2008 (Power et al., 2008) with a ground motion database and a corresponding set of GMMs. The GMMs were quickly adopted for applications in many parts of the world and by the US Geological Survey (USGS) for the development of the 2008 National Seismic Hazard Model (Petersen et al., 2008). NGA-West2, as a follow-up to NGA-West1, was started in

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2008 and completed in 2014 (Bozorgnia et al., 2014). The NGA-West2 database comprised 21,332 (mostly) three-component recordings, and the GMMs again were adopted by numerous agencies around the world, including for the 2014 National Seismic Hazard Model (Petersen et al., 2014; Rezaeian et al., 2014a). The scope of the next phase of the NGA programs was for stable continental regions, specifically Central and Eastern North America (NGA-East). Midway through the project, the NGA-East was switched from a science and engineering research program to a formal Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 study (SSHAC, 1997). Under the formal SSHAC Level 3 study, the project was extensively reviewed by a large review panel and was completed in 2018 (Goulet et al., 2018). Recently, after another internal review, the US Nuclear Regulatory Commission (NRC) validated the NGA-East GMMs for application to nuclear power plants (NRC, 2020). The NGA-East GMMs were also adopted by the USGS for the 2018 National Seismic Hazard Model (Petersen et al., 2019; Rezaeian et al., 2021b).

Having addressed ground motions from shallow crustal earthquakes in both active and stable continental tectonic regions in the NGA-West1, NGA-West2, and NGA-East programs, subduction regions were studied under a new program, NGA-Subduction or NGA-Sub (Bozorgnia et al., 2018). The goal of the NGA-Sub program was to develop a comprehensive database of ground motions recorded in worldwide subduction earthquakes, develop multiple GMMs, and provide epistemic uncertainty of the ground motion predictions.

Following the tradition of NGA research programs, the NGA-Sub project was organized such that GMM developers were engaged from the outset and participated in, or reviewed, the data collection, database development, and quality assurance (QA) processes. Because the NGA-Sub database is very large and was developed essentially from scratch, those processes were lengthy, requiring the development of consistent and systematic procedures for record processing and development of metadata parameters (e.g. for source, path, and site condition). In such an extensive and interactive process, a preliminary database is developed, the GMM developers examine the database, errors in the database or improvements in protocols are identified, the database is updated, GMMs are updated and debugged, and the final results are published. This process, albeit tedious, results in higher quality final products than each researcher could achieve individually.

This article summarizes the research activities of NGA-Sub, including the development of the NGA-Sub database and GMMs.

NGA-Sub database

Unlike the NGA-West1 and NGA-West2 databases that were started with an existing small and incomplete dataset, the NGA-Sub database was developed almost from scratch, especially in terms of collecting and processing of "raw" ground motion time series (i.e. digital records without instrument corrections, baseline correction, or filtering) and associated metadata. A key pre-NGA-Sub GMM for subduction earthquakes was BC Hydro (Abrahamson et al., 2016), in which the time series were collected from various sources with varying signal processing procedures. In addition, none of the prior global subduction databases included data from the 2011 Tohoku, Japan, and 2010 Maule, Chile large magnitude events (Mazzoni et al., this volume).

In NGA-Sub, we collected raw time series recorded in many parts of the world and uniformly processed them according to the well-established NGA signal processing protocols (e.g., Goulet et al., 2021). Strong-motion recordings, and the metadata, from seven regions in the world were collected, organized, and processed (Bozorgnia and Stewart, 2020). These regions are as follows:

1. Alaska (AK);
2. Cascadia (CASC);
3. Central America and Mexico (CAM);
4. Japan (JP);
5. New Zealand (NZ);
6. South America (SA);
7. Taiwan (TW).

The distribution of the epicenters of the worldwide NGA-Sub events is presented in Figure 1. In the case of New Zealand, the records that were obtained had been processed previously (from Van Houtte et al., 2017) and were adopted for NGA-Sub; however, for all other regions, we collected and processed raw records.

The NGA-Sub database includes 71,340 three-component recordings (a total of 214,020 individual records) from 1,880 worldwide events. After removing events without magnitudes, hypocenter locations, assigned event types, distances, or critical site data, the database was reduced to 65,403 three-component recordings (196,209 individual records) from 976 events (Mazzoni et al., this volume). By far, this is the largest database among all NGA programs. For example, the NGA-Sub database is by a factor of three larger than that for the NGA-West2. The NGA-Sub database also includes two large-magnitude events: the 2011 **M**9.1 Tohoku, Japan, and the 2010 **M**8.8 Maule, Chile earthquakes. The database may be accessed through the UCLA website (Mazzoni et al., 2021).

Figure 2 shows the magnitude–distance distribution of the NGA-Sub database after removing the incomplete data as explained above. Superimposed in Figure 2a is the dataset used in the BC Hydro (Abrahamson et al., 2016) project. The NGA-Sub database is by a factor of 6.5 (in terms of recordings) and a factor of 3.3 (in terms of events) larger than

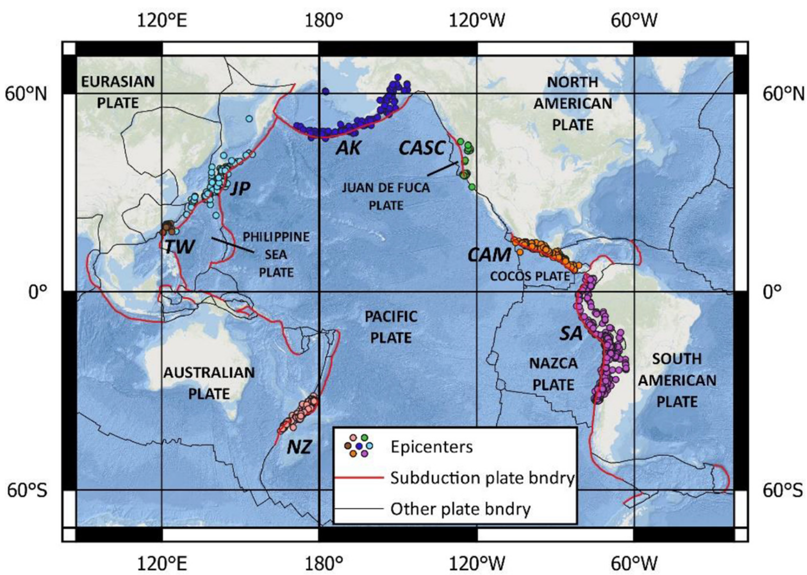

Figure 1. Locations of epicenters in the seven regions of the NGA-Sub database (adapted from Contreras et al., this volume).

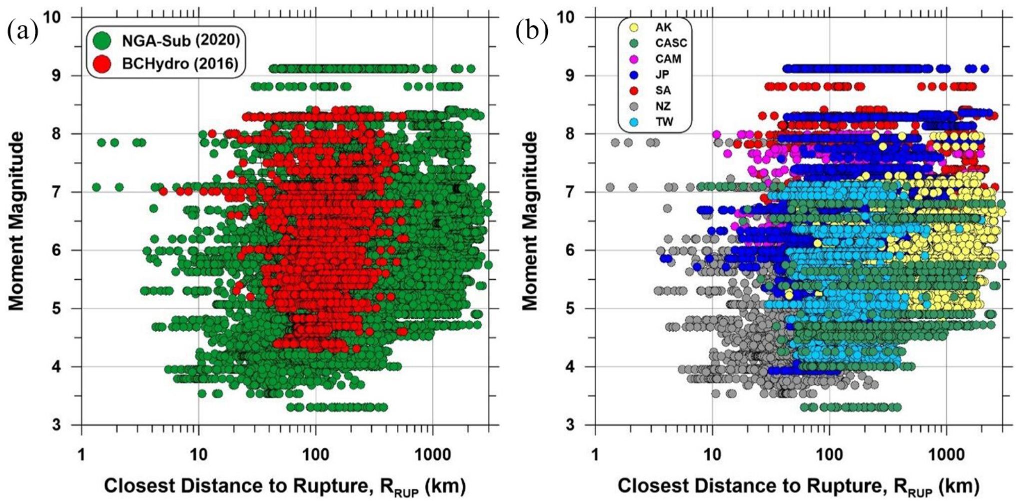

Figure 2. Magnitude–distance distribution of NGA-Sub database. (a) NGA-Sub versus BC Hydro (Abrahamson et al., 2016) datasets. (b) NGA-Sub data distributed over the seven regions. Figure 2b is adapted from Mazzoni et al. (this volume).

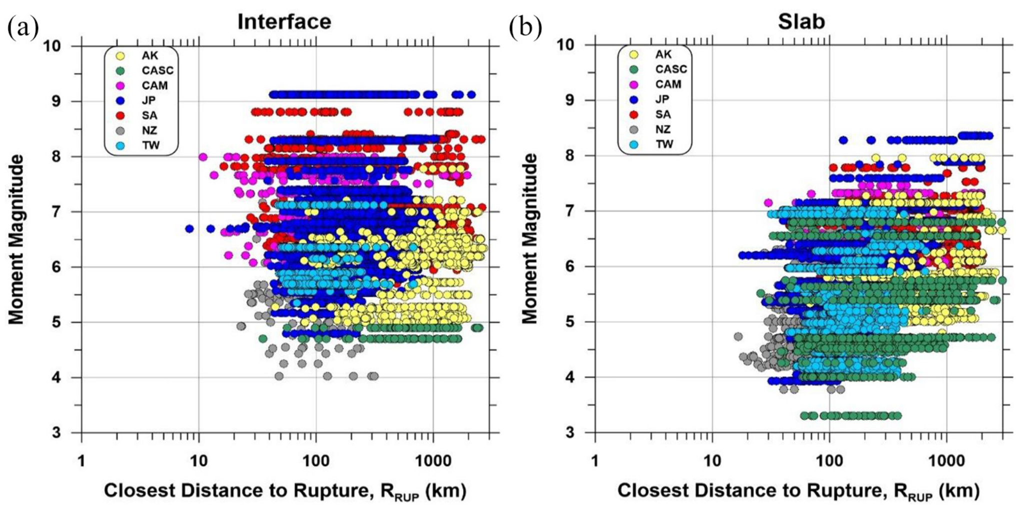

Figure 3. Regionalized magnitude–distance distribution of the NGA-Sub database. (a) Interface events. (b) Intraslab ("slab") events (adapted from Mazzoni et al., this volume).

the BC Hydro dataset. Figure 2b shows magnitude–distance distributions for the seven regions indicated above. The largest numbers of recordings and events in the NGA-Sub database are from Japan and South America, respectively (Contreras et al., this volume).

Figure 3 presents the magnitude–distance distribution of the database separated by interface and intraslab ("slab") events and by the seven regions. The interface subset of the database includes 361 events and 23,567 three-component recordings. The slab subset of the database includes 383 events and 27,593 three-component recordings. It should be noted that the overall NGA-Sub database also includes events classified other than interface and slab as elaborated in Contreras et al. (this volume).

Source parameters in the NGA-Sub database include (Contreras et al., 2020, this volume) the following:

- Moment magnitude (**M**);
- Event type (interface, intraslab, shallow crustal, outer-rise, etc.);
- Style of faulting classified from rake angle as either strike slip, normal, reverse, reverse oblique, or normal oblique;
- Event classification: mainshock/aftershock designations in the form of Class 1 or 2 (Wooddell, 2018);
- Rupture dimensions (along-strike, down-dip) of one or more planes; hypocentral depth and depth to top of rupture;
- Event location in forearc or backarc regions.

Path parameters in the database include (Contreras et al., 2020, this volume) the following:

- The closest distance to the rupture plane (R_{RUP});
- Closest distance to the surface projection of the rupture plane (R_{JB});
- The maximum rupture distance that should be considered for a given data provider and event to avoid sampling bias (R_{MAX});
- The portion of the source-to-site path in forearc and backarc regions (as applicable).

Site parameters include (Ahdi et al., 2020, this volume) the following:

- Recommended V_{S30} values and their uncertainty;
- Details related to measured shear-wave velocity (V_S) profiles when available, such as the maximum depth of the profile (z_p), time-averaged V_S to z_p, and data source;
- Proxies used for V_{S30} estimation in the absence of onsite measurements, such as surface geology, geomorphic terrain class, and topographic slope;
- Basin depth information, such as the depth to a particular V_S horizon (i.e. Z_x = the depth to the x km/s iso-surface) where available from measurements or regional 3D velocity models;
- Indicators of whether a station is located in the forearc or backarc of the particular subduction zone region for which it recorded data.

Intensity measures (IMs) in the database include (Mazzoni et al., 2020, this volume) the following:

- Peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD);
- Pseudo-spectral accelerations (PSA) for 111 oscillator periods ranging from 0.01 to 20 s. As always, care should be taken on using PSA values outside the signal processing usable bandwidth. PSA values for the following cases were computed:
    - Individual as-recorded components (H1, H2, and V)
    - Combinations of the two horizontal components: RotD00, RotD50, and RotD100 (Boore, 2010)
    - 11 viscous damping ratios between 0.5% and 30%.

- Arias Intensity and time intervals between different percentiles of Arias Intensity (5% to 95% in steps of 5%) used to compute significant durations
- Cumulative absolute velocity, CAV (see e.g. Campbell and Bozorgnia, 2010)
- Smoothed Fourier Amplitude Spectra (FAS) for the effective amplitude spectrum (EAS) (Goulet et al., 2018)

The NGA-Sub dataset was organized as a relational database (Mazzoni et al., this volume). Advantages of such a relational database are that updates (e.g. of V_{S30} for an individual site) can be efficiently made in pertinent individual tables without affecting other tables, and at appropriate times, desired data fields including updates can be automatically exported to a "flatfile," which is popular for GMM developers and applications. QA checks occur at the level of individual tables (e.g. for site parameters, various source parameters), which streamlines workflow and reduces errors. As is the characteristic of NGA programs, the elements of the database used for the GMM development are made available to the public. For example, the *final version* of the NGA-Sub relational database and flatfiles used by the GMM teams can be accessed from Mazzoni et al. (2021).

NGA-Sub GMMs

NGA-Sub GMMs were developed as the outcome of productive interactions between GMM developers and the database team. The NGA-Sub GMMs were developed based in part on the NGA-Sub database and are intended to predict the RotD50 horizontal component of ground motions for PGA, PGV, and 5%-damped PSA (0.01–10 s). Similar to the previous NGA programs, the GMM developers could select a subset of the database for their analyses; however, they were required to justify their specific inclusion/exclusion criteria. At the time of writing this article, four NGA-Sub GMMs are finalized and available to the public. These GMMs are listed below (alphabetically):

- Abrahamson and Gülerce (AG);
- Kuehn, Bozorgnia, Campbell, and Gregor (KBCG);
- Parker, Stewart, Boore, Atkinson, and Hassani (PSBAH);
- Si, Midorikawa, and Kishida (SMK).

Similar to other NGA programs, the GMMs have been developed to a large degree based on the recorded empirical ground motion data. Details of these four GMMs have been documented in the following series of reports and papers: Abrahamson and Gulerce (2020, this volume), Kuehn et al. (2020, this volume), Parker et al. (2020, this volume), and Si et al. (2020, this volume). The final versions of the NGA-Sub GMMs as published in *Earthquake Spectra* (this volume) are recommended to be used. The results of these models are compared in Gregor et al. (2020, this volume).

The regionalization has been implemented by varying the constant term of the GMM, the V_{S30} scaling term, the anelastic attenuation term, and the magnitude-scaling "breakpoint," where the slope of the IM versus magnitude is reduced (Campbell, 2020; Gregor et al., this volume; Ji and Archuleta, 2018). The SMK model is Japan-specific, as the developers used only subduction earthquakes recorded in Japan. These models also include basin effects for Cascadia (AG, KBCG, and PSBAH models) and for Japan (all models). Table 1 summarizes the independent variables used in the models, and Table 2 provides a

Table 1. Metadata used in AG, KBCG, PSBAH, and SMK models (Gregor et al., this volume).

Parameter	AG	KBCG	PSBAH	SMK
Moment magnitude	**M**	**M**	**M**	**M**
Closest distance to rupture plane (km)	R_{RUP}	R_{RUP}	R_{RUP}	R_{RUP}
Depth to top of rupture (km)	Z_{TOR} (slab only)	Z_{TOR}	–	–
Hypocentral depth (km)	–	–	Z_{HYP} (slab only)	D
Moho depth (km)	–	–	–	Moho depth
Average shear-wave velocity in top 30 m (m/s)	V_{S30}	V_{S30}	V_{S30}	V_{S30}
Depth to 2.5 km/s boundary (km)	$Z_{2.5}$ (only for Cascadia and Japan Basins)	$Z_{2.5}$ (only for Cascadia and Japan Basins)	$Z_{2.5}$ (only for Cascadia and Japan Basins)	$Z_{2.5}$ (only for Japan Basin)
Depth to 1.0 km/s boundary (km)	–	$Z_{1.0}$ (only for Taiwan and New Zealand Basins)	–	–
Interface/slab classification	0 = Interface / 1 = Slab	0 = Interface / 1 = Slab	0 = Interface / 1 = Slab	0 = Interface / 1 = Slab

summary of the applicable ranges in magnitude, distance, and V_{S30} values for each of the models (Gregor et al., this volume).

Each NGA-Sub GMM provides median and aleatory variability models for the selected IMs. A comparison of the median PSA predictions of the AG, KBCG, and PSBAH models is presented in Figure 4 for interface and slab scenarios for the Cascadia region. In this figure, the corresponding PSA predictions for the global cases are also shown for comparison. Gregor et al. (2020, this volume) present similar comparisons for other regions and comparisons of the NGA-Sub GMMs with existing subduction GMMs, such as BC Hydro (Abrahamson et al., 2016). Figure 5a shows a comparison of the total aleatory standard deviations for AG, KBCG, PSBAH, and SMK (Gregor et al., 2020, this volume). The aleatory standard deviations for the KBCG and SMK models are independent of distance, magnitude, and site conditions; and for the PSBAH model, they are a function of distance and V_{S30}. KBCG and PSBAH GMMs assume region-independent aleatory variability. The AG model has the between-event standard deviation as region- and distance-independent, whereas the within-event standard deviations are both region- and distance-dependent. Each of the four models assumes the same variability for interface and slab events (Gregor et al., 2020, this volume).

An important feature of the NGA-Sub GMMs is the quantification of within-model epistemic uncertainty. This is the *uncertainty in the median prediction*. For example, if region "A" has a substantially smaller number of recordings and/or earthquakes than region "B," the uncertainty of the median prediction of an IM for region A should be larger than that for B. The SMK model does not provide an estimate of epistemic uncertainty, and the other models treat this epistemic uncertainty quantification differently (Gregor et al., this volume). For the KBCG model, the within-model epistemic uncertainty is quantified by generating 800 samples of the posterior distributions of the model

Table 2. Ranges of applicability of AG, KBCG, PSBAH, and SMK models (Gregor et al., 2020, this volume).

	AG	KBCG	PSBAH	SMK
Magnitude	$6 \leqslant \mathbf{M} \leqslant 9.5$ (Interface) $5 \leqslant \mathbf{M} \leqslant 8.0$ (Slab)	$5 \leqslant \mathbf{M} \leqslant 9.5$ (Interface) $5 \leqslant \mathbf{M} \leqslant 8.5$ (Slab)	$4.5 \leqslant \mathbf{M} \leqslant 9.5$ (Interface) $4.5 \leqslant \mathbf{M} \leqslant 8.5$ (Slab)	$5.5 \leqslant \mathbf{M} \leqslant 9.1$ (Interface) $5.6 \leqslant \mathbf{M} \leqslant 8.3$ (Slab)
Distance (km)	$R_{RUP} \leqslant 500$ $R_{RUP} \leqslant 800$[a]	$10 \leqslant R_{RUP} \leqslant 1000$	$20 \leqslant R_{RUP} \leqslant 1000$ (Interface) $35 \leqslant R_{RUP} \leqslant 1000$ (Slab)	$14 \leqslant R_{RUP} \leqslant 300$ (Interface) $18 \leqslant R_{RUP} \leqslant 300$ (Slab)
V_{S30} (m/s)	$150 \leqslant V_{S30} \leqslant 1500$	$150 \leqslant V_{S30} \leqslant 1500$	$150 \leqslant V_{S30} \leqslant 2000$	$100 \leqslant V_{S30} \leqslant 1900$
Source depth (km)	$Z_{TOR} \leqslant 360$ (Slab)	$Z_{TOR} \leqslant 50$ (Interface) $Z_{TOR} \leqslant 200$ (Slab)[b]	$Z_{HYP} \leqslant 40$ (Interface) $20 \leqslant Z_{HYP} \leqslant 200$ (Slab)	$4 \leqslant D \leqslant 50$ (Interface) $18 \leqslant D \leqslant 100$ (Slab)
Region	Global and Regionalized	Global and Regionalized	Global and Regionalized	Japan

[a]For Cascadia events.
[b]For Columbia: $Z_{TOR} \leqslant 150$ km for slab events.

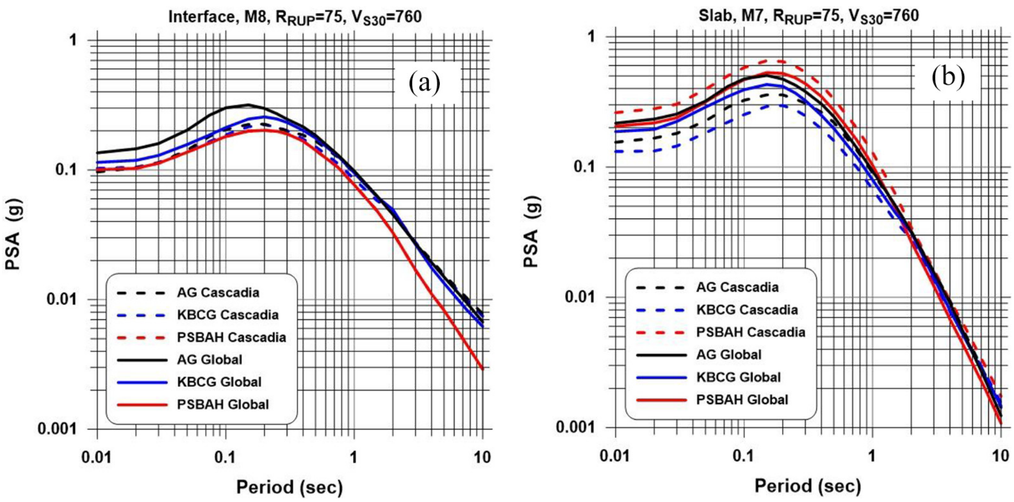

Figure 4. Comparison of the predicted median PSA from AG, KBCG, and PSBAH for the Global and Cascadia regions and for interface (a) and slab (b) scenarios (from Gregor et al., this volume). In (a), the PSBAH estimates for the Global and Cascadia scenarios are overlapping each other. In this figure, the following parameters were used: (a) AG: $Z_{2.5}$ = 2; KBCG: $Z_{2.5}$ = not used; and PSBAH: $Z_{2.5}$ = 1.3 km; (b) AG: $Z_{2.5}$ = 2, Z_{TOR} = 60 km; KBCG: $Z_{2.5}$ = not used, Z_{TOR} = 60 km; and PSBAH: $Z_{2.5}$ = 1.3, Z_{HYP} = 60 km.

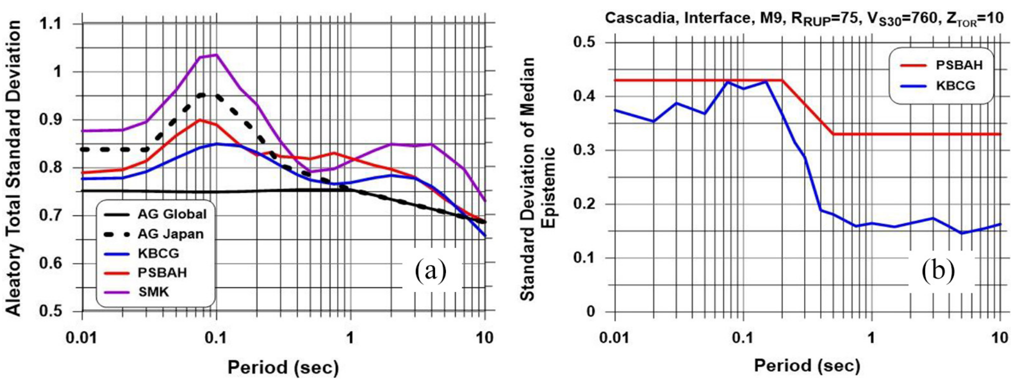

Figure 5. (a) Comparison of total aleatory standard deviations of AG, KBCG, PSBAH, and SMK. The AG and PSBAH cases are for $R_{RUP} \leqslant 200$ km and $V_{S30} \geqslant 500$ m/s. The AG Global aleatory model is for the Cascadia, New Zealand, and Taiwan Regions. (b) Within-model epistemic standard deviations of KBCG and PSBAH for an interface scenario in Cascadia for **M9**, R_{RUP} = 75 km, V_{S30} = 760 m/s, Z_{TOR} = 10 km (modified from Gregor et al. (this volume). Note: (a) and (b) have different vertical axis scales, and vertical axes are in terms of natural (base e) logarithms.

coefficients and standard deviations using Bayesian inference (Kuehn et al., 2020, this volume). For the PSBAH and AG models, epistemic uncertainty is provided on the constant term by region and for the global model, which is amenable to a "scaled-backbone" approach (Atkinson et al., 2014). A comparison of the epistemic uncertainties of the KBCG and PSBAH models for a Cascadia interface scenario is presented in Figure 5b. These epistemic uncertainties are region-, event type-, scenario-, and period-dependent.

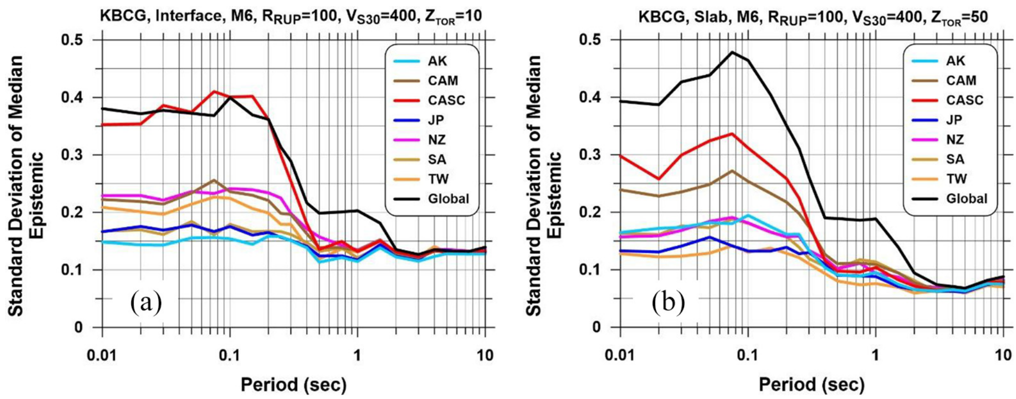

Figure 6. Within-model epistemic standard deviations of median predictions of KBCG. (a) For interface. (b) For slab. For these specific scenarios, the uncertainties for the global case and the seven regions are shown in these figures (adapted from Kuehn et al. (2020, this volume). Note: vertical axes are in terms of natural (base e) logarithms.

Figure 6 shows the KBCG epistemic uncertainty for interface and slab scenarios for different regions. This figure shows that for a region with fewer recordings and earthquakes, such as Cascadia, the uncertainty of the median prediction is larger than that for regions with more data, such as Japan. Thus, for applications of these models to regions with sparse data, the epistemic uncertainty of the median prediction should be considered.

Currently, the KBCG and PSBAH NGA-Sub models have been coded in Visual Basic, MATLAB, Python, and R, and posted on a UCLA website (Mazzoni, 2020). The results of these computer codes have been compared with each other to ensure consistency. The within-model epistemic uncertainty, as indicated above, has also been coded in these publicly available computer programs. For the AG model, currently the Excel file and Fortran code of the model have also been posted at a PEER website (Abrahamson and Gulerce, 2020).

Spectral damping scaling factors

The NGA-Sub GMMs are based on 5%-damped PSA data; thus, they can predict spectral ordinates only for 5% critical damping ratio. To scale the predicted PSA values to other damping ratios, a damping scaling factor (DSF) is needed. For NGA-West2, Rezaeian et al. (2014b) developed a parametric DSF model for damping ratios of 0.5%–30%. As part of NGA-Sub, magnitude- and distance-dependent parametric models of the DSF for subduction interface and intraslab earthquakes for the horizontal (RotD50) component of ground motion were developed by Rezaeian et al. (2021a). The functional form for the DSF model is the same as that of the NGA-West2 DSF model, but the coefficients were computed using the NGA-Sub database. The new subduction DSF model is applicable to periods longer than 0.1 s. Figure 7 presents the PSA for various damping ratios generated for **M**9 interface and **M**7 slab events at a distance of R_{RUP} = 75 km. In this figure, the 5%-damped PSA is the average of KBCG and PSBAH assuming Z_{TOR} = 10 km and Z_{HYP} (hypocentral depth) = 20 km for the interface scenario, and Z_{TOR} = 50 km and Z_{HYP} = 50 km for the slab scenario (Rezaeian et al., 2021a). Both scenarios are for V_{S30} = 760 m/s and default basin effects. A parametric model for the standard deviation

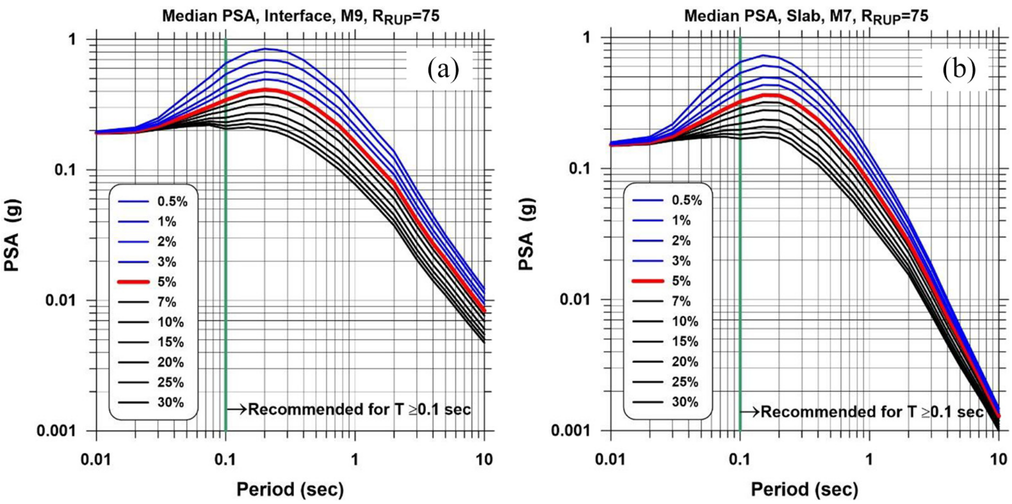

Figure 7. Damped PSA generated by applying the DSFs for interface (a) and slab (b) scenarios (adapted from Rezaeian et al., 2021a). The base 5%-damped spectra are based on the average of KBCG and PSBAH for V_{S30} = 760 m/s.

of the DSF was also developed empirically by Rezaeian et al. (2021a) for subduction earthquakes that can be used to adjust the aleatory variability of the 5%-damped PSA.

Concluding remarks

NGA-Sub is the latest research program in the NGA program series, and its focus is on the subduction regions of the world. A comprehensive database of subduction earthquake ground motions recorded worldwide is developed. The database includes a total of 214,020 individual records from 1,880 events. This is the largest database of any NGA program and is over a factor of three larger than that of the NGA-West2 program.

The recorded ground motion database is used by four modeling teams to develop GMMs. Three teams (AG, KBCG, and PSBAH) developed global subduction GMMs and regionalized models for seven worldwide regions: Alaska, Cascadia, Central America and Mexico, Japan, New Zealand, South America, and Taiwan. The SMK model is Japan-specific, as only Japanese data are used in its development. NGA-Sub GMMs produce median predictions of RotD50 horizontal components of PGA, PGV, and 5%-damped PSA at oscillator periods ranging from 0.01 to 10 s. The models also quantify the aleatory variability of the IMs. The final versions of the NGA-Sub GMMs as published in *Earthquake Spectra* (this volume) are recommended for use.

The SMK model does not provide an estimate of epistemic uncertainty. The AG, KBCG, and PSBAH models quantify "within-model" epistemic uncertainty of the median prediction. In regions with sparse data, such as Cascadia, the median prediction of the IM has larger within-model epistemic uncertainty than regions with more recorded ground motion data, such as Japan. Thus, it is important to incorporate such epistemic uncertainty in median prediction of the IMs, especially where the data are sparse. For some scenarios, the use of multiple GMMs may not be necessarily sufficient to capture within-model uncertainty.

As part of the NGA-Sub program, a damping scaling model is also developed to scale the predicted 5%-damped PSA of horizontal components to other damping ratios ranging from 0.5% to 30%.

Following the tradition of transparency in NGA programs, the NGA-Sub relational database and flatfile, as used for the development of the NGA-Sub GMMs, are made available to the public. The final version of the NGA-Sub database can be accessed from Mazzoni, et al. (2021). Currently, the KBCG and PSBAH NGA-Sub GMMs have also been coded in Visual Basic, MATLAB, Python, and R, verified for accuracy and posted for public use (Mazzoni, 2020).

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References

Abrahamson N and Gulerce Z (2020) *Regionalized ground-motion models for subduction earthquakes based on the NGA-SUB database*. PEER Report 2020/25. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Abrahamson N and Gulerce Z (this volume) Summary of the Abrahamson and Gulerce NGA-Sub ground-motion model for subduction earthquakes. *Earthquake Spectra*.

Abrahamson N, Gregor N and Addo K (2016) BCHydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra* 32: 23–44.

Ahdi SK, Ancheta TD, Contreras V, Kishida T, Kwak DY, Kwok AO-L, Parker GA, Ruz F and Stewart JP (2020) *Chapter 5: Site condition parameters, in Data Resources for NGA-Subduction*

Project. PEER Report No. 2020/02. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Ahdi SK, Ancheta TD, Contreras V, Kishida T, Kwak DY, Kwok AO-L, Parker GA, Ruz F and Stewart JP (this volume) Site parameters applied in NGA-Sub database. *Earthquake Spectra*.

Ancheta TD, Darragh RB, Stewart JP, Seyhan E, Silva WJ, Chiou BS-J, Wooddell KE, Graves RW, Kottke AR, Boore DM, Kishida T and Donahue JL (2014) NGA-West2 database. *Earthquake Spectra* 30: 989–1005.

Atkinson G, Bommer J and Abrahamson N (2014) Alternative approaches to modeling epistemic uncertainty in ground motions in probabilistic seismic-hazard analysis. *Seismological Research Letters* 85: 1–4.

Boore DM (2010) Orientation-independent, non geometric-mean measures of seismic intensity from two horizontal components of motion. *Bulletin of the Seismological Society of America* 100: 1830–1835.

Bozorgnia Y, Abrahamson NA, Al Atik L, Ancheta TD, Atkinson GM, Baker JW, Baltay A, Boore DM, Campbell KW, Chiou BS-J, Darragh RB, Day S, Donahue JL, Graves RW, Gregor N, Hanks T, Idriss IM, Kamai R, Kishida T, Kottke AR, Mahin SA, Rezaeian S, Rowshandel B, Seyhan E, Shahi S, Shantz T, Silva WJ, Spudich P, Stewart JP, Watson-Lamprey J, Wooddell KE and Youngs RR (2014) NGA-West2 Research Project. *Earthquake Spectra* 30: 973–987.

Bozorgnia Y and Stewart JP (2020) *Data resources for NGA-Subduction Project*. PEER Report 2020/02. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Bozorgnia Y, Kishida T, Abrahamson N, Ahdi SK, Ancheta TD, Archuleta R, Atkinson G, Boore DM, Campbell KW, Chiou BS-J, Contreras V, Darragh RB, Gregor N, Gulerce Z, Idriss IM, Ji C, Kamai R, Kuehn N, Kwak DY, Kwok AO-L, Lin P, Magistrale H, Mazzoni S, Muin S, Midorikawa S, Parker GA, Si H, Silva WJ, Stewart JP, Walling M, Wooddell KE and Youngs RR (2018) NGA-Subduction Research Program. In: *Proceedings of the11th U.S. National Conference on Earthquake Engineering (11NCEE)*, Los Angeles, CA, 25–29 June, paper 1705.

Campbell KW (2020) Proposed methodology for estimating the magnitude at which subduction megathrust ground motions and source dimensions exhibit a break in magnitude scaling: example for 79 global subduction zones. *Earthquake Spectra* 36: 1271–1297.

Campbell KW and Bozorgnia Y (2010) A ground motion prediction equation for the horizontal component of cumulative absolute velocity (CAV) using the PEER-NGA strong motion database. *Earthquake Spectra* 26: 635–650.

Contreras V, Stewart JP, Kishida T, Darragh RB, Chiou BS-J, Mazzoni S, Kuehn N, Ahdi SK, Wooddell K, Youngs RR, Bozorgnia Y, Boroschek R, Rojas F and Órdenes J (2020) *Chapter 4: Source and path metadata*, in Data Resources for NGA-Subduction Project, (ed. JP Stewart). PEER Report 2020/02. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Contreras V, Stewart JP, Kishida T, Darragh RB, Chiou BS-J, Mazzoni S, Youngs RR, Kuehn NM, Ahdi SK, Wooddell K, Boroschek R, Rojas F and Órdenes J (this volume) NGA-Sub source and path database. *Earthquake Spectra*.

Goulet CA, Bozorgnia Y, Abrahamson NA, Kuehn N, Al Atik L, Youngs RR, Graves RW and Atkinson GM (2018) *Central and Eastern North America ground-motion characterization: NGA-East final report*. PEER Report 2018/08. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley, December 2018.

Goulet CA, Kishida T, Ancheta TD, Cramer CH, Darragh RB, Silva WJ, Hashash YMA, Harmon J, Parker GA, Stewart JP and Youngs RR (2021) PEER NGA-East database. *Earthquake Spectra*, 37(S1), 1331–1353.

Gregor N, Abrahamson NA, Addo K, Al Atik L, Atkinson GM, Boore DM, Bozorgnia Y, Campbell KW, Chiou BS-J, Gulerce Z, Hassani B, Kishida T, Kuehn N, Midorikawa S, Mazzoni S, Parker GA, Si H, Stewart JP and Youngs RR (this volume) Comparisons of the NGA-Subduction ground motion models (GMMs). *Earthquake Spectra*.

Gregor N, Addo K, Al Atik L, Atkinson GM, Boore DM, Bozorgnia Y, Campbell KW, Chiou BS-J, Gulerce Z, Hassani B, Kishida T, Kuehn N, Midorikawa S, Mazzoni S, Parker GA, Si H, Stewart

JP and Youngs RR (2020) *Comparison of NGA-Sub ground motion models*. Berkeley, CA: PEER Report 2020/07. Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Ji C and Archuleta R (2018) *Scaling of PGA and PGV Deduced from Numerical Simulations of Intraslab Earthquakes*. Santa Barbara, CA: Department of Earth Science, University of California, Santa Barbara, CA.

Kuehn N, Bozorgnia Y, Campbell K and Gregor N (2020) *Partially non-ergodic ground-motion model for subduction regions using NGA-Subduction database*. PEER Report 2020/04. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Kuehn N, Bozorgnia Y, Campbell K and Gregor N (this volume) Partially non-ergodic ground-motion model for subduction regions using NGA-Subduction database. *Earthquake Spectra*.

Mazzoni S (2020) NGA-Sub web tools. Available at: https://www.risksciences.ucla.edu/nhr3/nga-subduction (accessed 25 July 2021).

Mazzoni S, Kishida T, Ahdi SK, Ancheta TD, Contreras V, Darragh RB, Kuehn NM, Kwak DY, Kwok AO-L, Chiou BS-J, Silva WJ, Bozorgnia Y and Stewart JP (2021) NGA-Sub Flatfile R211022. Available at: https://doi.org/10.34948/N3Z59T (accessed 23 November 2021).

Mazzoni S, Kishida T, Stewart JP, Contreras V, Darragh RB, Ancheta TD, Chiou BS-J, Silva WJ and Bozorgnia Y (this volume) Relational database used for ground-motion model development in the NGA-Sub project. *Earthquake Spectra*.

Nuclear Regulatory Commission (NRC) (2020) *NRC staff evaluation of the next generation attenuation for Central and Eastern North America Project (NGA-EAST) ground motion model characterization*. Research Information Letter RIL 2020-11. Washington, DC: US Nuclear Regulatory Commission (NRC), September 2020.

Parker GA, Stewart JP, Boore DM, Atkinson GM and Hassani B (2020) *NGA-Subduction global ground-motion models with regional adjustment factors*. PEER Report 2020/03. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Parker GA, Stewart JP, Boore DM, Atkinson GM and Hassani B (this volume) NGA-Subduction global ground motion models with regional adjustment factors. *Earthquake Spectra*. Epub ahead of print 13 August. DOI: 10.1177/87552930211034889.

Petersen MD, Frankel AD, Harmsen SC, Mueller CS, Haller KM, Wheeler RL, Wesson RL, Zeng Boyd OS, Perkins DM, Luco N, Field EH, Wills CJ and Rukstales KS (2008) *Documentation for the 2008 update of the United States national seismic hazard maps*. U.S. Geological Survey Open-File Report 2008-1128. Reston, VA: U.S. Geological Survey.

Petersen MD, Moschetti MP, Powers PM, Mueller CS, Haller KM, Frankel AD, Zeng Y, Rezaeian S, Harmsen SC, Boyd OS, Field EH, Chen R, Rukstales KS, Luco N, Wheeler RL, Williams RA and Olsen AH (2014) *Documentation for the 2014 update of the United States national seismic hazard maps*. U.S. Geological Survey Open-File Report 2014-1091. Reston, VA: U.S. Geological Survey.

Petersen MD, Shumway AM, Powers PM, Mueller CS, Moschetti MP, Frankel AD, Rezaeian S, McNamara DE, Luco N, Boyd OS, Rukstales KS, Jaiswal KS, Thompson EM, Hoover SM, Clayton BS, Field EH and Zeng Y (2019) The 2018 update of the US National Seismic Hazard Model: Overview of model and implications. *Earthquake Spectra* 36(1): 5–41.

Power M, Chiou BS-J, Abrahamson NA, Bozorgnia Y, Shantz T and Roblee C (2008) An overview of the NGA Project. *Earthquake Spectra* 24: 3–21.

Rezaeian S, Al Atik L, Kuehn N, Abrahamson NA, Bozorgnia Y, Mazzoni S, Whiters K and Campbell KW (2021a) Spectral damping scaling factors for horizontal components of ground motions from subduction earthquakes using NGA-Subduction data. *Earthquake Spectra*. Epub ahead of print 27 July. DOI: 10.1177/87552930211027903.

Rezaeian S, Bozorgnia Y, Idriss IM, Abrahamson NA, Campbell KW and Silva WJ (2014b) Damping scaling factors for elastic response spectra for shallow crustal earthquakes in active tectonic regions: "Average" horizontal component. *Earthquake Spectra* 30(2): 939–963.

Rezaeian S, Petersen MD, Moschetti MP, Powers PM, Harmsen SC and Frankel AD (2014a) Implementation of NGA-West2 ground motion models in the 2014 U.S. National Seismic Hazard Maps. *Earthquake Spectra* 30: 1319–1333.

Rezaeian S, Powers PM, Shumway AM, Petersen MD, Luco N, Frankel AD, Moschetti MP, Thompson EM and McNamara DE (2021b) The 2018 update of the U.S. National Seismic Hazard Model: Ground motion models in the central and eastern U.S. *Earthquake Spectra* 37(S1): 1354–1390.

Senior Seismic Hazard Analysis Committee (SSHAC) (1997) *Recommendations for probabilistic seismic hazard analysis: Guidance on uncertainty and use of experts*. U.S. Nuclear Regulatory Commission Report NUREG/CR-6372. Washington, DC: U.S. Nuclear Regulatory Commission.

Si H, Midorikawa S and Kishida T (2020) *Development of NGA-Sub ground motion model of 5%-damped pseudo-spectral acceleration based on database for subduction earthquakes in Japan*. PEER Report 2020/06. Berkeley, CA: Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Si H, Midorikawa S and Kishida T (this volume) Development of NGA-Sub ground motion model of 5%-damped pseudo-spectral acceleration based on database for subduction earthquakes in Japan. *Earthquake Spectra*.

Van Houtte C, Bannister S, Francois-Holden C, Bourguignon S and McVerry G (2017) The New Zealand Strong Motion Database. *Bulletin of the New Zealand Society for Earthquake Engineering* 50(1): 1–20.

Wooddell KE (2018) New earthquake classification for the NGA-subduction project. In: *Proceedings of the 11th National Conference on Earthquake Engineering* (11NCEE), Los Angeles, CA, 25–29 June, Paper 1275.