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Evolution of the BSSA14 GMM for the NGA-West3 Project

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ABSTRACT

We present the development of ground-motion models (GMMs) to predict 5% damped pseudo-spectral accelerations (PSA) and effective amplitude spectra (EAS) as part of the NGA-West3 project. Our approach utilizes the project dataset and shared functional forms for the PSA and EAS models, which are being developed in a coordinated manner to ensure internal consistency. This is different from other approaches that focus mainly on EAS models and then convert them to PSA using random vibration theory and duration models. Both our EAS and PSA models are conditioned on the same predictor variables and include broad regional adjustments to capture tectonic variability. The PSA model is being developed through a traditional period-by-period mixed-effects framework, whereas the EAS model utilizes a seismologically-based source parameterization and frequency-dependent path and site models. Ongoing work aims to refine regionalization, anelastic attenuation, and site response models.

Introduction

The Next Generation Attenuation (NGA)-West3 project is community-based, has already developed an extensive database of recorded earthquake ground-motions and related metadata from shallow-crustal earthquakes in active tectonic regions, and is in the process of developing suites of ground-motion models (GMMs). The authors of this article constitute one of six NGA-West3 modeling teams that are developing GMMs to predict 5% damped pseudo-spectral accelerations (PSA) and effective amplitude spectra (EAS) from a common NGA-West3 ground-motion database [1]. The models produced by our team reflect the evolution of the NGA-West2 BSSA14 GMM [2] through the integration of new data, modeling strategies, and expansion to include a model for EAS.

Our approach is to develop separate models for PSA and EAS in parallel from a consistent empirical dataset using common functional forms as much as possible, such that the final models are internally compatible. This approach differs from most other teams, which are instead concentrating their empirical modeling efforts on EAS and plan to convert to PSA (e.g., [3]). Both models are conditioned on moment magnitude (**M**), rupture depth (Z_{TOR}), Joyner-Boore distance (R_{JB}), time-averaged shear wave velocity (V_S) in the upper 30 m (V_{S30}), depth to the V_S = 1.0 km/s isosurface ($z_{1.0}$), and include adjustments to account for

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regional and sub-regional variations (e.g., constant term, anelastic attenuation, V_{S30}-scaling). Fundamental differences between PSA (a function of oscillator period) and EAS (a function of frequency), and certain modeling decisions discussed hereafter, dictate the need for additional model-specific input parameters for EAS that may not be required for PSA (e.g., the high-frequency attenuation parameter kappa, κ_0).

The objective of this article is to outline key features of the models, including modeling decisions made to date. The following sub-sections discuss our PSA model, EAS model, and approaches to modeling site response.

PSA Model

Eq. 1 presents the generalized functional form of the PSA model:

$$\ln(PSA) = c_0 + F_E(\mathbf{M}, SoF, Z_{TOR}) + F_P\left(R_{JB}, \mathbf{M}, Z_{TOR}, region\right) + F_S(V_{S30}, z_{1.0}, PGA_{rock}, region) \quad (1)$$

in which c_0 is a constant, *SoF* represents the style of faulting, PGA_{rock} is the peak ground acceleration for the reference rock site condition of V_{ref} = 760 m/s (which, in turn is conditioned on the source and path parameters), and F_E, F_P, and F_S are additive terms to account for source-, path-, and site-effects conditioned on the indicated variables. Model coefficients are fit period-by-period through independent mixed-effects regressions and are subsequently smoothed to yield spectral shapes that lack irregularities. Key attributes are described below:

1. Unlike BSSA14, this model incorporates rupture depth (Z_{TOR}) in its source term (F_E).
2. Geometrical spreading is modeled using a bilinear function with a hinge distance (R_h) set to 50 km the slopes include **M**-dependence.
3. The near-source saturation term (h) is formulated using the same framework as our EAS model [4] and is **M**-, Z_{TOR}-, and period-dependent as described by Eq. 2 and illustrated in Fig. 1:

$$\log_{10}(h) = \begin{cases} h_0 + \left(\frac{h_1}{\max(3.0, Z_{TOR})}\right)(\boldsymbol{M} - M_b) & \boldsymbol{M} < M_b \\ h_0 & \boldsymbol{M} \geq M_b \end{cases} \quad (2)$$

   in which h_0 and h_1 are model coefficients that control the behavior of h for large-**M** and the Z_{TOR}-scaling, respectively, and M_b represents a hinge **M** where h no longer scales with Z_{TOR}.
4. The constant (c_0), anelastic attenuation, and V_{S30}-scaling coefficients are regionalized for broad regions (e.g., California, Italy, Japan, New Zealand, and Taiwan).
5. We plan to refine the anelastic attenuation in California using the subregionalization approach described in [5], however as of September 2025 this has not been completed.
6. The nonlinear site amplification model is adopted from [6] and is conditioned on PGA_{rock}, however, we plan to update the model as described later in the article.

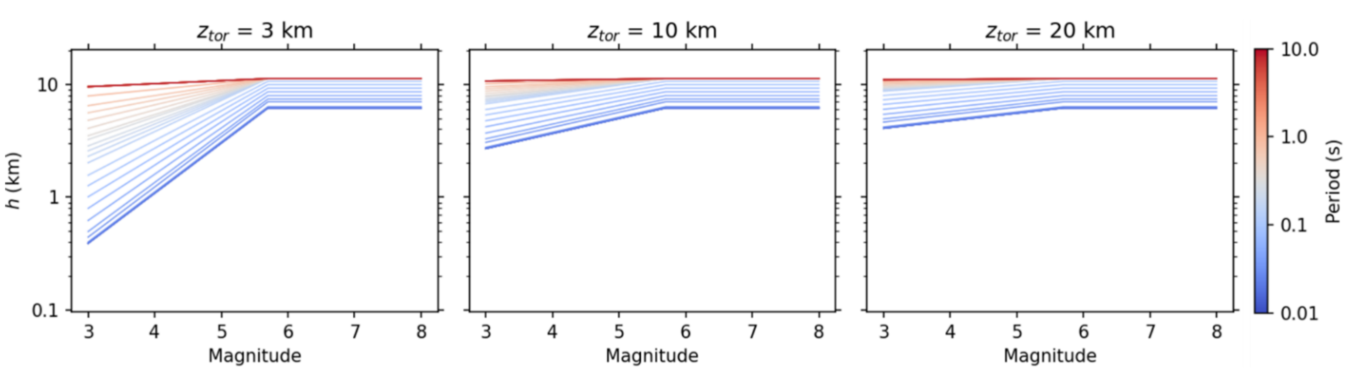

Figure 1. Preliminary near-source saturation models (h) for PSA using Eq. 2 for different Z_{TOR} and periods.

EAS Model

Eq. 3 presents the generalized functional form of the EAS model:

$$\ln(EAS) = c_0 + F_E(\boldsymbol{M}, \Delta\sigma) + F_P\left(R_{JB}, \boldsymbol{M}, Z_{TOR}, region\right) + F_S(V_{S30}, \kappa_0, z_{1.0}, PGA_{rock}, region) \quad (3)$$

in which $\Delta\sigma$ represents the earthquake stress drop and the other terms are as defined previously. The source term (F_E) is formulated using classical seismological models as a function of frequency (e.g., [7], [8], and [9]), therefore, all coefficients must be regressed simultaneously as opposed to frequency-by-frequency. This approach differs from the other NGA-West3 EAS GMMs that are instead using statistical or heuristic models regressed for each frequency to model source effects. Other key attributes are described below:

1. $\Delta\sigma$ can be specified by the user, set to the global **M**-independent average (4.42 MPa), or computed from a relation that depends on **M** and hypocentral depth.
2. Geometrical spreading is modeled using a bilinear function with R_h = 50 km.
3. h is formulated using Eq. (2) and illustrated in Fig.2, and exhibits greater **M**-dependence than the h model for PSA because there is no **M**-dependence in the geometrical spreading term.
4. Low-to-intermediate frequencies of F_S are characterized through V_{S30}-scaling and basin effects ($z_{1.0}$).
5. The shape of the high-frequency spectrum is controlled by κ_0, which is estimated as a modeled parameter [10].
6. The nonlinear site amplification model is adopted from [11] and is conditioned on PGA_{rock}, however, we plan to update the model as described in the subsequent section.

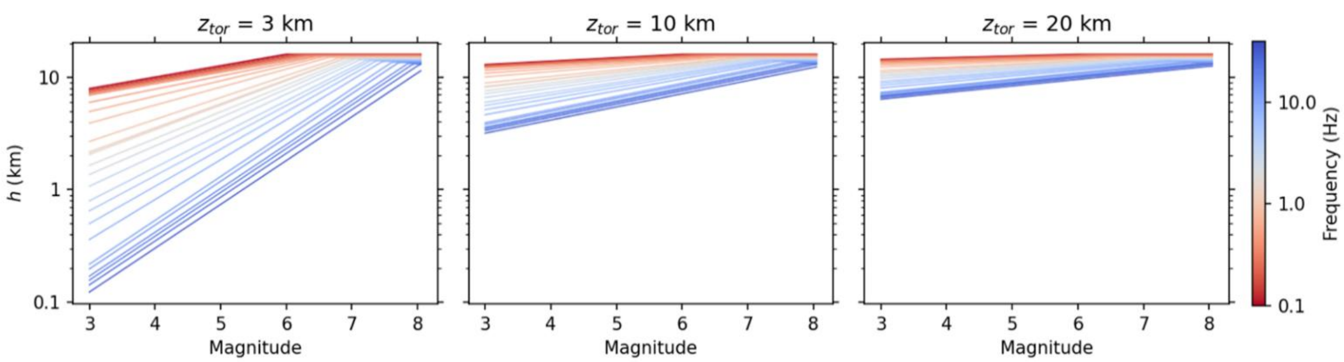

Figure 2. Preliminary near-source saturation models (h) for EAS using Eq. 2 for different Z_{TOR} and frequencies.

Approach for Modeling Site Response

For linear site amplification, both PSA and EAS models include broad regionalization to account for variations in V_{S30}- and $z_{1.0}$-scaling, however we have plans to pursue an approach that leverages existing sub-regional models (notably those calibrated for parts of California; [12] and [13]) to account for smaller-scale variations in geologic conditions that affect site response. We plan to incorporate categorical parameters that distinguish sites in sedimentary basins from those in non-basin regions, which have been repeatedly shown to exhibit different site responses. Our preferred classification scheme is based on detailed geomorphology, geologic information, and community velocity models, which have been previously used to create spatial maps of geomorphic categories in high-interest areas, such as the San Francisco Bay Area [13] depicted in Fig. 3.

The nonlinear amplification models used by most NGA-West3 GMMs (PSA and EAS) are based solely on numerical simulations, however we intend to investigate empirical data in combination with simulations and results from centrifuge tests to inform our nonlinear model. This approach has previously been used to develop a nonlinear model for sites in subduction zones [14] and in NGA-West2 [6].

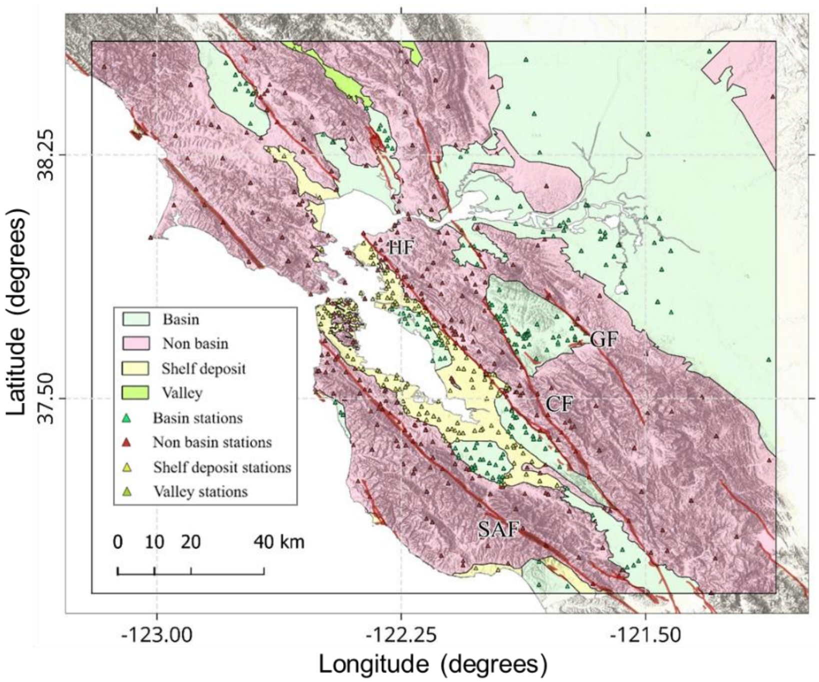

Figure 3. Map of San Francisco Bay Area showing selected geomorphic provinces proposed by [12]; CF = Calaveras Fault; GF = Greenville Fault; HF = Hayward Fault; and SAF = San Andreas Fault. Adapted from [1].

Conclusions

The NGA-West3 project represents a significant advancement in the development of empirical GMMs. Our team's approach uniquely emphasizes parallel development of both PSA and EAS models from a common dataset, leverages shared functional forms, and provides internally consistent GMMs. Key attributes include a bilinear model for the geometrical spreading with R_h = 50 km, identical parameterization of the near-source saturation term, and regionally variable coefficients for the constant, anelastic attenuation, and V_{S30}-scaling terms. Our EAS model departs from other NGA-West3 EAS models in that the source term (F_E) is adapted from classical seismological models. Ongoing work is refining the anelastic attenuation model through a sub-regional framework [5]; incorporating linear site response models for high-interest urban centers following an approach developed in prior work (e.g., [12] and [13]); and developing a nonlinear site response model using an approach that considers strong motion data in combination with simulations.

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