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RISK-TARGETED MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION CALCULATIONS FOR 500 LOCATIONS USING THE OPENQUAKE ENGINE

Manuela VILLANI[1,2], Kendra JOHNSON[3], Marco PAGANI[4], Nicolas LUCO[5] & Zachary KORTUM[6]

Abstract: *The American Society of Civil Engineers (ASCE) Earthquake Loads Overseas (AELO) project is an ongoing collaboration between the U.S. Geological Survey (USGS) and the Global Earthquake Model (GEM) Foundation to compute Risk-targeted Maximum Considered Earthquake (MCE_R) and other ground motions for locations outside of the United States. The ASCE 7 Standard requires that probabilistic and deterministic ground motions be calculated for high-hazard sites, from which the governing MCE_R ground motion is defined as the lesser of the two. For the AELO project, the ground motions are derived using models from GEM's Global Seismic Hazard Mosaic. For the deterministic ground motions, ASCE7-16 states that the deterministic spectral response acceleration at each period shall be calculated as the largest 84th-percentile ground motions across the characteristic earthquakes on all known active faults within the region, subject to a deterministic lower limit. Due to the ambiguities of "characteristic earthquakes" and "active faults," the more recent ASCE7-22 calls for using disaggregation of the probabilistic ground motions to identify the deterministic earthquakes/scenarios. For the ASCE7-22 MCE_R maps, the 84th-percentile ground motion is then approximated from the magnitude-distance-epsilon disaggregation results by source. The largest deterministic 84th-percentile ground motion calculated across all the selected scenarios is taken as the final deterministic ground motion, still subject to a deterministic lower limit. The workflow developed herein derives the risk-targeted probabilistic, deterministic, and governing MCE_R ground motion using the OpenQuake (OQ) Engine - GEM's seismic hazard software - and Python tools that use OQ libraries. As an improvement with respect to ASCE 7 Standard, the workflow directly adopts the aleatory standard deviations of the ground motion models used by the seismic hazard model, improving the consistency between the probabilistic and deterministic calculations. This study presents the methodology and examples of its application.*

Introduction

The AELO project is an ongoing collaboration between USGS and GEM to compute Risk-targeted Maximum Considered Earthquake (MCE_R) and other ground motions for locations outside of the United States. Previous values computed at these sites originated from a variety of sources, including site-specific studies, rough approximations from the Global Seismic Hazard Assessment Program (Grunthal et al., 1999), and approximations from previously assigned Uniform Building Code (UBC, 1997) zones. The AELO project aims to update the MCE_R and other ground motions using a consistent approach for all locations. This paper details our workflow for calculating updated ASCE7-16 (ASCE, 2016) ground motions within the OpenQuake Engine (OQ Engine), for the first year of the four-year AELO project.

The OpenQuake Engine and the GEM Mosaic

The OQ Engine is GEM's calculation software for earthquake hazard and risk modelling (Pagani et al., 2014, Silva et al., 2014). The OQ Engine is open-source and collaboratively developed at https://github.com/gem/oq-engine.

The first version of GEM's global seismic hazard map was completed in December 2018 (Pagani et al., 2020). The map was computed from an underlying database of models referred to as GEM's Global Hazard Mosaic. The Mosaic is a collection of Probabilistic Seismic Hazard Analysis

[1] Senior Seismic Hazard Scientist, GEM Foundation, Pavia, Italy, Manuela.villani@globalquakemodel.org
[2] Associate, Arup, London, UK
[3] Seismic Hazard Scientist, GEM Foundation, Pavia, Italy
[4] Seismic Hazard Coordinator, GEM Foundation, Pavia, Italy
[5] Research Civil Engineer, U.S. Geological Survey, Golden, U.S.A.
[6] Civil Engineer, U.S. Geological Survey, Golden, U.S.A.

(PSHA) models that together achieve near-global coverage. Maintained by GEM, the Mosaic includes models contributed by national agencies, cooperative scientific projects, and the literature, as well as models developed by the GEM Secretariat. The models of the Mosaic have all been formatted such that they are compatible with the same calculation software, the OQ Engine. In addition to the models, the GEM Foundation maintains a repository of precomputed hazard results for each model of the Mosaic. Periodically, the national and regional outputs are combined to produce global hazard maps that correspond to an instance of the Mosaic. Updates to the models of the Mosaic are made as deemed appropriate and can be in the form of both small changes (e.g., bug fixes) as well as more significant ones, such as replacing the ground motion characterization (GMC) logic tree or even an entire model with a newly released version. Each update is tracked using a versioning system.

Implementation of MCE_R and MCE_G in the OQ Engine

The ASCE 7 Standards require that probabilistic and deterministic ground motions are calculated for high-hazard sites, from which the governing MCE_R ground motion is defined as the lesser of the two. For the AELO project, the ground motions are derived using models from GEM's Global Seismic Hazard Mosaic. For the deterministic ground motions, ASCE7-16 states that the deterministic spectral response acceleration at each period shall be calculated as the largest 84th-percentile ground motion across the characteristic earthquakes on all known active faults within the region, subject to a deterministic lower limit. Due to the ambiguities of "characteristic earthquakes" and "active faults," the more recent ASCE7-22 (ASCE, 2022) calls for using disaggregation of the probabilistic ground motions to identify the deterministic earthquakes/scenarios. For the ASCE7-22 MCE_R maps, the 84th-percentile ground motion is then approximated from the magnitude-distance-epsilon disaggregation results by source. The largest deterministic 84th-percentile ground motion calculated across all the selected scenarios is taken as the final deterministic ground motion, still subject to a deterministic lower limit.

During the first year of the AELO project, we developed a workflow for deriving MCE_R (risk-targeted maximum considered earthquake) spectral accelerations at 0.2 and 1.0s and MCE_G (geometric-mean maximum considered earthquake) peak ground accelerations (PGAs) that are consistent with ASCE7-16. The workflow was implemented in the OQ Engine using the procedures of ASCE7-22 for the deterministic calculations, with some improvements to enhance consistency between the derived probabilistic and deterministic ground motions. The entire workflow, as implemented in the OQ Engine, is shown in Figure 1 and described in the following sections.

Probabilistic MCE_R and MCE_G

The first step of the workflow is the computation of the seismic hazard curves for the peak ground acceleration (PGA) and two spectral accelerations of interest: SA(0.2) and SA(1.0). A PSHA was therefore performed at each site. For the AELO project, the starting point for the derivation of the probabilistic ground motions is GEM's Global Seismic Hazard Mosaic. Each PSHA model in the Mosaic includes two main components:

- the Seismic Source Characterization (SSC), consisting of one or more seismic source models which define all the potential earthquake ruptures scenarios that can generate ground motion levels of engineering interest at the study area. A seismic source model is a comprehensive list of all sources of seismicity within the proximity of the site or region covered by the model. Each source in the source model is characterized by geometric and occurrence parameters that indicate the main properties of the ruptures that can be produced by these sources (e.g., their surfaces and magnitudes), and how frequently they will occur. Seismic source models are developed using seismological, geological, and geodetic data that help constrain the main properties. These data include catalogues of observed earthquakes and fault slip rates.
- the Ground Motion Characterization (GMC) consists of one or more Ground Motion Models (GMMs) which estimate the ground motion levels, also called Intensity Measure Levels (IMLs), that can be expected due to the ruptures produced by the Seismic Source Characterization. A GMM computes expected IMLs and their variability for a range of spectral periods with parameters such as earthquake magnitude, source-to-site distance and shear-wave conditions.

The epistemic uncertainty (or modelling uncertainty) that is included both in the Seismic Source Characterization and Ground Motion Characterization is handled through a logic tree approach (e.g., Kulkarni et al., 1984), where each branch represents an alternative credible interpretation, and all the branches are assumed to be mutually exclusive and collectively exhaustive.

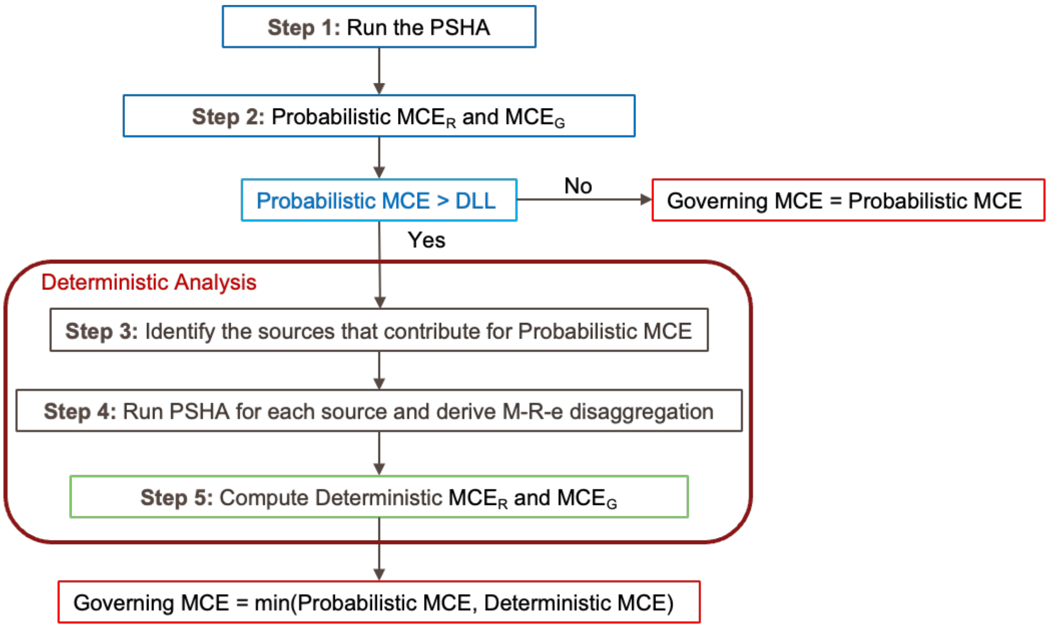

Figure 1. Workflow for the derivation of the MCE$_R$ and MCE$_G$ as implemented in the OQ Engine.

As mentioned before, the models in the Mosaic were created by many scientists, organizations, and projects, and therefore were not all developed according to the same principles or standards. To ensure some consistency in the probabilistic calculations, the models in the Mosaic were reviewed and updated as described below.

The seismic source characterizations of the Mosaic models do not all assume the same minimum magnitude (M_{min}). For the PSHA calculations, the M_{min} represents an engineering parameter defining a threshold for potentially damaging earthquakes. Bommer and Crowley (2017) define M_{min} as the lower limit of integration over earthquake magnitudes such that using a smaller value may result in higher estimates of seismic hazard but would not alter the estimated risk. In this definition, it is assumed that not all the earthquakes with magnitude above M_{min} will cause damage to the structures, while all earthquakes smaller than M_{min} will never be damaging. In the current Mosaic, M_{min} is a calculation performance factor that has been hardcoded into the source input files and depends on the minimum magnitude defined in the magnitude recurrence relationship. We considered that these values implicitly derived from the source input in the Mosaic were not necessarily representing the minimum level of damage in a consistent way across the globe. To choose a M_{min} for the PSHA calculations, we (1) considered the approaches used in the literature (e.g., Bommer and Crowley, 2017); (2) performed sensitivity analyses of the seismic hazard curves and ground motions for the 20% probability of exceedance (POE) in 50 years; and (3) compared the ground motion values given by some GMMs with threshold values for which a probability of slight damage greater than 0 would be expected. Following the review of a variety of fragility functions, a PGA threshold value for slight damage of 0.06 g was considered. Based on these analyses, we chose M_{min} = 4.0, though for Canada and India, due to limitations of the models, we were not able to use this value of M_{min}.

For modelling epistemic uncertainty in the ground motion characterizations, the seismic hazard models currently included in the Mosaic use the multiple GMMs approach, except for the models for Canada and Europe, which adopt the backbone approach. However, the rationale for the selection of the GMMs varies from model to model, with some hazard models using out-of-date GMMs. In addition, although for some of the seismic hazard models in the Mosaic the selection of the GMMs was informed by comparisons against recorded ground motions, in some cases the GMMs in the original hazard models were based on expert judgement. Given the limited time available for the AELO project, the multiple GMMs approach was kept, but the selection of GMMs was reviewed, and updated when necessary. The review and update were based on the exclusion criteria defined by Bommer et al. (2010) and investigation of the similarities between the initially selected GMMs to avoid including GMMs yielding similar ground motion predictions and thereby underestimating the epistemic uncertainty (Bommer et al., 2015). To evaluate similarities in the GMMs, Trellis Plots (i.e., graphical comparison of the attenuation curves for a particular magnitude value and spectral ordinate) were combined with two statistical approaches:

- Sammon's maps (Sammon, 1969; Scherbaum et al., 2010), i.e. visualisation of a statistical technique that enables the projection of high-dimensional vectors onto 2D maps in such a way that the distances between the vectors can be preserved, as shown in Figure 2.
- Dendrograms, a second visualisation approach, which better highlight the clustering of the predictions. The dendrogram is a visual representation of the compound correlation data. The individual compounds are arranged along the bottom or the left of the dendrogram and are referred to as leaf nodes. Compound clusters are formed by joining individual compounds or existing compound clusters with the join point, referred to as a node. This is usually used in hierarchical clustering and is illustrated in Figure 3.

The above analyses, far from providing a complete justification of the GMMs adopted for the AELO project, aimed to guide the new selection for those seismic hazard models for which now-outdated GMMs were originally adopted in the Mosaic.

Finally, the seismic hazard curves were all derived for the geometric mean (GM) of the two horizontal components. This was done by implementing in the OQ engine the empirical correlations of Beyer and Bommer (2006) for the arithmetic mean, GMRotI50 and random component, and Boore and Kishida (2016) for the greater of the two horizontal components and RotD50.

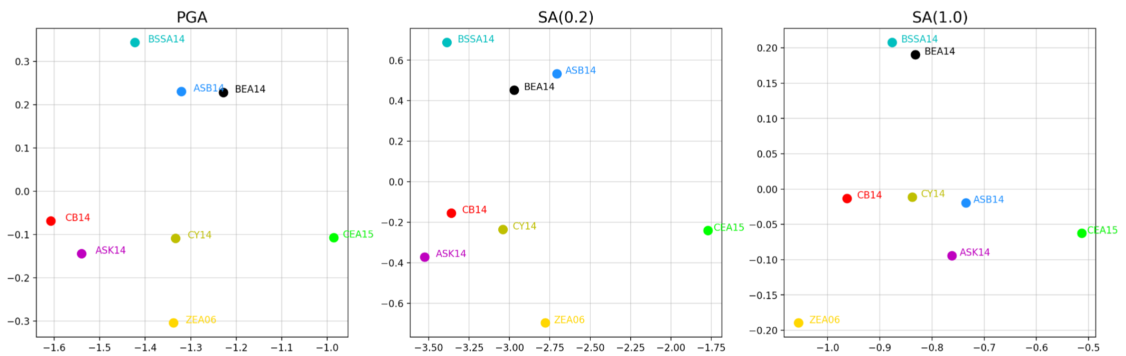

Figure 2. Sammon's maps for initially selected GMMs for active shallow crustal regions (ASCR).

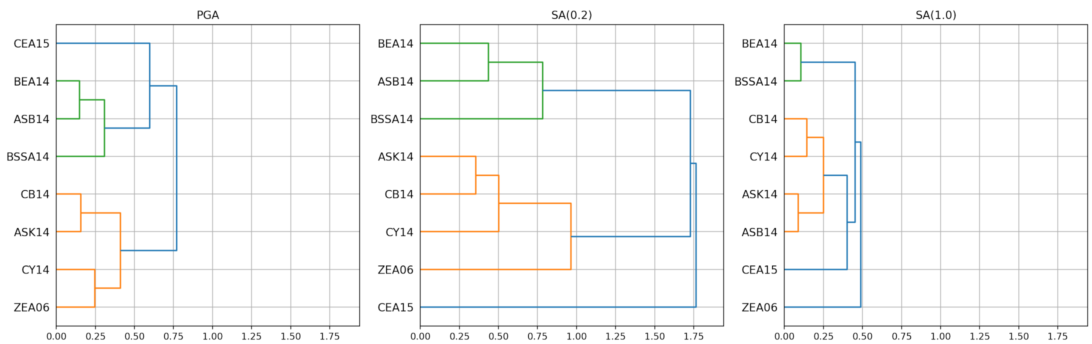

Figure 3. Dendogram representation for initially selected GMMs for ASCR.

The probabilistic ground motions were computed following ASCE7-16, starting from the hazard curves, first converted from geometric mean to maximum horizontal response using the following scale factors: 1.1 for the spectral acceleration at 0.2 s, and 1.3 for the spectral acceleration at 1.0 s. The spectral accelerations at 0.2 and 1.0 s expected to achieve a 1% probability of collapse within a 50-year period were computed using a Python implementation of the USGS Risk-Targeted Ground Motion Calculator (https://earthquake.usgs.gov/designmaps/rtgm/). This ensures uniform structural performance in terms of collapse risk. More specifically, the full ground motion hazard curve is convolved with the notional fragility curve for structural collapse specified by ASCE7-16. Figure 4 shows an example of the seismic hazard curves for PGA, SA(0.2) and SA(1.0), along with the accelerations for 2% in 50 years POE (black dashed lines) and the probabilistic MCE_R and MCE_G values (red dashed lines).

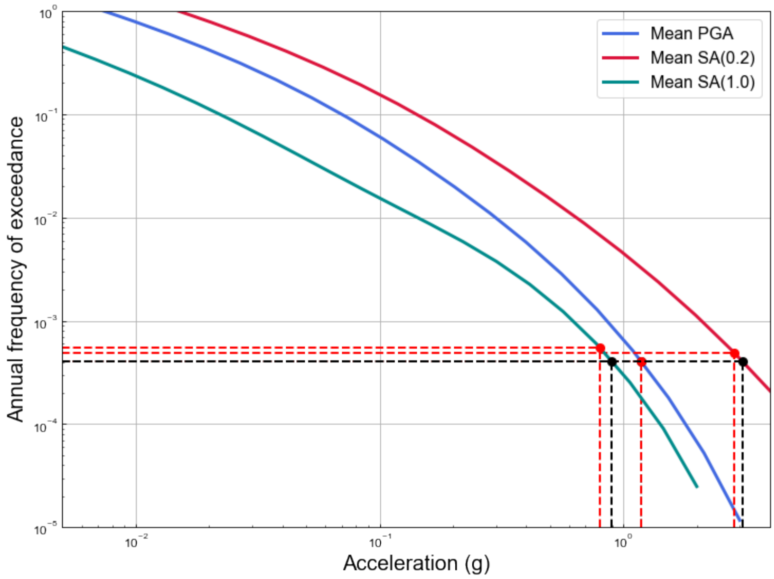

Figure 4. Examples of the mean hazard curves. Black dashed lines correspond to the ground motions for a probability of exceedance of 2% in 50 years, while red dashed lines correspond to the probabilistic MCE_R and MCE_G.

Deterministic MCE_R and MCE_G (Steps 3, 4 and 5)

As mentioned above, for the deterministic calculations we followed ASCE7-22 which recommends using disaggregation of the probabilistic ground motions to identify scenario earthquakes; the largest deterministic 84th-percentile ground motion calculated across all the selected scenario earthquakes, subject to a deterministic lower limit, is still used.

According to ASCE7-16 and ASCE7-22, the deterministic ground motion at each spectral period needs to be calculated only for those sites where the corresponding probabilistic ground motion is larger than a deterministic lower limit (DLL). For the site condition of the ASCE7-16 ground motions computed in the first year of the AELO project (V_{S30} = 760m/s, the site class B/C boundary), these DLL thresholds are 0.5g for the MCE_G PGA, and 1.5g and 0.6g for the MCE_R spectral accelerations at 0.2 and 1.0 s, respectively.

Based on the above thresholds, we performed deterministic analyses for 104 of the approximately 500 sites. For each site and spectral period T (including PGA), Steps 3 to 5 in the workflow in Figure 1 were performed.

Step 3. The sources that contribute to the hazard at each probabilistic ground motion (MCE_R and MCE_G) were identified from the seismic hazard curves computed for the sources. Sources contributing less than 10% of the largest contributor are ignored. Figure 5 shows this identification for the site ID 102. The black lines are the mean hazard curves, the coloured lines are hazard curves of individual sources that most contribute to the hazard (those used in further steps), and the grey lines are the hazard curves of sources that contribute less than 10% of the largest contributor.

Step 4. New PSHA calculations were run for each source identified in Step 3 to obtain the disaggregation of the hazard for that source in terms of magnitude, distance and ε (i.e., the number of standard deviations between the natural logarithm of a ground motion value and the mean value computed using a GMM).

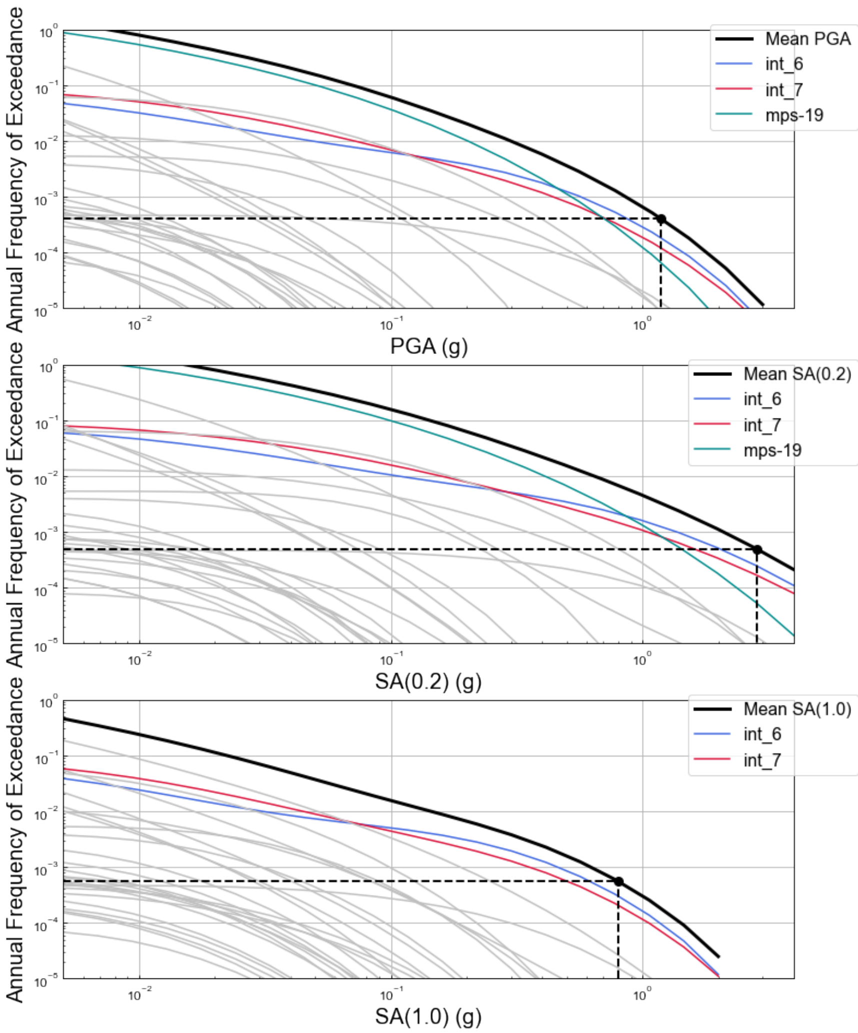

Figure 5. Example of identification of the sources that contribute most to the hazard for the probabilistic MCE_R and MCE_G ground motions for site ID 102 from the South America (SAM) hazard model.

Step 5. For the ASCE7-22 ground motion maps, the deterministic 84th-percentile ground motion for each source at period T, $Det84^{th}{}_{source}$ (T), is then computed as:

$$Det84^{th}{}_{source}(\mathrm{T}) = MCE_{prob}(T)\frac{\exp(\sigma)}{\exp(\varepsilon\sigma)} \quad (1)$$

where MCE_{prob}(T) is either the probabilistic MCE_R or MCE_G for the spectral period T, ε is the number of standard deviations defined in Step 4 through the disaggregation and σ is the standard deviation of the GMM. ASCE7-22 assumes a σ of 0.6. However, this value is not always consistent with the σ of the GMMs used in the hazard models, which varies with the GMM, spectral period, and other factors (e.g., magnitude). For consistency with the GMMs adopted for the probabilistic ground motions, the following approach is proposed as an improvement to the ASCE7-22 approach.

In the seismic hazard model, each source is associated with a GMC logic tree with one or more GMMs based on its encompassing tectonic region. Using the same GMC logic tree:

1. For each GMM, we computed the standard deviation (σ_{GMM}) considering the magnitude and distance from the disaggregation performed in Step 4. This more accurate value replaces σ = 0.6 in equation (1), to derive the $Det84^{th}{}_{source,\ GMM}$.
2. The deterministic 84th-percentile ground motion for the source, $Det84^{th}{}_{source}$, is then computed as the weighted average of the $Det84^{th}{}_{source,\ GMM}$, using the same weights of the original GMC logic tree (Figure 6).

3. Finally, the deterministic ground motion at the site is defined at each period by taking the maximum across all the deterministic ground motions from all the sources and the deterministic lower limit (DLL):

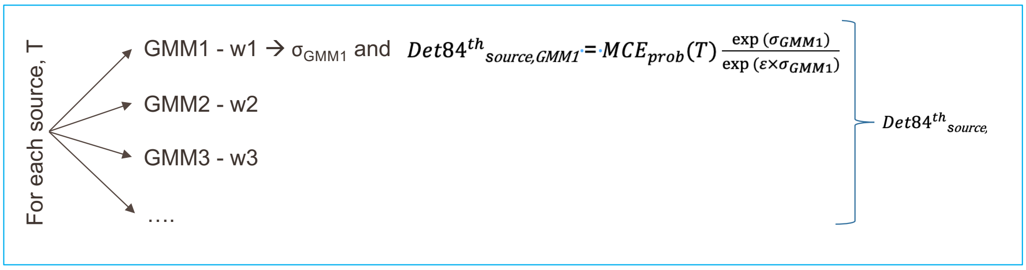

Figure 6. Computation of the deterministic ground motion per source using the same GMC logic tree adopted in the PSHA.

Governing MCE_R and MCE_G

The governing MCE_R and MCE_G value at any period is given by the lesser between the probabilistic ground motion computed in Step 2 and the deterministic ground motion computed in Step 5. Figure 7 shows the probabilistic, deterministic, and governing ground motions along with the deterministic lower limits at six example sites. In the figures, the MCE_G PGA values are plotted as spectral accelerations at 0.0 s. Figure 8 provides an overview of the probabilistic, deterministic, and governing ground motions at sites in the Caribbean and Central America (CCA) hazard model.

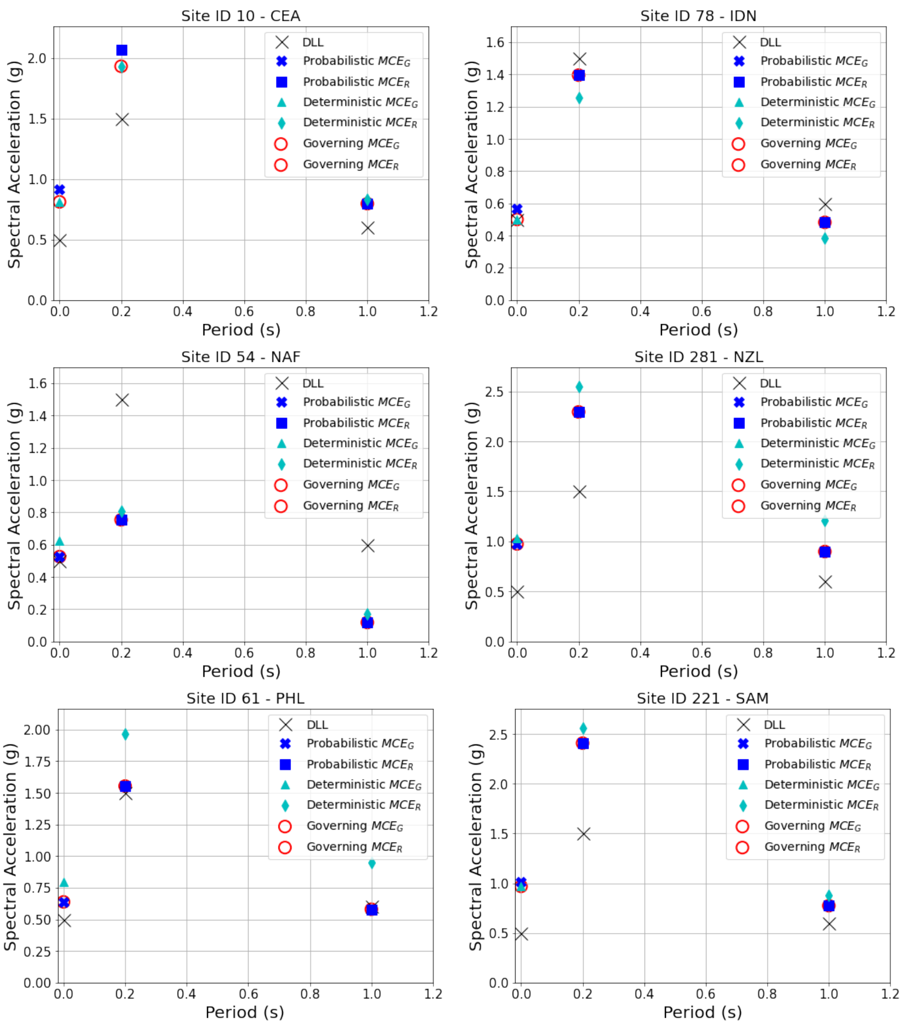

Figure 7. Probabilistic, deterministic, and governing MCE_R and MCE_G ground motions for six example sites.

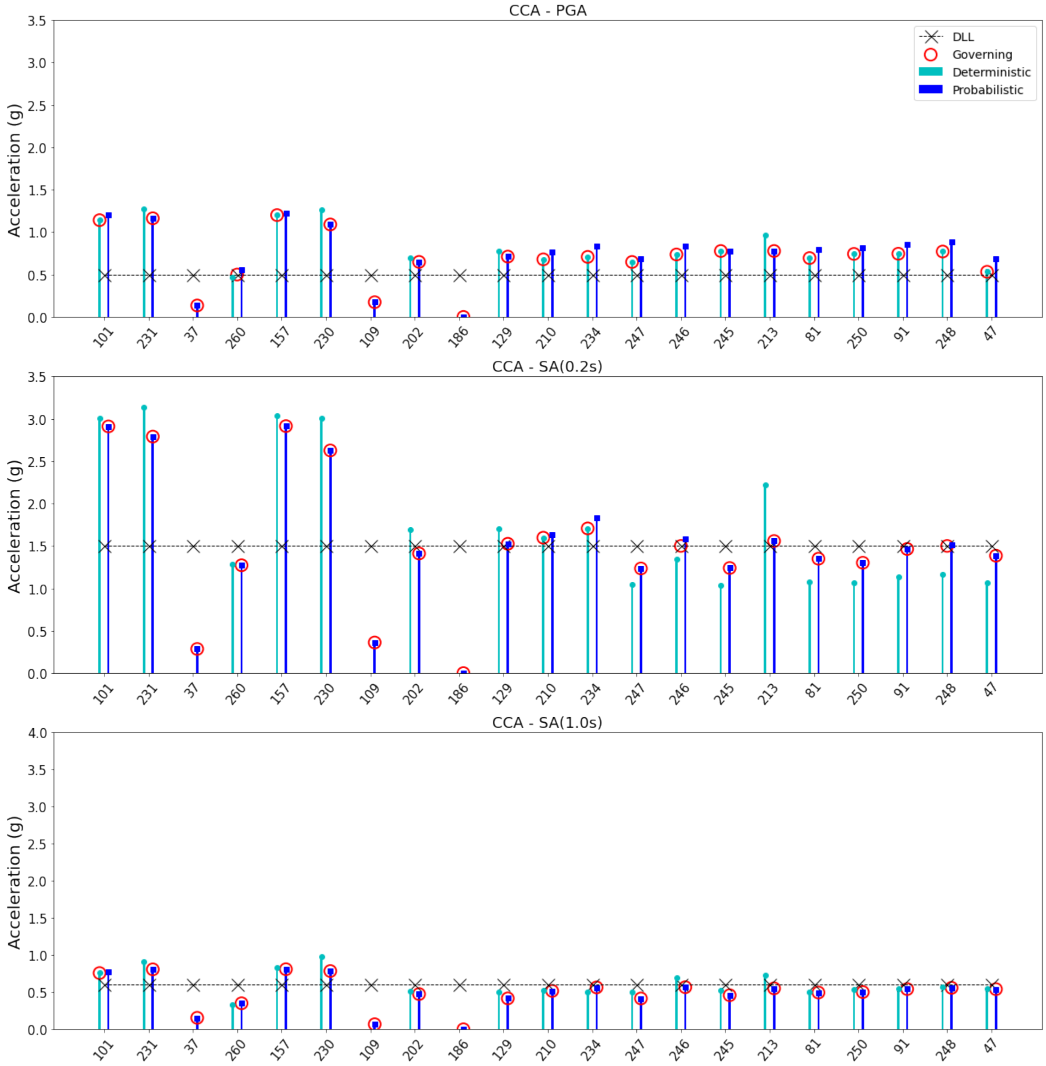

Figure 8. Probabilistic, deterministic, and governing MCE_R and MCE_G ground motions for the sites included in the CCA (Caribbean and Central America) hazard model.

Summary and Conclusions

With updates and improvements to the underlying hazard models, and changes to the GEM OpenQuake Engine, we first computed the mean hazard curves for approximately 500 sites outside the United States and derived the probabilistic MCE_R and MCE_G ground motions. We then followed the ASCE7-22 approach to derive the deterministic ground motions for those sites for which the probabilistic ground motions were larger than the deterministic lower limits. For the deterministic ground motions, we introduce an improvement to the standard deviation used in the ASCE7-22 approach that leads to more consistency between the probabilistic and deterministic results. Finally, the governing MCE_R and MCE_G ground motions were computed for all the sites. The entire workflow is implemented in the OQ Engine and requires as input only the coordinates of the sites.

Kortum et al. (2023) compare the updated MCE_R values with previous values provided by the U.S. Department of State and U.S. Department of Defense. Whereas all the updated values are based on the regional PSHA results from GEM, the previous values were either (i) roughly approximated from Uniform Building Code seismic zones; (ii) roughly approximated from 10%-in-50yr PGA values from the Global Seismic Hazard Assessment Program; (iii) based on site-specific PSHA results for PGA but approximate factors for 0.2- and 1-second spectral accelerations; or (iv) directly based on site-specific or regional (prior to the GEM Mosaic) PSHA results for PGA and the two spectral accelerations.

As detailed in Kortum et al. (2023), approximately two-thirds of the updated MCE_R values are more than +/-20% different from the previous values. Most of these changes are at locations where the previous values are not directly based on site-specific or regional hazard models for the 0.2- and 1-second MCE_R spectral accelerations. On average, these "indirect" previous values appear to be biased high. Additional differences result from the selection of ground motion models, the definition of seismic sources, along with the approach adopted to compute the MCE_R values.

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