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An Empirical Model for Fourier Amplitude Spectra Using the NGA-West2 Database

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Introduction

We present an empirical global ground motion model (GMM) for shallow crustal earthquakes in active tectonic regions based on the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation-West 2 (NGA-West2) database (Ancheta et al., 2014). This model is developed for the median and variance of the smoothed effective amplitude spectrum (EAS), as defined by PEER (PEER, 2015).

To develop this model, we have used the empirical data as well as SCEC Broadband Platform (Maechling et al., 2015) finite-fault simulations to constrain the near-fault large-magnitude scaling, and incorporated analytical site response modeling (Hashash et al., 2018) to capture the nonlinear site amplification. Rather than simply fitting the empirical data, which is limited in critical ranges, emphasis has been placed on building the model using both the empirical data and analytical results from these seismological and geotechnical models.

The model is applicable to moment magnitudes 3.0-8.0, distances 0-300 km, and spans frequencies 0.1-100 Hz. We model regional differences in large distance attenuation and site amplification between the Western United States (WUS), Japan, and Taiwan.

(1) Database and GM Intensity Measure

We use the PEER NGA-West2 strong motion database (Ancheta et al, 2014). After screening for record quality, recording distance, minimum station requirements, and usable frequency limitations, our final dataset consists of 13,346 unique records from 232 earthquakes, both of which vary as a function of frequency (Fig 1).

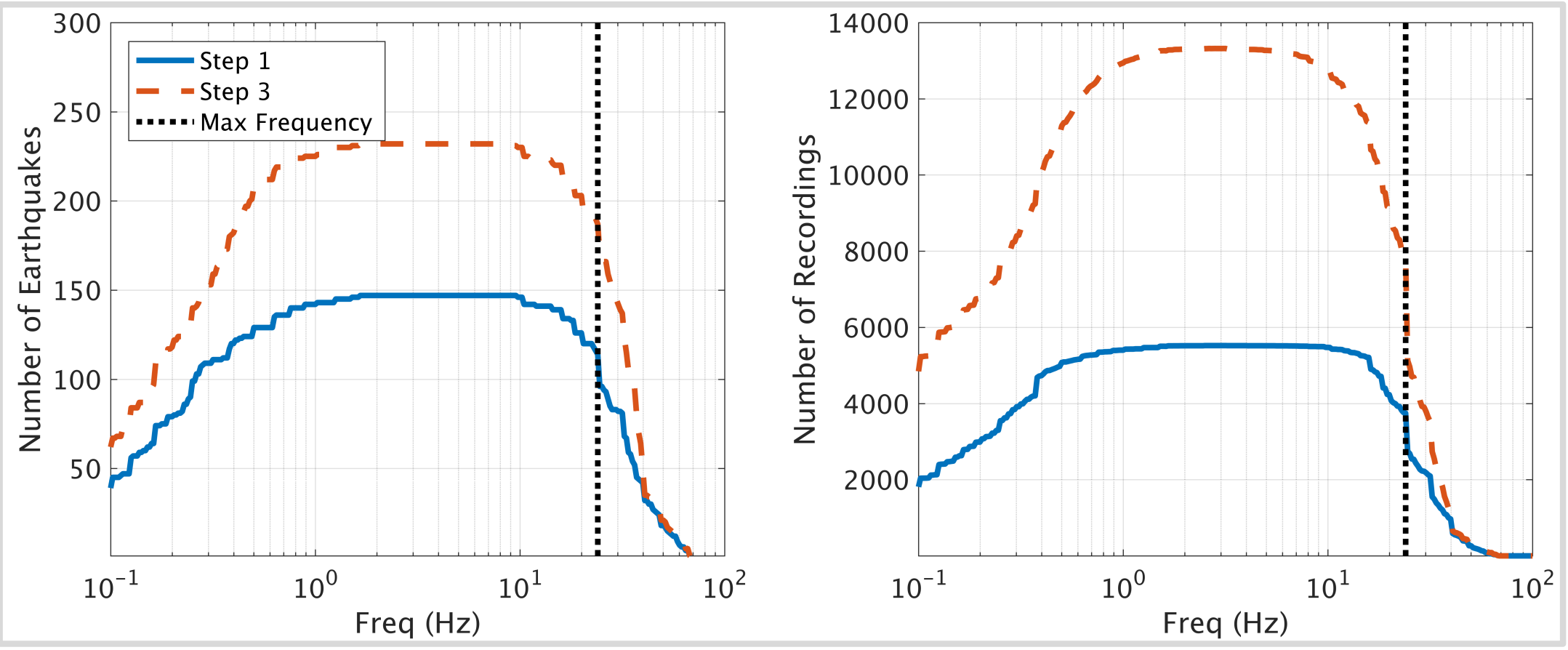

Figure 1: Number of earthquakes and recordings from the NGA-West2 EAS database used in the regression steps 1 and 3, versus frequency

The model is developed for the median and standard deviation of the Effective Amplitude Spectrum (EAS), which is the orientation-independent horizontal component Fourier amplitude spectrum (FAS) of ground acceleration . The EAS was defined in Kottke et al., (2015) and used in the PEER NGA-East project (PEER, 2015):

$$EAS(f) = \sqrt{\frac{1}{2}\left[FAS_{HC1}(f)^2 + FAS_{HC2}(f)^2\right]}$$

We smooth the EAS using the $\log_{10}$-scale Konno and Ohmachi (1998) smoothing window, with the same smoothing parameters as described in Kottke et al. (2015) for consistency with the PEER database and with NGA East.

Advantages of using an FAS model over PSA include:

- Because the FAS high frequencies don't depend on the predominant frequency, allows for simpler site response in the linear range, where PSA models need to account for spectral shape.
- It is easier to relate the model to seismological theory, allowing for extrapolation to ranges not well constrained by the data.
- Can provide better feedback to ground motion simulation validations (model tuning)

The median model functional form is summarized in the table at right.

Component	Formulation	Description
General Equation	$ln\ EAS_{med} = f_M + f_P + f_S + f_{Ztor} + f_{NM} + f_{Z1} + \delta B + \delta W$	Components described below
Magnitude Scaling	$f_M = c_1 + c_2(\mathbf{M} - 6) + c_3 ln(1 + e^{c_n(c_M - \mathbf{M})})$	Formulation adopted from Chiou and Youngs (2014), which is based on seismological models for the earthquake source Fourier amplitude spectra. • The coefficient c_2 is the frequency independent linear **M** scaling slope for frequencies well above the theoretical corner frequency. • The term with coefficient c_3 captures both the approximately linear scaling of the FAS below the theoretical corner frequency, and the non-linear transition to that scaling. • The coefficient c_n controls the width of the magnitude range over which the transition between low- and high-frequency linear scaling occurs .
Path Scaling	$f_P = c_4\, ln\left(R_{rup} + c_5 \cosh(c_6 \max(\mathbf{M} - c_{hm}, 0))\right) + (-0.5 - c_4)\, ln(\hat{R}) + c_7 R_{rup}$	Chiou and Youngs (2014) formulation: • The c_4 term models near source geometric spreading • The c_5 term represents an additive distance designed to capture the near-source amplitude saturation effects of fault rupture area • The c_7 term models anelastic attenuation, regional models are developed. • The (0.5 - c_4) term models the transition to surface wave geometric spreading at large distances.
Site Response	$f_S = f_{SL} + f_{NL}$ $f_{SL} = c_8\, ln\left(\frac{\min(V_{s30}, 1000)}{1000}\right)$ $f_{NL} = f_2 ln\left(\frac{I_R + f_3}{f_3}\right)$ $f_2 = f_4\left(e^{f_5(min(V_{s30}, V_{ref}) - 360)} - e^{f_5(V_{ref} - 360)}\right)$	The linear model is constrained by the empirical data and is developed separately for the WUS, Taiwan, and Japan. The nonlinear model is modified from the Hashash et al. (2018) analytical model, which was developed by performing large-scale 1D site response simulations of input rock motions propagated through soil columns representative of WUS site conditions.
Depth to Top of Rupture Scaling	$f_{Ztor} = c_9 \min(Z_{tor}, 20)$	To model differences in the ground motions for surface and buried ruptures.
Style of Faulting Scaling	$f_{NM} = c_{10} F_{NM}$	F_{NM}= 1 for normal style of faulting earthquakes, 0 for all others
Sediment Depth Scaling	$f_{Z1} = c_{11}\, ln\left(\frac{\min(Z_1, 2.0) + 0.01}{Z_{1Ref} + 0.01}\right)$	c_{11} is binned by V_{s30}, regional model.

(2) Model Development

Regionalization

The To account for the known differences in regional crustal structure, we developed three regionalized models: Japan, Taiwan, and the base model which is for the WUS (dominated by California data). We regionalized the linear V_{s30} scaling, soil depth scaling, anelastic attenuation and mean spectral shape coefficients.

Regression

The random-effects model is used for the regression analysis following the procedure described by Abrahamson and Youngs (1992). This procedure leads to the separation of total residuals into between-event residuals (δB) and within-event residuals (δW) (e.g. Figures 2 and 3) following the notation of Al Atik et al., (2010). Following this notation, the total standard deviation is expressed as $\sigma = \sqrt{\tau^2 + \phi^2}$.

The regression is performed in a series of steps to prevent trade-off of correlated model coefficients and to constrain different components of the model using the data relevant to each piece. For all steps the regression is performed independently at each of 239 log-spaced frequencies spanning 0.1-24 Hz.

Smoothing and Extrapolation

Smoothing of the coefficients is performed to assure smooth spectra and, in some cases, to constrain the model to a more physical behavior where the data is sparse (Abrahamson et al., 2014).

Model coefficients were obtained by regression for frequencies up to 24 Hz. At high frequencies, the FAS decays rapidly (Hanks 1982; Anderson and Hough, 1984). Anderson and Hough (1984) introduced the spectral decay factor kappa (κ) to model the rate of the decrease, where the amplitude of the log(FAS) decays linearly versus frequency (linear spaced), and κ is related to the slope. The total site amplification is the combined effect of crustal amplification and damping (κ and Q), but the effect of κ is so strong that it controls the spectral decay of the FAS at high frequencies, and is the only parameter we specify in the extrapolation to 100 Hz.

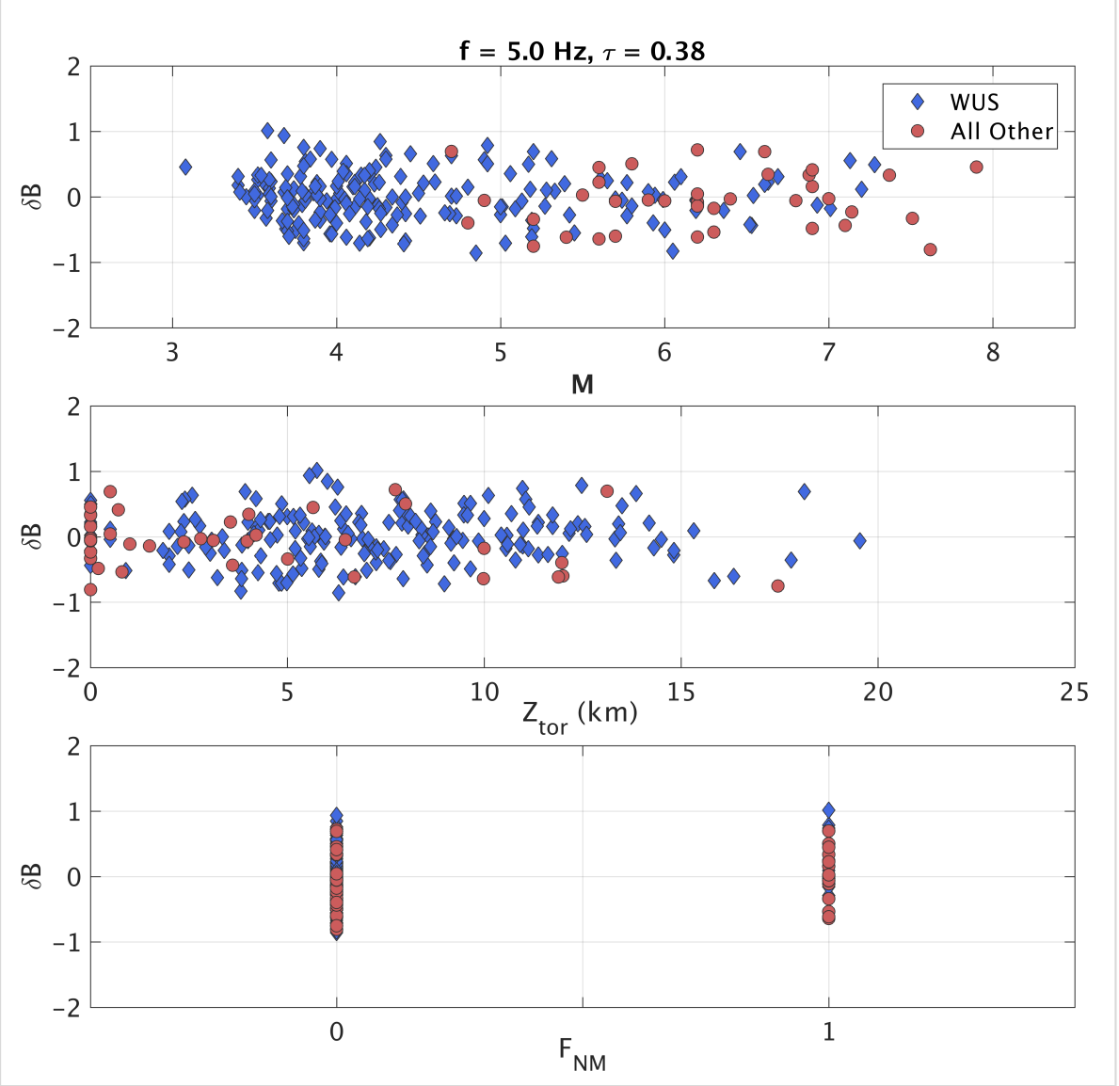

Figure 2: Between-event residuals versus source parameters, f = 5 Hz

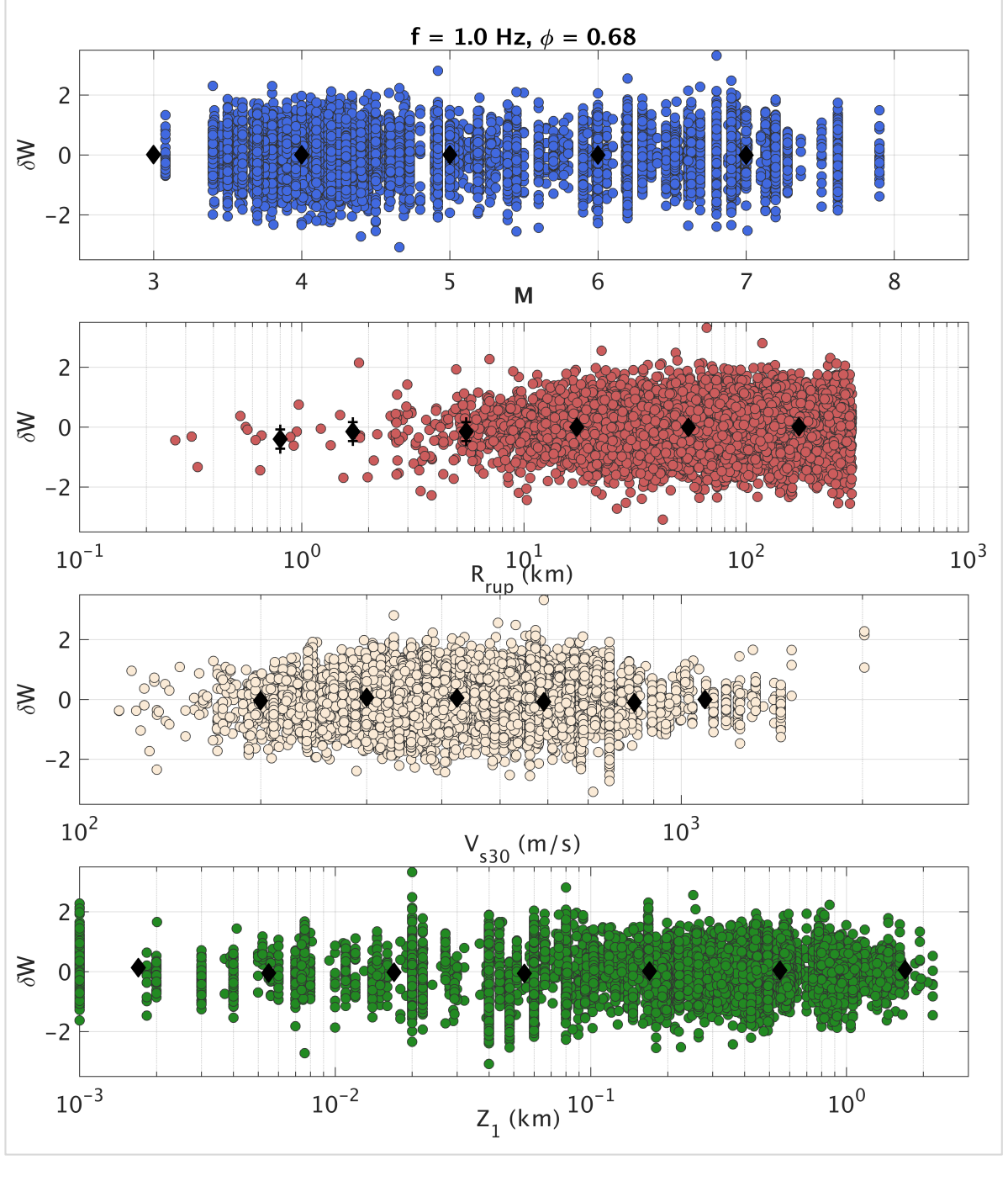

Figure 3: Within-event residuals versus main model parameters, f = 1 Hz

(3) Summary and Conclusions

The prediction for the EAS ground motion is given by

$$ln\ EAS = ln\ EAS_{med} + \epsilon\sigma$$

A selection of the key median model features are shown in Figure 4.

- The model is not inconsistent with the additive double-corner point source model (dashed lines) up to large **M** (if the appropriate distance correction term is selected), except at the high frequencies of small **M**.
- The model is also not inconsistent with **M** scaling from the finite fault simulations. The model features stronger **M** scaling (less saturation) than the PSA models, which we expect based on the fundamental differences between FAS and PSA.

The standard deviation model is described in our soon-to-be submitted BSSA paper.

Future Steps

For engineering applications one can use RVT to convert the FAS to response spectra. The advantage of this approach is that the extrapolation outside the data range is constrained by the FAS (as opposed to PSA) which are better explained by seismological theory.

Model Applicability

The global model includes regionalization for the WUS, Taiwan, or Japan, and is applicable to shallow crustal earthquakes, with moment magnitudes 3.0-8.0, distances 0-300 km, and is valid over frequencies 0.1-100 Hz.

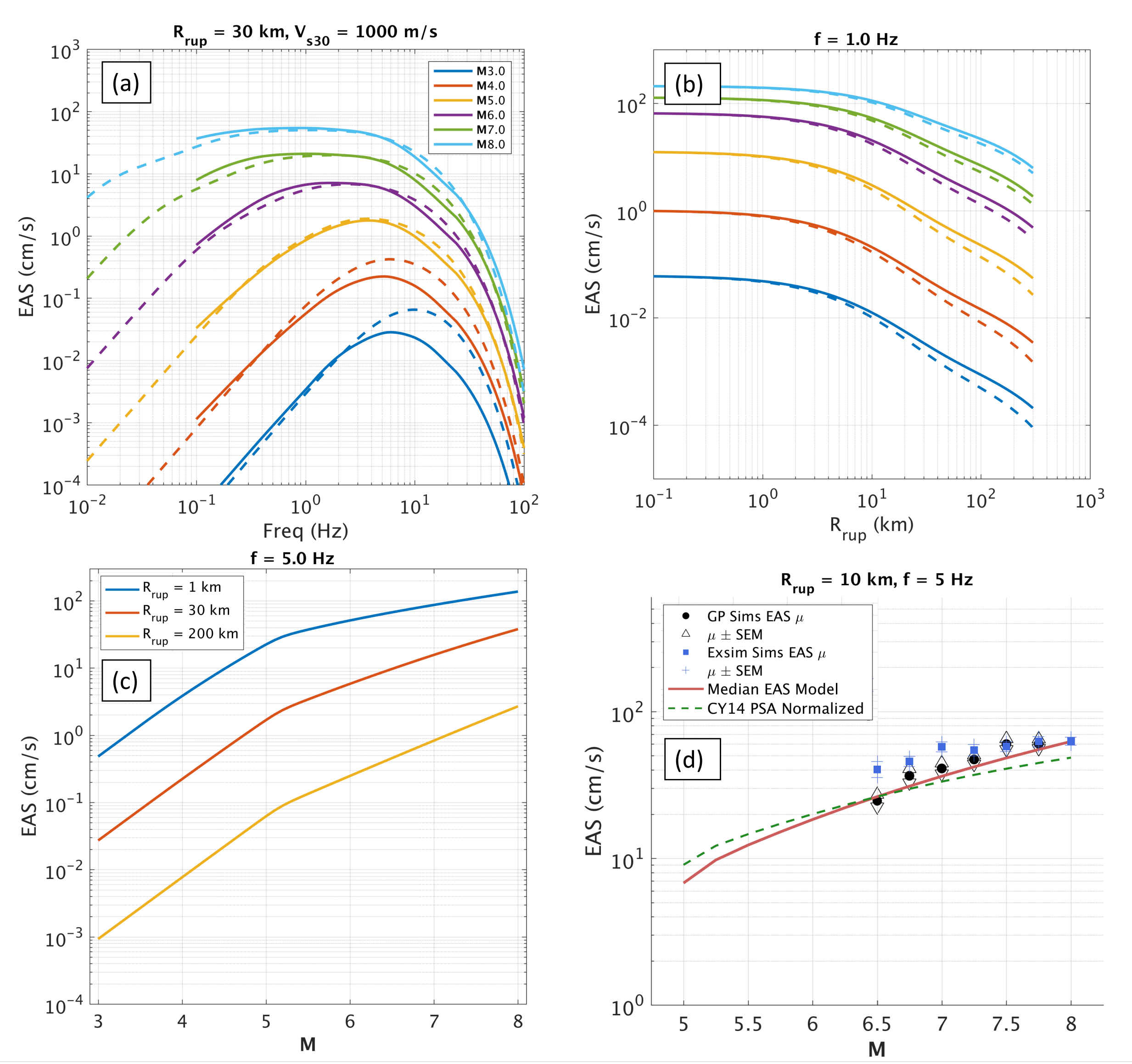

Figure 4: Summary of key model features

Thanks to PEER for providing the ground motion database.