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How well can we test probabilistic seismic hazard maps?

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Recent large earthquakes that gave rise to shaking much stronger than shown in probabilistic seismic hazard (PSH) maps have stimulated discussion about how well these maps forecast future shaking. These discussions have brought home the fact that although the maps are designed to achieve certain goals, we know little about how well they actually perform. As for any other forecast, this question involves verification and validation. Verification involves assessing how well the algorithm used to produce hazard maps implements the conceptual PSH model ("have we built the model right?"). Validation asks how well the model forecasts the shaking that actually occurs ("have we built the right model?").

We explore the verification issue by simulating shaking histories for an area with assumed uniform distribution of earthquakes, Gutenberg-Richter magnitude-frequency relation, Poisson temporal occurrence model, and ground-motion prediction equation (GMPE). We compare the maximum simulated shaking at many sites over time with that predicted by a hazard map generated for the same set of parameters. The Poisson model predicts that the fraction of sites at which shaking will exceed that of the hazard map is $p = 1 - \exp(-t/T)$, where t is the duration of observations and T is the map's return period. Exceedance is typically associated with infrequent large earthquakes, as observed in real cases. The ensemble of simulated earthquake histories yields distributions of fractional exceedance with mean equal to the predicted value. Hence, the PSH algorithm appears to be internally consistent and can be regarded as verified for this set of simulations. However, simulated fractional exceedances show a large scatter about the mean value that decreases with increasing t/T, increasing observation time and increasing Gutenberg-Richter a-value (combining intrinsic activity rate and surface area), but is independent of GMPE uncertainty. This scatter is due to the variability of earthquake recurrence, and so decreases as the largest earthquakes occur in more simulations. Our results are important for evaluating the performance of a hazard map based on misfits in fractional exceedance, and for assessing whether such misfit arises by chance or reflects a bias in the map. More specifically, we determined for a broad range of Gutenberg-Richter a-values theoretical confidence intervals on allowed misfits in fractional exceedance and on the percentage of hazard-map bias that can thus be detected by comparison with observed shaking histories. Given that in the real world we only have one shaking history for an area, these results indicate that even if a hazard map does not fit the observations, it is very difficult to assess its veracity, especially for low-to-moderate-seismicity regions. Because our model is a simplified version of reality, any additional uncertainty or complexity will tend to widen these confidence intervals.