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PROBABILISTIC SEISMIC HAZARD DEAGGREGATION OF GROUND MOTION PREDICTION MODELS

Ting LIN [1], **Jack BAKER**[2]

ABSTRACT

Probabilistic seismic hazard analysis (PSHA) combines the probabilities of all earthquake scenarios with different magnitudes and distances with predictions of resulting ground motion intensity, in order to compute seismic hazard at a site. PSHA also incorporates uncertainties in ground motion predictions, by considering multiple Ground Motion Prediction ("attenuation") Models (GMPMs). Current ground motion selection utilizes probabilistic seismic hazard deaggregation to identify the distribution of earthquake scenarios that contribute to exceedance of a given spectral acceleration (*Sa*) level. That calculation quantifies effects of the aleatory uncertainties in earthquake events, but does not describe the epistemic uncertainties from multiple GMPMs. This paper describes ways to calculate contributions of multiple GMPMs to *Sa* exceedance using deaggregation calculations. Deaggregation of GMPMs plays an important role in target response spectrum computation for ground motion selection, in a similar way as assigned logic tree weights of GMPMs do in PSHA computation. Just as the deaggregation of magnitude and distance identifies the relative contribution of each earthquake scenario to *Sa* exceedance, the deaggregation of GMPMs tells us the probability that the exceedance of that *Sa* level is predicted by a specific GMPM. We can further extend deaggregation to other ground motion parameters, such as earthquake fault mechanism, to more fully quantify the parameters that contribute to *Sa* values of interest. The proposed methodology for deaggregation of prediction models can be immediately applicable to other procedures which require multiple prediction models in an earlier stage of total prediction and a later stage of new target computation.

Keywords: probabilistic seismic hazard analysis; deaggregation; ground motion prediction models; response spectrum; uncertainties

INTRODUCTION

Probabilistic seismic hazard analysis (PSHA) is commonly used in geotechnical earthquake engineering (Kramer 1996) and structural dynamic analysis (Chopra 2001) to identify the ground motion hazard for which geotechnical and structural systems are analyzed and designed. PSHA combines the probabilities of all earthquake scenarios with different magnitudes and distances with predictions of resulting ground motion intensity in order to compute seismic hazard at a site (McGuire 2004). PSHA also incorporates uncertainties in ground motion predictions, by considering multiple ground motion prediction models (GMPMs), formerly known as attenuation equations (e.g., Boore and Atkinson 2008). In PSHA, aleatory uncertainties, which are inherently random, are accounted for by considering earthquake events with all possible magnitudes and distances; epistemic uncertainties, which are due to the lack of knowledge, can come from the uncertainty in identifying correct models such as GMPMs. GMPMs have inputs such as

[1] Ph.D. Candidate, Department of Civil and Environmental Engineering, Stanford University, e-mail: tinglin@stanford.edu
[2] Assistant Professor, Department of Civil and Environmental Engineering, Stanford University.

magnitude and distance, and outputs in terms of logarithmic mean and standard deviation of spectral acceleration (*Sa*) for various periods of vibration. When multiple GMPMs are considered in PSHA to represent the epistemic uncertainty, a logic tree is often used to assign weights to each GMPM (Petersen et al. 2008; Scherbaum et al. 2005). PSHA then estimates seismic hazard at a site incorporating uncertainties in both earthquake scenarios and GMPMs.

As a key step in defining the seismic load input to dynamic analysis, ground motion selection often involves specification of a target spectrum such as the Conditional Mean Spectrum (CMS), which consists of the expected *Sa* values at all periods conditional on the *Sa* value at the period of interest (Baker 2010). The computation of this target spectrum requires specification of a GMPM. Current implementation of this ground motion selection approach uses the information from earthquake scenarios without considering multiple GMPMs. While PSHA computes the total seismic hazard using total probability theorem, PSHA deaggregation (Bazzurro and Cornell 1999; Harmsen 2001; McGuire 1995) computes the relative contribution of earthquake parameters to the total hazard using Bayes' rule (Benjamin and Cornell 1970). Current ground motion selection utilizes deaggregation results of magnitude and distance to identify causal events for a given *Sa* value associated with an annual rate of exceedance. In this paper we consider ways to incorporate multiple GMPMs into ground motion selection techniques using refinements to PSHA deaggregation.

METHODOLOGY

PSHA deaggregation links the computation of a target spectrum to the total hazard prediction. Computation of a target Conditional Mean Spectrum requires deaggregation to identify the causal parameters, along with the choice of a GMPM. Multiple GMPMs are typically used for PSHA computation. For instance, the United States Geological Survey (USGS) specify three models (Boore and Atkinson 2008; Campbell and Bozorgnia 2008; Chiou and Youngs 2008) with equal weights for Coastal California (Petersen et al. 2008) in the logic tree, as highlighted in Figure 1. These models can be adjusted up or down to reflect additional epistemic uncertainties, as illustrated in the right-most branch in Figure 1. When multiple GMPMs are used in the total hazard prediction, PSHA deaggregation can be extended to include the relative contribution of GMPMs to the computation of a target spectrum for ground motion selection. This section will discuss the issues associated with obtaining this deaggregation, and using it to perform CMS calculations.

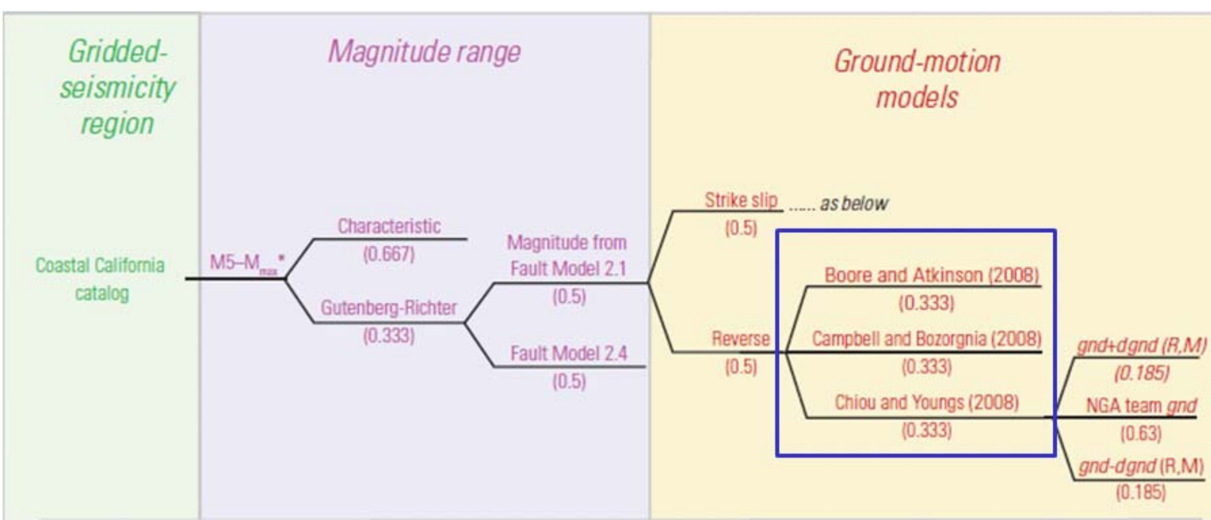

Figure 1. USGS PSHA logic tree for Coastal California. (from Petersen et al. 2008)

Probabilistic Seismic Hazard Analysis

PSHA integrates over all *j* potential earthquake sources with their associated annual rates of occurrence, ν_j, and aleatory uncertainties such as magnitudes (M), distances (R), and epsilons (ε) in order to compute the annual rate of exceedance of a spectral acceleration level of interest, $\nu(Sa > y)$. PSHA is usually done with multiple GMPMs, an epistemic source of uncertainties. For instance, Figure 1 depicts the uncertainties in PSHA calculation through a logic tree with various weights assigned to magnitude range and GMPMs. We explicitly consider the epistemic uncertainty in PSHA by incorporating weights of GMPMs, $P(GMPM_k)$, into Equation 1, to compute the total hazard rate (Kramer 1996) using the total probability theorem:

$$\nu(Sa > y) = \sum_k \sum_j \nu_j \iiint f_{M,R,\mathrm{E}}(m,r,\varepsilon) P(Sa > y \mid m,r,\varepsilon,GMPM_k)\, dm\, dr\, d\varepsilon\, P(GMPM_k) \qquad (1)$$

where $f_{M,R,\mathrm{E}}(m,r,\varepsilon)$ is the joint probability density function for magnitude *m*, distance *r*, and epsilon ε, and $P(Sa > y \mid m,r,\varepsilon,GMPM_k)$ is the probability of *Sa* exceeding a value *y* given *m*, *r*, ε, and $GMPM_k$. The incorporation of GMPMs is directly related to the computation of a target spectrum, e.g. the Conditional Mean Spectrum (CMS), as such computation requires the predictions from GMPMs.

Parameters

Equation 1 is the standard simplified equation for describing a PSHA calculation. As multiple GMPMs are used, variations in the parameters used must be considered. For instance, the models may differ in their distance definitions, as well as how they group and classify fault mechanisms; Table 1 illustrates these differences for the three models used to predict ground motions from Coastal California crustal earthquakes in the USGS hazard maps. This variation presents challenges for the deaggregation process. When different definitions or groupings are used for similar ground motion properties, we need to convert one definition to another (e.g., using the distance conversion approaches proposed in Scherbaum et al. 2004) or re-group the inputs, in order to facilitate consistent deaggregation across GMPMs.

Table 1: Parameters used for the Ground Motion Prediction Models considered here

GMPM	Boore and Atkinson 2008	Campbell and Bozorgnia 2008	Chiou and Youngs 2008
Magnitude	M_W	M_W	M_W
Distance	R_{JB}	R_{JB}, R_{RUP}	R_{JB}, R_{RUP}, R_X
Fault Mechanism	Unspecified, strike slip, normal, thrust/reverse	Strike slip, normal/normal-oblique, reverse/reverse-oblique (dip and rake angles)	Strike slip/normal-oblique, normal, reverse/reverse-oblique (dip and rake angles)
Other Variables	V_{S30}	V_{S30}, Z_{TOR}, $Z_{2.5}$	V_{S30}, Z_{TOR}, $Z_{1.0}$, *AS*

M_W = Moment magnitude.
R_{JB} = Shortest distance from the recording site to the surface projection of the rupture.
R_{RUP} = Shortest distance from the recording site to the rupture.
R_X = Site coordinate measured perpendicular to the fault strike from the surface projection of the updip edge of the rupture, with the downdip direction being positive; used to determine hanging-wall flag.
V_{S30} = Shear wave velocity averaged over the top 30 m.
Z_{TOR} = Depth to the top of the rupture.
$Z_{1.0}$ = Depth to the 1.0 km/s shear-wave velocity horizon.
$Z_{2.5}$ = Depth to the 2.5 km/s shear-wave velocity horizon.
AS = Aftershock flag.

Deaggregation of Magnitude, Distance, and Epsilon

Now we have computed the total hazard rate in Equation 1, we can find the distribution of magnitudes, distances, and epsilons that cause $Sa > y$ through deaggregation using Bayes' rule. For instance, the conditional distribution of magnitude given $Sa > y$, $f_{M|Sa>y}(m,y)$, can be computed as follows:

$$f_{M|Sa>y}(m,y) = \frac{1}{\nu(Sa>y)}\sum_k\sum_j \nu_j \iint f_{M,R,\mathrm{E}}(m,r,\varepsilon)P(Sa>y\,|\,m,r,\varepsilon,GMPM_k)drd\varepsilon P(GMPM_k) \qquad (2)$$

Since these parameters of interest are usually discretized in practice, the corresponding conditional distribution is expressed in terms of a percentage contribution to $Sa > y$, e.g., $P(M = m_j \,|\, Sa > y)$, instead of $f_{M|Sa>y}(m,y)$.

The associated deaggregated mean magnitude, $\bar{M}$ can also be calculated as follows:

$$\bar{M} = E(M\,|\,Sa>y) = \sum_j m_j P(M = m_j\,|\,Sa>y) \qquad (3)$$

Conditional distributions and mean values of magnitudes, distances, and epsilons given *Sa*, e.g., $f_{M|Sa>y}(m,y)$, are standard outputs of nearly all PSHA software, and are easily obtainable from the USGS interactive deaggregation web tool (USGS 2009).

Deaggregation of Other Parameters

Magnitude, distance, and epsilon are currently the ground motion parameters that are of most interest, and deaggregation results for these parameters can be easily obtained from standard PSHA software. In certain regions or special applications, other uncertain parameters may also be of interest. The total hazard, $\nu(Sa > y)$, can be computed if other uncertain parameters, expressed as θ, are considered:

$$\nu(Sa>y) = \sum_k\sum_j \nu_j \iiiint f_{M,R,\mathrm{E},\Theta}(m,r,\varepsilon,\theta)P(Sa>y\,|\,m,r,\varepsilon,\theta,GMPM_k)dmdrd\varepsilon d\theta P(GMPM_k) \qquad (4)$$

Deaggregation can be extended to other parameters in a similar fashion:

$$f_{\Theta|Sa>y}(\theta,y) = \frac{1}{\nu(Sa>y)}\sum_k\sum_j \nu_j \iiint f_{M,R,\mathrm{E},\Theta}(m,r,\varepsilon,\theta)P(Sa>y\,|\,m,r,\varepsilon,\theta,GMPM_k)dmdrd\varepsilon P(GMPM_k) \qquad (5)$$

For instance, θ could represent fault mechanism. Fault mechanism can be treated as discrete random variables, sometimes with several types lumped into one group. In practice, this distribution is often inferred instead of explicitly calculated, by computing contributions of each earthquake source to exceedance of a given *Sa* value, and identifying typical mechanisms associated with that source.

Deaggregation of Ground Motion Prediction Models

The deaggregation of GMPMs is similar in concept to the deaggregation of magnitude, distance, and epsilon. It tells us the probability that the exceedance of a given *Sa* level is predicted by a specific GMPM, $P(GMPM_k\,|\,Sa>y)$, and can be found as follows, similar to Equation 2:

$$P(GMPM_k\,|\,Sa>y) = \frac{1}{\nu(Sa>y)}\sum_j \nu_j \iiint f_{M,R,\mathrm{E}}(m,r,\varepsilon)P(Sa>y\,|\,m,r,\varepsilon,GMPM_k)dmdrd\varepsilon P(GMPM_k) \qquad (6)$$

This conditional probability is not necessarily equal to the weight assigned to the GMPM at the beginning of analysis, $P(GMPM_k)$. The initially assigned weight, $P(GMPM_k)$, is analogous to a prior probability, while the deaggregated weight, $P(GMPM_k \mid Sa > y)$, is analogous to a posterior probability in decision analysis (Benjamin and Cornell 1970). Note that all of the terms required in Equation 6 are already computed as part of the standard PSHA calculation of Equation 1, so obtaining this probability is merely a matter of outputting additional information and does not require any complex calculations.

Deaggregation of Magnitude, Distance, and Epsilon Associated with Each Ground Motion Prediction Model

To match the contribution of each GMPM to its associated ground motion parameters, we also need to obtain the joint conditional distribution of magnitudes (or distances or epsilons) and the specified GMPM that cause *Sa* > *y*, as follows:

$$f_{M,GMPM|Sa>y}(m, GMPM_k, y) = \frac{1}{\nu(Sa > y)} \sum_j \nu_j \iint f_{M,R,\mathrm{E}}(m,r,\varepsilon) P(Sa > y \mid m,r,\varepsilon, GMPM_k)\, dr\, d\varepsilon\, P(GMPM_k) \tag{7}$$

Similarly to above, when the continuous variables are discretized, the corresponding conditional distribution is expressed as $P(M = m_j, GMPM_k \mid Sa > y)$ instead. It follows that the relative contribution of magnitude to *Sa* > *y* given a GMPM is:

$$P(M = m_j \mid GMPM_k, Sa > y) = \frac{P(M = m_j, GMPM_k \mid Sa > y)}{P(GMPM_k \mid Sa > y)} \tag{8}$$

The resulting expected magnitude can be calculated as follows:

$$\bar{M}_k = E(M \mid GMPM_k, Sa > y) = \sum_j m_j P(M = m_j \mid GMPM_k, Sa > y) \tag{9}$$

where $\bar{M}_k$ is used to denote the deaggregated mean magnitude associated with $GMPM_k$.

Target Spectrum Computation

The computation of a target spectrum, e.g., the CMS, requires deaggregation to identify the causal parameters, along with the choice of a GMPM. From each GMPM, logarithmic *Sa* mean ($\mu_{\ln Sa}$) and standard deviation ($\sigma_{\ln Sa}$) can be obtained at all periods of vibration using the magnitude (*M*) and distance (*R*) associated with a causal event. The CMS then estimates the expected *Sa* values at all periods of vibration (T_i) conditional on the target *Sa* value at the period of interest (*T**), $\mu_{\ln Sa(T_i)|\ln Sa(T^*)}$, using the correlation coefficient between pairs of spectral values at two periods ($\rho(T_i, T^*)$), as follows (Baker 2010):

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*)} = \mu_{\ln Sa}(M, R, T_i) + \rho(T_i, T^*)\sigma_{\ln Sa}(M, T_i)\varepsilon(T^*) \tag{10}$$

Given a target *Sa*(*T**) value *y*, the deaggregation of magnitudes, distances, and epsilons, e.g., $\bar{M}$, can be obtained. This deaggregation result is based on all GMPMs. The computation of CMS, however, requires the choice of a GMPM. An approximate calculation would be to use each GMPM considered in the PSHA calculation, to obtain logarithmic *Sa* mean ($\mu_{\ln Sa,k}$) and standard deviation ($\sigma_{\ln Sa,k}$) at T_i, and use these values in Equation 11 to obtain $\mu_{\ln Sa(T_i)|\ln Sa(T^*),k}$.

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*),k} \approx \mu_{\ln Sa,k}(\bar{M}, \bar{R}, T_i) + \rho(T_i, T^*)\sigma_{\ln Sa,k}(\bar{M}, T_i)\bar{\varepsilon}(T^*) \tag{11}$$

These GMPM-specific spectra can then be averaged with their prior probabilities, $P(GMPM_k)$, to obtain $\mu_{\ln Sa(T_i)|\ln Sa(T^*)}$.

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*)} \approx \sum_k \mu_{\ln Sa(T_i)|\ln Sa(T^*),k} P(GMPM_k) \tag{12}$$

With the refinements in PSHA deaggregation in Equation 9 that incorporate multiple GMPMs, it is also possible to obtain the deaggregation results given each GMPM, $\bar{M}_k$, and compute the CMS using the corresponding GMPM,

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*),GMPM_k} \approx \mu_{\ln Sa,k}(\bar{M}_k, \bar{R}_k, T_i) + \rho(T_i, T^*)\sigma_{\ln Sa,k}(\bar{M}_k, T_i)\bar{\varepsilon}_k(T^*) \tag{13}$$

and then weight the resulting GMPM-specific CMSs with the posterior probability, $P(GMPM_k \mid Sa > y)$.

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*)} = \sum_k \mu_{\ln Sa(T_i)|\ln Sa(T^*),GMPM_k} P(GMPM_k \mid Sa > y) \tag{14}$$

If the exact solution is desired for multiple earthquake events (m_j, r_j) and multiple GMPMs ($GMPM_k$), we can also compute the CMS with the refined posterior probability, $P(m_j, r_j, GMPM_k \mid Sa > y)$.

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*),m_j,r_j,GMPM_k} = \mu_{\ln Sa,k}(m_j, r_j, T_i) + \rho(T_i, T^*)\sigma_{\ln Sa,k}(m_j, T_i)\varepsilon_{j,k}(T^*) \tag{15}$$

$$\mu_{\ln Sa(T_i)|\ln Sa(T^*)} = \sum_k \sum_j \mu_{\ln Sa(T_i)|\ln Sa(T^*),m_j,r_j,GMPM_k} P(m_j, r_j, GMPM_k \mid Sa > y) \tag{16}$$

Deaggregation of GMPMs with their associated ground motion parameters enables the improved computation of the target spectrum with probabilistic consistency.

EXAMPLE APPLICATION

To illustrate the use of the above equations, we now perform PSHA, deaggregation and CMS computation for an example site. First, we estimate the ground motion hazard at the example site using PSHA that incorporates multiple GMPMs. Next, we identify the relative contributions of the events (with associated properties) and GMPMs to the hazard prediction using the refined PSHA deaggregation. Finally, approximate or exact target spectrum can be computed for various intensity levels conditional on the period of interest.

Description of Site and Events

The example site considered has two faults, as shown in Figure 2. Fault A, produces earthquakes with magnitude, M = 6 and distance, R = 10 km from the site, and has an annual occurrence rate of ν = 0.01; we denote this earthquake Event A. Fault B produces earthquakes with magnitude, M = 8 and distance, R = 25 km from the site, and has an annual occurrence rate of ν = 0.002; we denote this earthquake Event B. Both events have strike slip mechanism. The site has shear wave velocity V_{S30} = 760 m/s, corresponding to NEHRP Site Class B/C. Assuming a vertical fault that extends to the ground surface (a reasonable assumption for shallow crustal earthquakes in Coastal California), rupture distance, R_{RUP}, is the same as R_{JB}. The earthquake events are assumed to rupture the whole of faults A and B, so the closest distance to the site for a given earthquake will be a known constant. We study the site for a structure with a period of vibration, T^*, of 1 s.

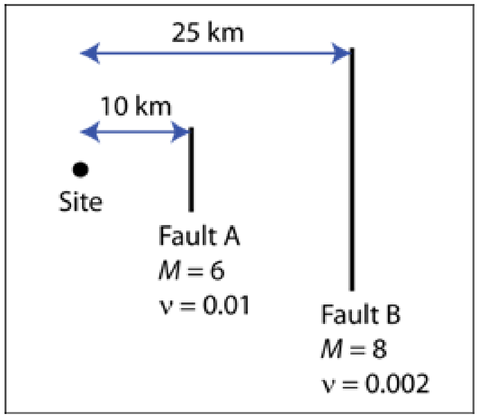

Figure 2. Layout of an example site dominated by two earthquake events A and B.

PSHA Computation

We use the three GMPMs discussed above with equal prior weights to evaluate the annual rates of exceeding a target *Sa* level for both events. The probability of exceeding a target *Sa* level given an event with its associated magnitude (m_j) and distance (r_j), $P(Sa > y \mid m_j, r_j, GMPM_k)$, is computed using logarithmic *Sa* mean ($\mu_{\ln Sa(T^*)}$) and standard deviation ($\sigma_{\ln Sa(T^*)}$) predictions from each GMPM. The annual rate of *Sa* exceedance, $\nu(Sa > y)$, is computed using Equation 11 for multiple values of *y*, and the resulting hazard curve is shown in Figure 3, along with individual hazard curves for Events A and B. We can find the target *Sa* values of interest from the hazard curve.

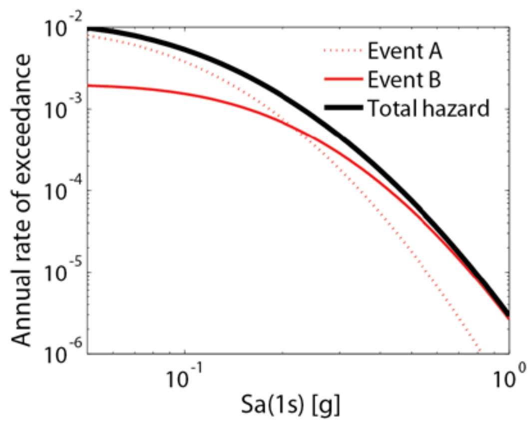

Figure 3. Hazard curves for the example site.

Deaggregation of Events

In this simplified site, each event ($Event_j$) corresponds to a single magnitude (m_j) and distance (r_j). The conditional probability that each event causes $Sa > y$ is given by expressions such as Equation 2, and can be simplified for this site as follows:

$$P(Event_j \mid Sa > y) = \frac{\nu(Sa > y, Event_j)}{\nu(Sa > y)} \tag{17}$$

where

$$\nu(Sa > y, Event_j) = \sum_k P(Sa > y \mid Event_j, GMPM_k)\nu(Event_j)P(GMPM_k) \qquad (18)$$

The probabilities obtained from Equation 17 are plotted in Figure 4. From Figure 4, we can see that the smaller but more frequent Event A is most likely to cause exceedance of small *Sa* levels, whereas the larger and rarer Event B is most likely to cause exceedance of large *Sa* levels. This is because the annual hazard rate involves two competing factors: annual rate of occurrence for an earthquake, and probability of exceeding a *Sa* level given that earthquake. The results in Figure 4 are typical of PSHA analyses for more realistic sites.

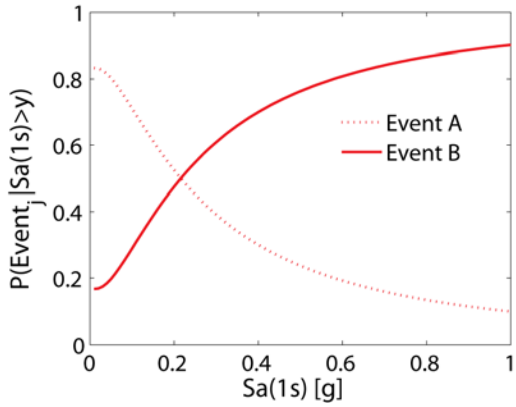

Figure 4. Deaggregation of events given *Sa*(1s) > y for the example site.

Deaggregation of Ground Motion Prediction Models

Following Equation 6, the deaggregation of GMPMs is performed, and the results of this deaggregation calculation are shown in Figure 5. The deaggregated GMPM contributions vary from 0.09 to 0.55, instead of having an equal weight of 0.33, as target *Sa* values vary. This is because the GMPMs are not equally likely to predict the exceedance of a given *Sa* level.

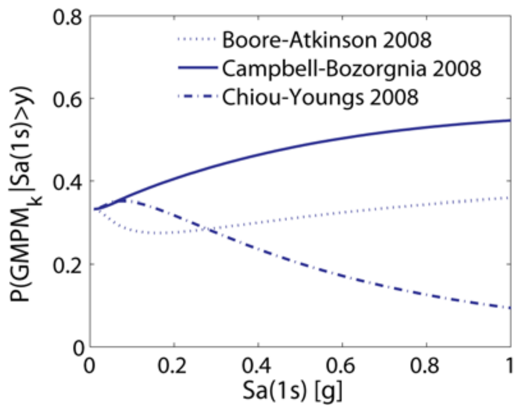

Figure 5. Deaggregation of GMPMs given *Sa*(1s) > y for the example site.

Deaggregation of Magnitude, Distance, and Epsilon

The deaggregated mean magnitude associated with a specific GMPM can be found using Equation 9. The results are shown in Figure 6. In this figure, the thin lines indicate the mean magnitude, given $Sa > y$ and given that the associated GMPM is the model that predicts $Sa > y$. The heavy line provides a weighted average (composite) over all GMPMs, as computed using Equation 3.

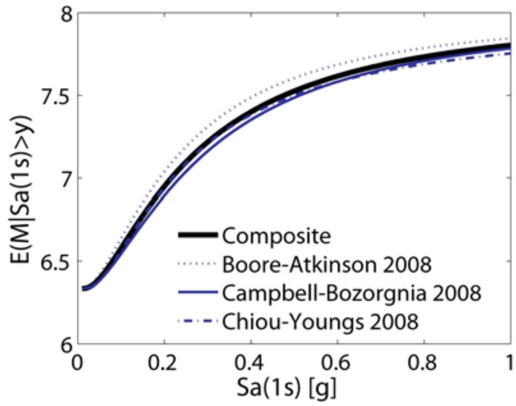

Figure 6. Deaggregation of magnitudes given *Sa*(1s) > y for the example site.

The deaggregated mean distance and epsilon values can be obtained using similar procedures and are plotted in Figure 7 and Figure 8. The distance deaggregation results resemble the magnitude deaggregation results due to the one-to-one correspondence between magnitudes and distances in this simple example.

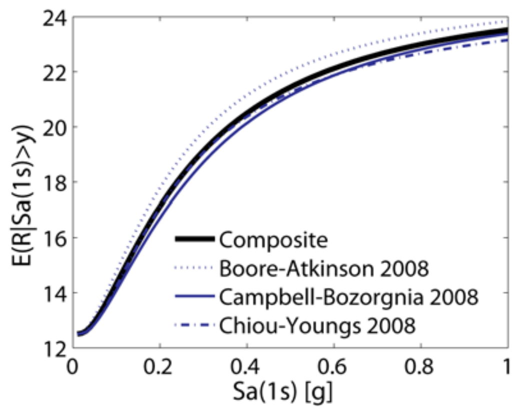

Figure 7. Deaggregation of distances given *Sa*(1s) > y for the example site.

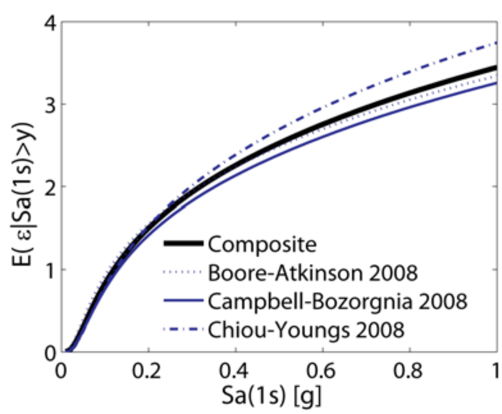

Figure 8. Deaggregation of epsilons given *Sa*(1s) > y for the example site.

Conditional Mean Spectrum Computation

Using the results obtained in this section, the Conditional Mean Spectrum can be computed while accounting for the multiple GMPMs that were used in the hazard calculation. Approximate CMS can be computed using Equations 11 and 12, refined CMS can be computed using Equations 13 and 14 (composite average), and exact CMS can be computed using Equations 15 and 16. The inputs for Equations 11 to 14 are available from the above plots. An example plot of CMSs given *Sa*(1s) > 0.9g is shown in Figure 9. In this example, while the GMPM-specific CMSs (Equation 13) differ more, the approximate CMS with logic tree weights (Equation 12) deviates less from the composite CMS with posterior probability (Equation 14).

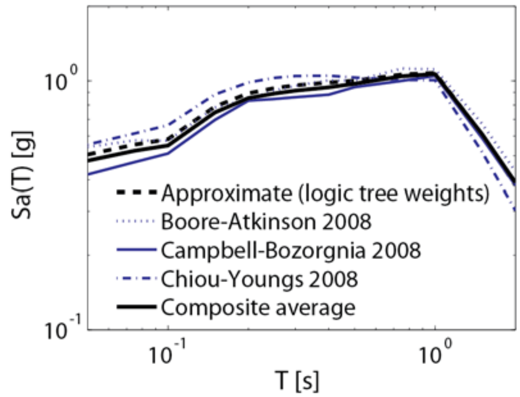

Figure 9. Conditional Mean Spectra given *Sa*(1s) > 0.9g for the example site.

AVAILABILITY OF GMPM DEAGGREGATION

The USGS has recently begun providing GMPM deaggregation outputs in the 2008 Interactive Deaggregation website (USGS 2009), as seen in the illustration of the tool shown in Figure 10. The deaggregation outputs now optionally include deaggregation of M, R, ε combinations for each GMPM as well as individual GMPM contribution to the overall hazard in real sites. This will enable the assessment of the CMS computation incorporating aleatory and epistemic uncertainties, and benefit ground motion selection for real sites. The authors are actively using this tool to perform calculations similar to the above example for real sites, in order to understand the implications of GMPM variability and the impact of potential approximations in CMS calculations listed above.

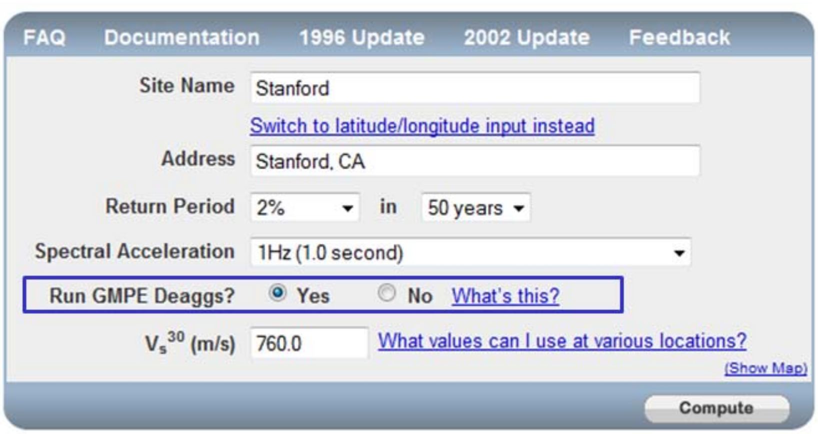

Figure 10. USGS implementation of GMPM deaggregation. (from USGS 2009)

CONCLUSIONS

Probabilistic seismic hazard analysis (PSHA) deaggregation of Ground Motion Prediction Models (GMPMs) links the computation of a target spectrum to the total hazard prediction. PSHA is commonly used to compute the ground motion hazard for which geotechnical and structural systems are analyzed and designed. As a key step in defining the seismic load input to dynamic analysis, ground motion selection often involves specification of a target spectrum, e.g., the Conditional Mean Spectrum (CMS). Computation of such a target spectrum requires deaggregation to identify the causal ground motion parameters, along with the predictions from multiple GMPMs. Current ground motion selection incorporates the aleatory uncertainties from earthquake scenarios without considering the epistemic uncertainties from multiple GMPMs. Here we account for both aleatory and epistemic uncertainties in ground motion selection through PSHA deaggregation of GMPMs.

This GMPM deaggregation is consistent with the probabilistic treatment of the magnitude and distance random variables in traditional PSHA. The deaggregation of GMPMs provides additional insights into which GMPM contributes most to prediction of *Sa* values of interest. To match the contribution of each GMPM to its associated ground motion parameters, separate deaggregation of M/R/ε parameters for each GMPM is also performed. These calculations are illustrated through applications on an example site. First, we estimate the hazard using PSHA that incorporates multiple GMPMs. Next, we identify the relative contributions of events and GMPMs to the hazard prediction using the refined deaggregation procedures. Finally, approximate or exact target spectra can be computed for various intensity levels conditional on the period of interest. Such target spectra can be used to select ground motions for engineering analysis.

This GMPM deaggregation is now available at the USGS Interactive Deaggregation website. This tool facilitates assessments of real sites incorporating aleatory and epistemic uncertainties, and aids ground motion selection efforts. The proposed methodology for deaggregation of prediction models can also be immediately applicable to other procedures which require multiple prediction models in an earlier stage of total prediction and a later stage of new target computation.

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REFERENCES

Baker, J. W. (2010). "The Conditional Mean Spectrum: a tool for ground motion selection." *Journal of Structural Engineering*(in press).

Bazzurro, P., and Cornell, C. A. (1999). "Disaggregation of Seismic Hazard." *Bulletin of the Seismological Society of America*, 89(2), 501-520.

Benjamin, J. R., and Cornell, C. A. (1970). *Probability, Statistics, and Decision for Civil Engineers*, McGraw-Hill, New York.

Boore, D. M., and Atkinson, G. M. (2008). "Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s." *Earthquake Spectra*, 24(1), 99-138.

Campbell, K. W., and Bozorgnia, Y. (2008). "NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s." *Earthquake Spectra*, 24(1), 139-171.

Chiou, B. S. J., and Youngs, R. R. (2008). "An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra." *Earthquake Spectra*, 24(1), 173-215.

Chopra, A. K. (2001). *Dynamics of structures: theory and applications to earthquake engineering*, Prentice Hall, Upper Saddle River, NJ.

Harmsen, S. C. (2001). "Mean and Modal ε in the Deaggregation of Probabilistic Ground Motion." *Bulletin of the Seismological Society of America*, 91(6), 1537-1552.

Kramer, S. L. (1996). *Geotechnical earthquake engineering*, Prentice Hall, Upper Saddle River, N.J.

McGuire, R. K. (1995). "Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop." *Bulletin of the Seismological Society of America*, 85(5), 1275-1284.

McGuire, R. K. (2004). *Seismic hazard and risk analysis*, Earthquake Engineering Research Institute, Oakland, CA.

Petersen, M. D., Frankel, A. D., Harmsen, S. C., Mueller, C. S., Haller, K. M., Wheeler, R. L., Wesson, R. L., Zeng, Y., Boyd, O. S., Perkins, D. M., Luco, N., Field, E. H., Wills, C. J., and Rukstales, K. S. (2008). *Documentation for the 2008 Update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008–1128*.

Scherbaum, F., Bommer, J. J., Bungum, H., Cotton, F., and Abrahamson, N. A. (2005). "Composite Ground-Motion Models and Logic Trees: Methodology, Sensitivities, and Uncertainties." *Bulletin of the Seismological Society of America*, 95(5), 1575-1593.

Scherbaum, F., Schmedes, J., and Cotton, F. (2004). "On the Conversion of Source-to-Site Distance Measures for Extended Earthquake Source Models." *Bulletin of the Seismological Society of America*, 94(3), 1053-1069.

USGS. (2009). "2008 Interactive Deaggregations (Beta)." Earthquake Hazards Program, http://eqint.cr.usgs.gov/deaggint/2008/.