5
CHAPTER 5
EPRI (2004, 2006) GROUND-MOTION MODEL (GMM): OVERVIEW OF KEY FEATURES

5.1 EPRI (2004) GMM Framework

5.1.1 Historical Background

The EPRI (2004) Ground-Motion Model (GMM) Project developed a CEUS GMM for use by utilities in developing applications for Early Site Permits (ESPs) and Combined Operating License Applications (COLAs). The EPRI (1989) seismic hazard analysis for CEUS power plant sites had shown that uncertainty in ground-motion characterization was a large contributor to the uncertainty in seismic hazard estimates. A follow-on study by EPRI (1993a, 1993b) stimulated active research by a number of investigators, resulting in significant advances in seismological knowledge of ground-motion prediction, as well as the development of a number of proponent ground-motion-prediction equations (GMPEs) during the following years. The purpose of the EPRI (2004) GMM study was to develop a composite model for ground-motion estimation from the results of the research that had been completed to date.

EPRI implemented a SSHAC Level 3 assessment process for development of the EPRI (2004) GMM. Considering the SSHAC criteria for selecting the assessment level for a study and the fact that ground-motion prediction is a focused discipline of seismology, and because of the high visibility of the intended use of the study results, the Project Team[1] concluded that a SSHAC Level 3 assessment process was appropriate for the study. The PPRP concurred with that conclusion. The project represented the first implementation of a formal SSHAC Level 3 assessment process. Consistent with the SSHAC Guidance, the project participants consisted of a three-person TI Team (including experienced ground-motion-modeling experts), a six-person Expert Panel, and a participatory peer review panel (PPRP). The Expert Panel consisted of proponent GMPE development experts and broadly represented the range of seismological attributes of then-existing proponent GMPEs. The PPRP had nationally recognized expertise in ground-motion modeling for engineering application, as well as recognized expertise in application of seismic hazard modeling in seismic regulation (EPRI, 2004).

Consistent with the SSHAC Guidance, a series of three workshops were held to develop the EPRI (2004) GMM. TI Team working meetings took place as needed between workshops. The TI Team organized and conducted each workshop. Participants in each workshop included the TI Team, Expert Panel, PPRP, and Observers. Resource Experts participated in Workshops 1 and 2. Expert Panel members identified viable GMPEs, data, and evaluation and integration issues;

[1] As used here, the Project Team includes the Project Manager and the TI Team.

completed questionnaires; and very actively participated in each workshop. The Expert Panel additionally provided a critical review of the draft EPRI (2004) GMM.

5.1.2 Grouping GMPEs into Clusters

An important outcome of Workshop 1 in the EPRI (2004) GMM project was consensus that simply weighting the technically defensible GMPEs based on the degree to which each predicts the available data would not adequately capture epistemic uncertainty. Considering approaches for structuring the evaluation and integration of the GMM to more fully understand and capture epistemic uncertainty, the workshop developed a structure for grouping the GMPEs into four clusters based on similar seismological (primarily, representation of the earthquake source) attributes. This structure permitted evaluation and assessment of within-cluster epistemic uncertainty as well as epistemic uncertainty based on an assessment of the seismologic attributes of the four clusters. Implementation of the cluster structure resulted in four model clusters defined as follows:

- Single-Corner, Point-Source Stochastic (Cluster 1)
- Double-Corner, Point-Source Stochastic (Cluster 2)
- Hybrid (Cluster 3)
- Finite-Source/Green's Function (Cluster 4)

The 13 technically defensible GMPEs existing at the time were grouped into the four clusters, as shown in Table 5.1.2-1.

5.1.3 Methodology Steps

The EPRI (2004) GMM project used a three-step process to develop the model for median ground motions. The first step was to assign to each of the GMPEs within a cluster relative weights that were based on comparisons with recorded ground-motion data—primarily, the data assembled by EPRI (1993a) and southeastern Canada data provided to the EPRI (2004) GMM project by Dr. Gail Atkinson (pers. comm., 2002, as cited in EPRI [2004]). The GMPEs within each cluster were used to compute residuals with respect to the assembled data, and the relative variance of the residuals for each GMPE was used to assign relative weights. The relative weights assigned to each model within a cluster were used to compute weighted averages of median (mean log) ground motions for a range of magnitudes and distances. These values were then fit with a selected algebraic form to represent the central estimate of median ground motions for each cluster.

The second step was to develop a representation of the epistemic uncertainty in estimating median ground motions for each cluster. The within-cluster epistemic uncertainty was developed as a combination of the model-to-model variability of the ground-motion predictions among the GMPEs and estimates of parametric uncertainty in seismic source and wave propagation characterization that were not captured by the range of models within each cluster. The estimated epistemic uncertainty in median ground motions for each cluster was quantified by a standard deviation in log ground motions as a function of magnitude and distance. For the purpose of seismic hazard analyses, this epistemic uncertainty was represented by developing low (5th percentile) and high (95th percentile) GMPEs for each cluster.

The third step was to assign relative weights to the four ground-motion clusters. These weights were assigned based on two aspects. The first was comparisons with the available strong motion data, similar to the process used to develop the within-cluster weights. The second was a relative weighting based on an evaluation of the degree to which seismological principles and explicit consideration of uncertainty were used in development of the GMPEs in a cluster. The two sets of weights were combined to produce a composite weight for each cluster.

5.1.4 Adjustment for Gulf Coast Region

EPRI (1993a) evaluated the variability of ground-motion attenuation in the CEUS and concluded that there were two regions with significant differences in ground motion attenuation: the Midcontinent region, which encompassed most of the CEUS, and a Gulf Coast region. EPRI (2004) implemented this approach. The process described above was used to develop the GMPEs for the Midcontinent region. Then ground-motion simulations were used to develop transfer functions to adjust the Midcontinent GMPEs for application in the Gulf Coast region. Figure 5.1.4-1 shows the Gulf Coast region defined by EPRI (1993a) and used by EPRI (2004).

5.2 EPRI (2004) Aleatory Model Studies

EPRI (2004) developed models for aleatory variability independently from the development of models for median ground motions. This approach was motivated by the fact that the empirical ground motion data for Central and Eastern North America (CENA) available at the time were too limited to constrain aleatory variability and most of the aleatory variability models associated with the GMPEs were based on either estimates from empirical data in active tectonic regions or parametric variability of ground-motion simulation parameters, combined with modeling error derived from calibration of the simulation approaches. The EPRI (2004) study used the range of aleatory variability models associated with the individual GMPEs considered, along with the assessments of aleatory variability from the Trial Implementation Project (TIP) sponsored by the U.S. NRC (Savy et al., 2002). The TIP implemented a trial SSHAC Level 4 assessment process addressing all aspects needed to perform a PSHA, including specification of aleatory variability models for ground-motion assessment. Based on this information, EPRI (2004) developed four alternative models for the aleatory variability.

- The first model was based on the empirical aleatory variability model developed by Abrahamson and Silva (2002) for CENA earthquakes. The Abrahamson and Silva model consists of the Abrahamson and Silva (1997) aleatory model for shallow crustal earthquakes in active tectonic regions, combined with an assessment of the uncertainty in translating ground-motion estimates from active regions to CENA. Factors considered included the potential for greater variability in stress drop for CENA earthquakes than for earthquakes in active tectonic regions.
- The second model was based on the aleatory variability model in the Toro et al. (1997) GMPE. The Toro et al. (1997) GMPE, which is derived from the model developed by EPRI (1993a), is based on ground-motion simulations. The associated model for aleatory variability was based on parametric variability in the parameters used in the ground-motion simulations, combined with modeling error derived from calibration of the simulation method against recorded data, primarily in active tectonic regions.

- The third model was based on the composite results of the TIP study (Savy et al., 2002). It represents the average model developed from a trial SSHAC Level 4 study.
- The fourth model was based on the aleatory model developed by Silva et al. (2002). This aleatory model was developed in a fashion similar to that of the Toro et al. (1997) model, a combination of parametric variability in simulation parameters and modeling misfit. Silva et al. (2002) incorporated revisions to the parametric variability used by EPRI (1993a) and the results of more extensive model validation studies.

Similar to the EPRI (1993a) and Toro et al. (1997) models, the EPRI (2004) aleatory model included an additional component of variability at small distances to apply to those GMPEs that use Joyner-Boore distance, R_{JB}. The additional aleatory variability was due to the range in rupture distances, R_{Rup}, for a given value of R_{JB} and was based on calculations of the variability in ground motions at a given R_{JB} using a focal depth distribution and assuming ground motions scale with $1/R_{Rup}$.

The EPRI (2004) model for aleatory variability was superseded by the results of the EPRI (2006) project, which is described below.

5.3 EPRI (2006) Aleatory Model Study

EPRI (2006) performed a further assessment of aleatory variability for CEUS ground motions. The study addressed two aspects: identification of a technical basis to truncate the upper tail of the ground-motion distribution, and evaluation of the basis for appropriate levels of aleatory variability for CEUS ground motions. As described above, the EPRI (2004) model for aleatory variability was based on the available assessments in the literature. However, some of the models used specified standard deviations of log ground-motion amplitude that were much larger than had been found in later studies of large data sets of empirical ground motions recorded in active tectonic regions. The EPRI (2006) study was conducted following a SSHAC Level 2 assessment process. The conclusions of the study were as follows:

- There is no basis for truncation of the lognormal distribution for ground motions at any value less than three standard deviations above the median (mean log), and that values at standard deviations greater than three above the median have been observed. The only defensible basis suggested for truncation was exceedance of the physical limits of the subsurface materials to transmit motions; what the physical limits might be was not addressed.
- The level of aleatory variability of CEUS ground motions should be similar to or slightly greater than that observed empirically for ground motions in active tectonic regions. Most modern assessments of ground motions consider the aleatory variability to be made up of two components, an intra-event component that represents the variability in ground motions observed in a single earthquake among multiple sites with similar site conditions, and an inter-event component that represents the variability in the average level of ground motions among different earthquakes of the same size. The EPRI (2006) study examined these two components of aleatory variability individually to identify potential sources of differences between the CEUS and active tectonic regions.

The inter-event component was examined using teleseismic and regional seismographic network data. The variability in source characteristics for earthquakes in active tectonic regions was compared to that for earthquakes in stable continental regions (such as the CEUS) using teleseismic data. The results indicated similarity in source variability for the two groups of earthquakes. The variability in the level of high-frequency ground motion for CENA earthquakes was also estimated based on the variability in stress drop and magnitude estimated from seismographic network data. The conclusion reached was that the variability for CENA earthquakes may be slightly greater than for earthquakes in active tectonic regions.

The intra-event component was examined using ground-motion simulations. Suites of crustal velocity profiles were developed to represent the variability of crustal structure in CENA and western North America (WNA). Ground-motion simulations were then performed using these suites of velocity profiles for a range of magnitudes and distances. The variability in simulated ground motions for the two regions was then compared. The results indicated similar to slightly smaller variability in ground-motion peak amplitudes for CENA compared to WNA. The variability in ground motions from active tectonic regions was examined for trends as a function of site shear-wave velocity. It was found that sites with high shear-wave velocities maintained comparable levels of variability at frequencies above 10 Hz to that seen for 10 Hz motions, while typical WNA sites exhibited a decrease in ground-motion variability with increasing frequency above 10 Hz. The greater variability in ground motions at high frequencies for the high-velocity sites was attributed to greater energy at high frequencies for these sites. For typical WNA sites, the energy in ground motions at frequencies above 10 Hz is damped out by the crustal properties.

The issue of an increase in aleatory variability at small values of Joyner-Boore distance was evaluated by examining the trends in residuals for empirical ground motion data with respect to focal depth. The increase in ground-motion variability in the EPRI (1993a), Toro et al. (1997), and EPRI (2004) models at small values of Joyner-Boore distance implies that there should be a negative correlation of the residuals with focal depth. Such trends were found to only a limited extent in some empirical databases.

Based on the analyses described above, EPRI (2006) developed an updated model for aleatory variability of CENA ground motions. The favored model was that the intra-event components should be the same as those seen for active tectonic regions, and the inter-event component should be slightly larger by 0.03 units in the natural log of ground-motion peak amplitude. In addition, the variability at frequencies above 10 Hz should be set equal to that derived for 10 Hz motions from active tectonic regions. This was not applied to PGA. An alternative model was included that has a small reduction of the intra-event component (0.03 units) to represent the lower variability seen in simulations used to explore the effects of variability in crustal structure. Alternative models were developed for the increase in aleatory variability at small Joyner-Boore distances, with the favored model being no increase, and the alternative models have smaller increases than those proposed by EPRI (1993a), Toro et al. (1997), and EPRI (2004).

The reader is referred to Section 2.1 for a description of how the EPRI (2004, 2006) GMM was evaluated before the start of this project, with the help of recognized ground-motion experts, to make a preliminary determination about whether the GMM needed updating.

Table 5.1.2-1
EPRI (2004) Models Grouped by Cluster

Cluster	Model Type	Models[1]
1	Single-Corner Stochastic	Hwang and Huo (1997) Silva et al. (2002) –SC-CS Silva et al. (2002) – SC-CS-Sat Silva et al. (2002) – SC-VS Toro et al. (1997) Frankel et al. (1996)
2	Double-Corner Stochastic	Atkinson and Boore (1995) Silva et al. (2002) – DC Silva et al. (2002) – DC-Sat
3	Hybrid	Abrahamson and Silva (2002) Atkinson (2001) and Sadigh et al. (1997) Campbell (2003)
4	Finite Source /Green's Function	Somerville et al. (2001)

[1] SC = single corner; DC = double corner; CS = constant stress; VS = variable stress; Sat = saturation

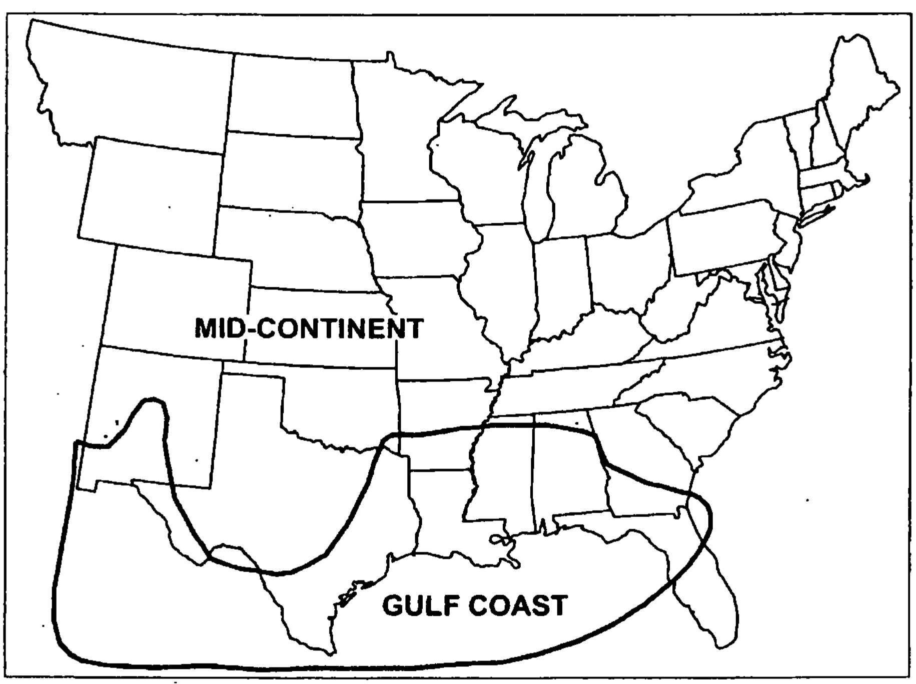

Figure 5.1.4-1
EPRI (2004) Ground Motion Model regionalization based on EPRI (1993a)