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Insights from Residual Analyses for an Improved Parametrization of Ground-Motion Models

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In this decade we are witnessing a tremendous growth in ground-motion data and the emerging application machine-learning techniques in ground-motion characterization. Each new generation of Ground-Motion Prediction Equations (GMPEs) supersedes the previous in terms of its applicability, owing to the expanding ranges of recorded magnitude and recording distance, source properties and local site conditions within the underlying ground-motion datasets. Indeed, large sets of ground-motion data reduce the epistemic uncertainty of GMPE median predictions modeled using these explanatory variables, but a reduction in the residual aleatory variability has been difficult. Increasing ground-motion data, however, also means an increasing number of GMPE residuals. Advanced statistical techniques can be applied to these large datasets of GMPE residuals in order to quantify repeatable patterns that may be indicative of the underlying physical processes; meaning new explanatory parameters can identified and introduced into the GMPEs to enhance their predictive power.
We used the largest engineering strong ground-motion datasets available worldwide (KiK-net of Japan, NGA-West 2 of the Western United States and worldwide, and the Engineering Strong Motion database of Europe) to demonstrate the potential of exploratory residual analyses to reveal deeper insights into the earthquake process. With each of these datasets, we perform mixed-effects GMPE regressions to quantify the event, site, and record-specific residuals. On the site-specific residuals, we apply machine-learning techniques to classify stations with similar soil-response to seismic action, evaluate the physical meaning of such data-driven classifications and demonstrate the prospects of site-specific GMPEs at regional scales. From the record-specific residuals, which contain the path-effects, we find a previously undetected anisotropic shear-wave radiation pattern. Calibrating a cross-correlation model between theoretical and empirical shear-wave radiation coefficients, we could enhance the GMPEs to predict azimuth and style-of-faulting (depth and focal-mechanism) dependent distance attenuation. With these additional improvements to the ground-motion predictions we are able reduce the GMPE aleatory variability, which can help substantially in improving the estimation of seismic hazard and risk. Continued assimilation of ground-motion data and thorough event and site characterization, combined with the adoption of advanced statistical tools, will be indispensable to the future of ground-motion prediction.