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Resilience Through **Community Engagement** and **Technology**

Development of Fourier Amplitude Spectrum and Response Spectral Ground-Motion Models for NGA-West3

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ABSTRACT

We present the development of new empirical ground-motion models (GMMs) for the NGA-West3 project. Our approach is to first develop an ergodic model for the Effective Amplitude Spectrum (EAS), which benefits from the linearity of the Fourier domain to better constrain magnitude scaling, distance attenuation, and site amplification. We then transform the EAS model into a response spectral acceleration (PSA) model using an empirically calibrated random vibration theory (RVT) operator. The resulting PSA GMM is directly applicable for engineering practice while maintaining the physical and statistical constraints provided by the EAS formulation. The EAS GMM captures stable magnitude scaling across the NGA-West3 dataset and provides an improved representation of site response. The PSA model inherits these constraints and shows improved fit to the data relative to NGA-West2. This combined framework offers a more robust basis for seismic hazard analysis and engineering design applications.

Introduction

Ground-motion models (GMMs) for pseudo-spectral acceleration (PSA) are essential for seismic hazard analysis and engineering design. However, PSA models combine source, path, and site effects in a nonlinear manner that can be difficult to constrain directly from data. By contrast, Fourier Amplitude Spectrum (FAS) models are defined in a linear domain, which provides clearer separation of scaling effects. We therefore developed a GMM for the Effective Amplitude Spectrum (EAS), and then transformed it to a PSA model through an empirically calibrated random vibration theory (RVT) operator. This two-step framework yields a PSA GMM with improved physical constraints.

Methodology

We used the NGA-West3 strong-motion database, consisting of more than 60,000 recordings from shallow crustal earthquakes across active tectonic regions. The EAS model was developed using mixed-effects regression with magnitude, distance, and site scaling terms. Additional source and path parameters such as finite-fault effects, hanging-wall scaling, and proxies for kappa and static stress drop were also considered. The PSA model was then derived by applying an empirical RVT-type model to the median EAS predictions, allowing conversion into 5%-damped spectral accelerations. Aleatory variability was modeled with magnitude-, distance-, and site-dependent terms. The regression framework employed a mixed-effects approach, in which between-event and within-event residuals were explicitly modeled to capture event-to-event variability and site-to-site differences. Magnitude scaling was represented with logistic hinge function that capture both linear growth at moderate magnitudes and saturation at larger magnitudes. Distance attenuation was modeled using both geometric spreading and anelastic attenuation terms, with magnitude-dependent coefficients to account for differences between small and large events. Nonlinear site response was represented by a function of V_{s30} and reference spectral acceleration, with coefficients constrained by the

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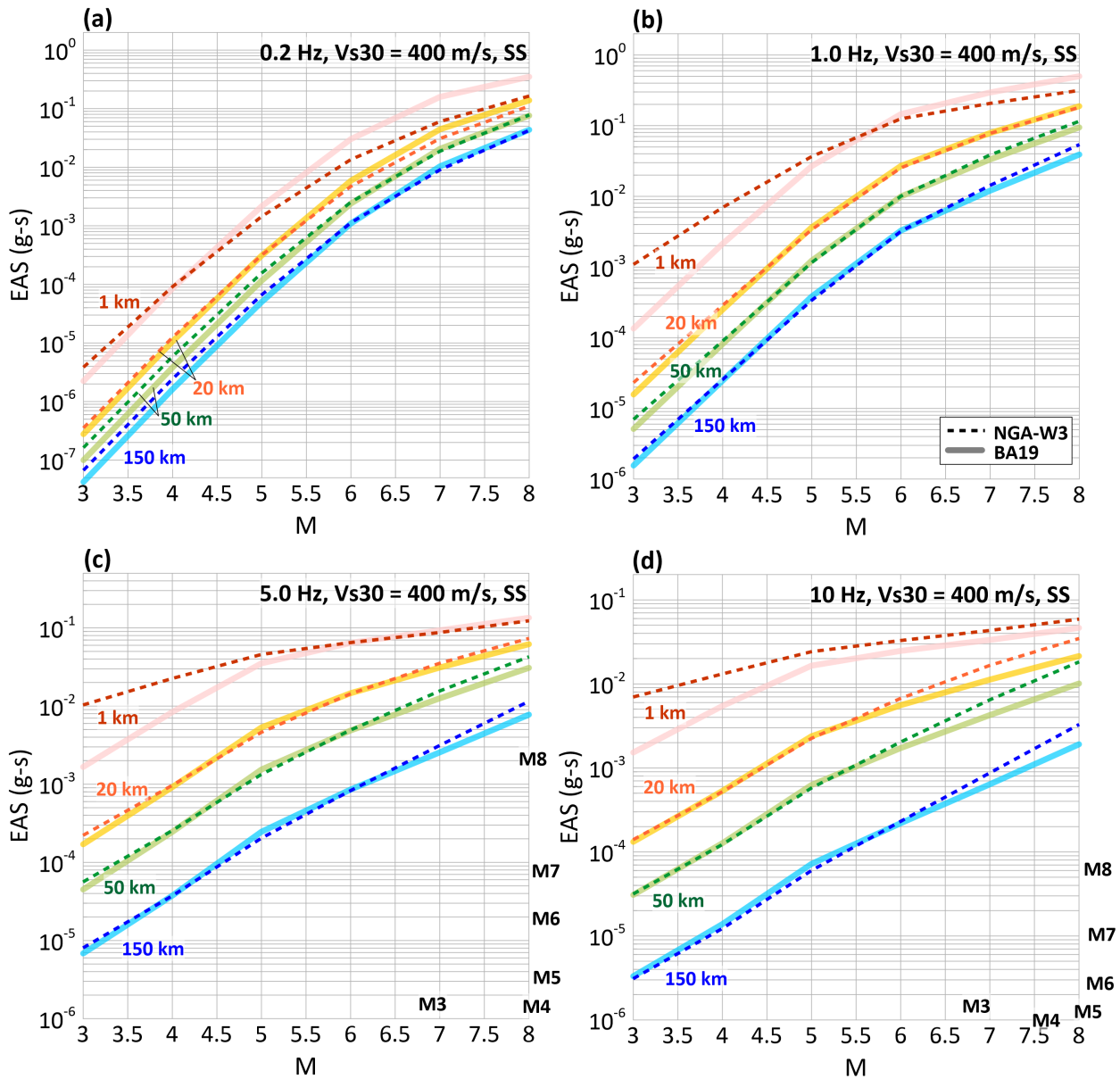


Figure 1 Magnitude scaling of the median EAS for a strike-slip event with $Rrup = 1, 20, 50$ and 150 km, with $Vs30 = 400$ m/s and $Z1.0 = 0.033$ km at (a) 0.2 Hz, (b) 1.0 Hz, (c) 5 Hz, and (d) 10 Hz. $Ztor = 0, 0, 2, 5, 10, 20$ km for M8, M7, M6, M5, M4, M3.

NGA-West3 site response group. The RVT operator was calibrated using both empirical Fourier spectra and simulations, with separate parameterizations of effective duration and oscillator bandwidth to ensure consistency across a wide range of frequencies. Together, these developments ensured a physically consistent framework that is statistically robust and broadly applicable.

Results

The EAS model provides stable constraints on magnitude scaling and site response. Figure 1 illustrates magnitude scaling at a reference distance, showing smooth transitions across magnitude ranges. In particular, the use of the expanded NGA-West3 dataset allowed us to better resolve the transition from small- to large-

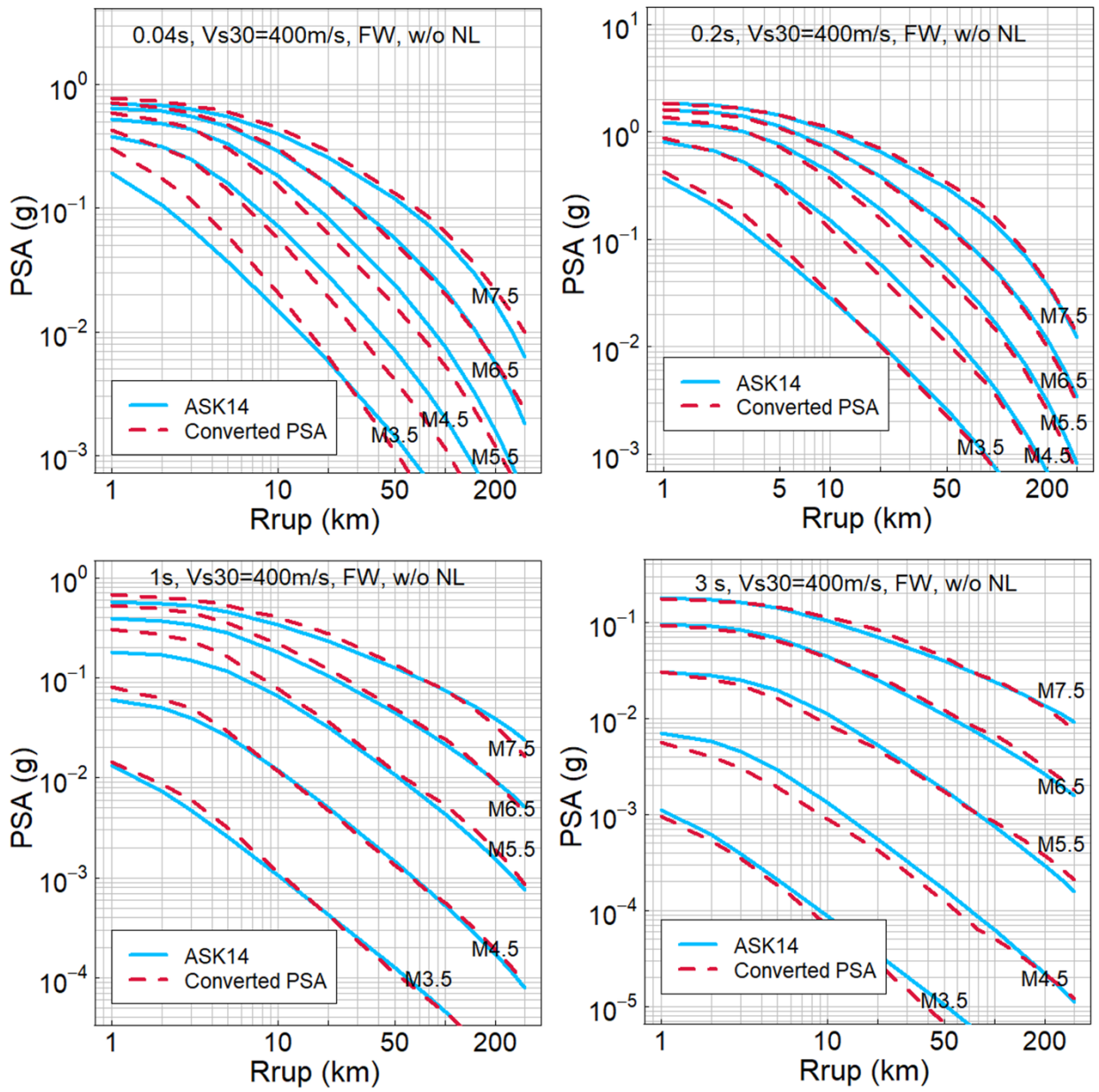


Figure 2 Distance scaling of the PSA from the EAS GMM and for the ASK14 GMM for strike-slip events, without the non-linear site effect

magnitude scaling, and to capture nonlinear site effects across a wide range of V_{s30} values. The magnitude scaling exhibits smoother behavior than in previous models, with clear saturation at large magnitudes consistent with seismological theory. Site scaling results indicate stronger amplification at soft-soil sites, and reduced amplification for hard-rock sites, with nonlinear effects becoming noticeable at higher shaking levels. The PSA model obtained through RVT conversion reproduces the main features of the NGA-West3 dataset. Figure 2 shows PSA median predictions versus observations, with comparison to NGA-West2. The new PSA model better captures the magnitude dependence and site amplification observed in the data, leading to more stable predictions across a wide range of scenarios. Variability analysis shows that the new models maintain

comparable total sigma while providing better partitioning of between- and within-event variability. Residual analyses further confirm the robustness of the models. Between-event residuals show systematic trends with magnitude that are smaller than those observed in NGA-West2 models, demonstrating that the magnitude scaling is better captured in the new framework. Within-event residuals are reduced in variance, particularly at short periods where previous PSA models exhibited larger scatter. Partitioning of aleatory variability indicates that the between-event component (τ) is smaller for large-magnitude earthquakes, while the within-event component (ϕ) remains consistent across distance ranges. These results suggest that future non-ergodic models will benefit from an even greater reduction in total sigma once regional and site-specific terms are incorporated. Importantly, the improved residual structure enhances confidence in using the new models for probabilistic seismic hazard analysis (PSHA), particularly for regions where large magnitude earthquakes are expected but sparsely recorded.

Conclusions

We developed new empirical GMMs for both the Fourier amplitude spectrum and response spectra as part of the NGA-West3 project. The EAS model leverages the linearity of the Fourier domain to constrain scaling terms, while the PSA model produced through RVT conversion is directly applicable to engineering practice. The models show improved magnitude and site scaling compared to previous NGA-West2 models. These improvements provide more stable predictions for seismic hazard and design applications.

Acknowledgments

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