Enclosure A

Turkey Point Units 6 and 7

COL Application

SSHAC Caribbean GMPE Questionnaire

SSHAC Caribbean GMPE Questionnaire

We have developed a suite of ground motion prediction equations (GMPEs) for use in a probabilistic seismic hazard analysis (PSHA) for an electrical generation plant located in southern Florida. The PSHA incorporates contributions to seismic hazard from seismic sources both in the immediate region of the southeastern United States and, as well, seismic sources located at distances greater than 1,000 km in the Caribbean region.

The newly developed GMPE models that are the subject of this questionnaire are applied only to Caribbean seismic sources.

Our motivation in developing these GMPEs is the lack of a suite of region-specific empirical GMPE(s) that could be used within the PSHA study for large magnitude earthquakes (i.e., magnitudes greater than 7) and over the large distance range (i.e., 150 – 2,000km) needed. We employed a stochastic simulation procedure to generate a dataset on which we performed a regression analysis. Critical to any stochastic simulation procedure is the selection of the necessary seismological input parameter values. Our selected values are listed in Table 1 and are based on the empirical ground motion study for the island of Puerto Rico (Motazedian and Atkinson, 2005) along with an uncertainty on the stress parameter and quality factor models.

Table 1. Regional attenuation and source parameters used in the Motazedian and Atkinson (2005) study for the simulation of ground motions.

Parameter	Simulation Values
Stress Parameter	65 bars (Low Case)[1] 130 bars (Base Case) 260 bars (High Case)[1]
Geometrical Spreading	1/R for R<75km 1.0 for 75<R<100km 1/SQRT(R) for R>100km
Quality Factor (Q) Model	241 f^0.59 (Low Case)[2] 359 f^0.59 (Base Case) 536 f^0.59 (High Case)[2]
Path Duration	Atkinson and Boore (1995) Model with hinge points at 75 and 100 km
Site Amplification	Chen and Atkinson (2002) CEUS Hard Rock
Kappa	0.006 sec (EPRI, 1993)
Shear Wave Velocity (Vs) at the Source	3.6 km/sec
Density	2.8 g/cm^3

[1] Based on assumed sigma of 0.7 (natural log units) taken from EPRI, 1993.
[2] Based on assumed sigma of 0.4 (natural log units) taken from Silva et al., 2003.

We also considered three source spectra models: single corner with constant stress parameter (Boore, 2005), single corner with variable stress parameter (Silva et al., 2003), and double corner stress parameter (Atkinson and Boore, 1995) source models. For the variable stress parameter model, the magnitude dependence is given in Table 2.

Table 2. Variable stress parameter values used in the simulation for the single corner variable stress parameter model (from Silva et al., 2003).

Magnitude	Low Stress Parameter	Base Stress Parameter	High Stress Parameter
4.75	65	130	260
5.00	65	130	260
5.25	65	130	260
5.50	65	130	260
5.75	61	122	244
6.00	57	114	228
6.25	53	106	212
6.50	49	98	196
6.75	46	91	182
7.00	43	85	170
7.25	40	79	158
7.50	37	73	146
7.75	35	69	138
8.00	33	65	130
8.25	31	61	122
8.50	29	57	114
8.75	29	57	114

The results for the several stress parameter cases for the single corner scaling models were found to vary about the base case and were combined for a given Q model variation. These combined stress drop attenuation curves are designated "SDAll" below. For the double corner [2C] source model, the variation in stress parameter is not included because this source model is not stress parameter dependent.

GMPE models were developed for the seven spectral frequencies used in the PSHA: PGA, 25Hz, 10Hz, 5Hz, 2.5Hz, 1Hz, and 0.5Hz. These newly developed GMPEs are applicable for CEUS hard rock site conditions (i.e., Vs=2.8km/sec). A recommended total sigma of 0.645 in natural log units was proposed based on the estimated sigma value given in the Motazedian and Atkinson (2005) study.

For the suite of nine ground motion models (three source models and three Q factor models), a non-uniform weighting scheme was recommended. The single corner [1C] source model (both constant stress parameter [1CC] and variable [1CV] stress parameter) fall into Cluster 1 of the EPRI (2004) ground motion study for General Area seismic sources, while the double corner [2C] model falls into Cluster 2. The third Cluster in the EPRI (2004) study is based on hybrid empirical attenuation models, which we have not considered. The relative weights (from Table 5, EPRI 2004) are listed as:

Cluster 1 = 0.3512
Cluster 2 = 0.3985
Cluster 3 = 0.2503
Total = 1.0

Given these values, and specifically the nearly equal weights of Clusters 1 and 2, we have recommended that the relative weights between the single corner source models and double corner source model be weighted equally. Within the single corner source model case, the constant [1CC] and variable [1CV] stress parameter cases are also considered equally weighted. Finally, because of the large uncertainty in the regional anelastic attenuation, the relative weighting between the three Q low, base, and high models was assigned to be equal (i.e., 0.333, 0.334, 0.333). Combining these weights the weights for each of the nine recommended models are as listed in Table 3.

Table 3. Summary of attenuation tables listing regression coefficients and associated weights for each of nine recommended models.

Attenuation Model	Model Weight
1CC, Q Base	0.0834
1CC, Q High	0.0833
1CC, Q Low	0.0833
1CV, Q Base	0.0834
1CV, Q High	0.0833
1CV, Q Low	0.0833
2C, Q Base	0.1667
2C, Q High	0.1667
2C, Q Low	0.1666

A comparison is presented in Figures 1 – 7 of the newly developed Caribbean GMPE (red curves) with the EPRI (2004) Mid-Continent (blue curves) and Gulf Coast (red curves) regional GMPE models. Attenuation curves are presented for magnitudes 7 and 8 between distances of 200 – 1,000 km. For each of the three GMPE models, the individual models are graphically plotted as thin color coded lines with the weighted mean attenuation curve being shown as the heavy color coded line.

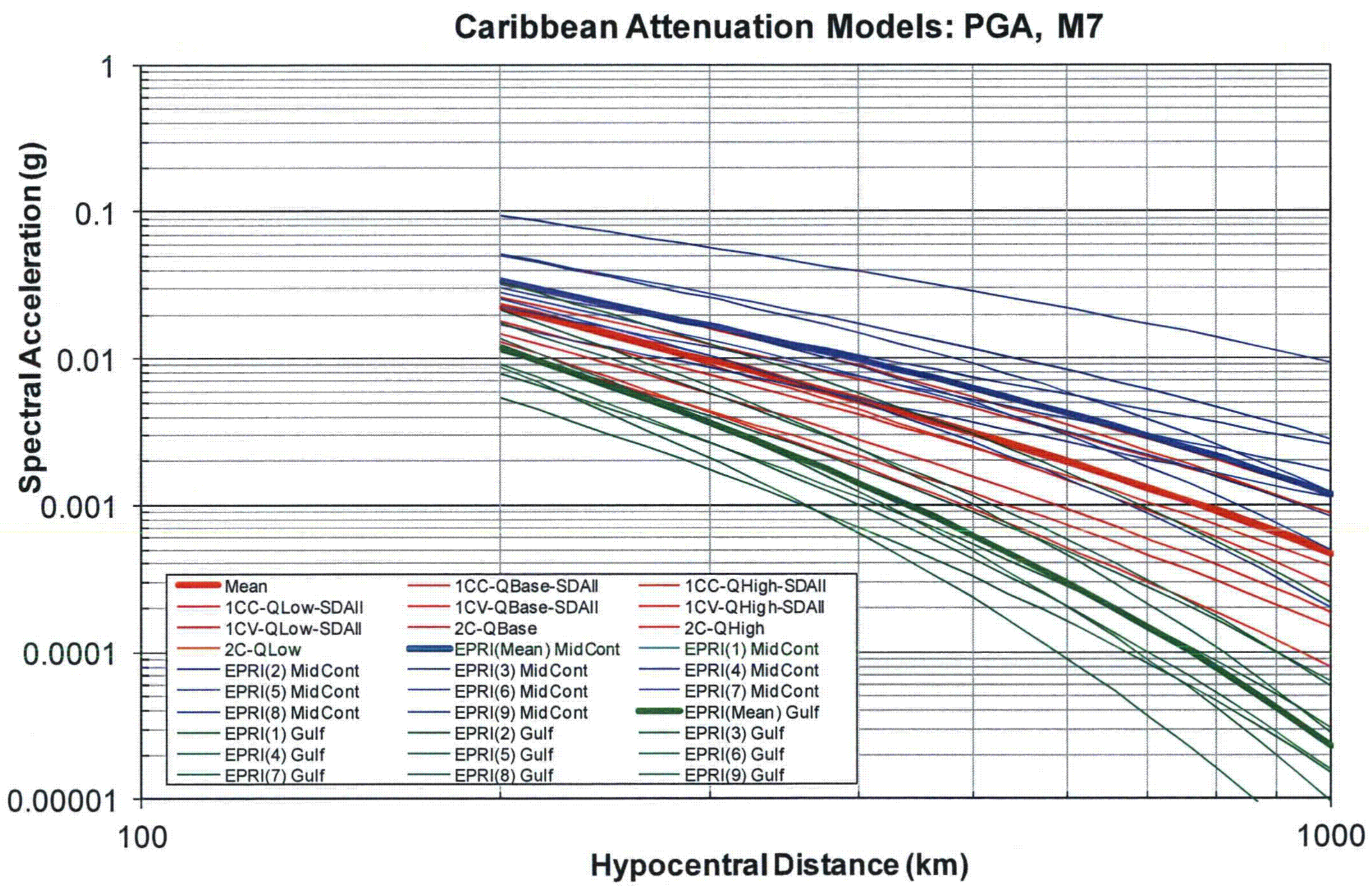

Figure 1a. Magnitude 7 attenuation curve for PGA for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

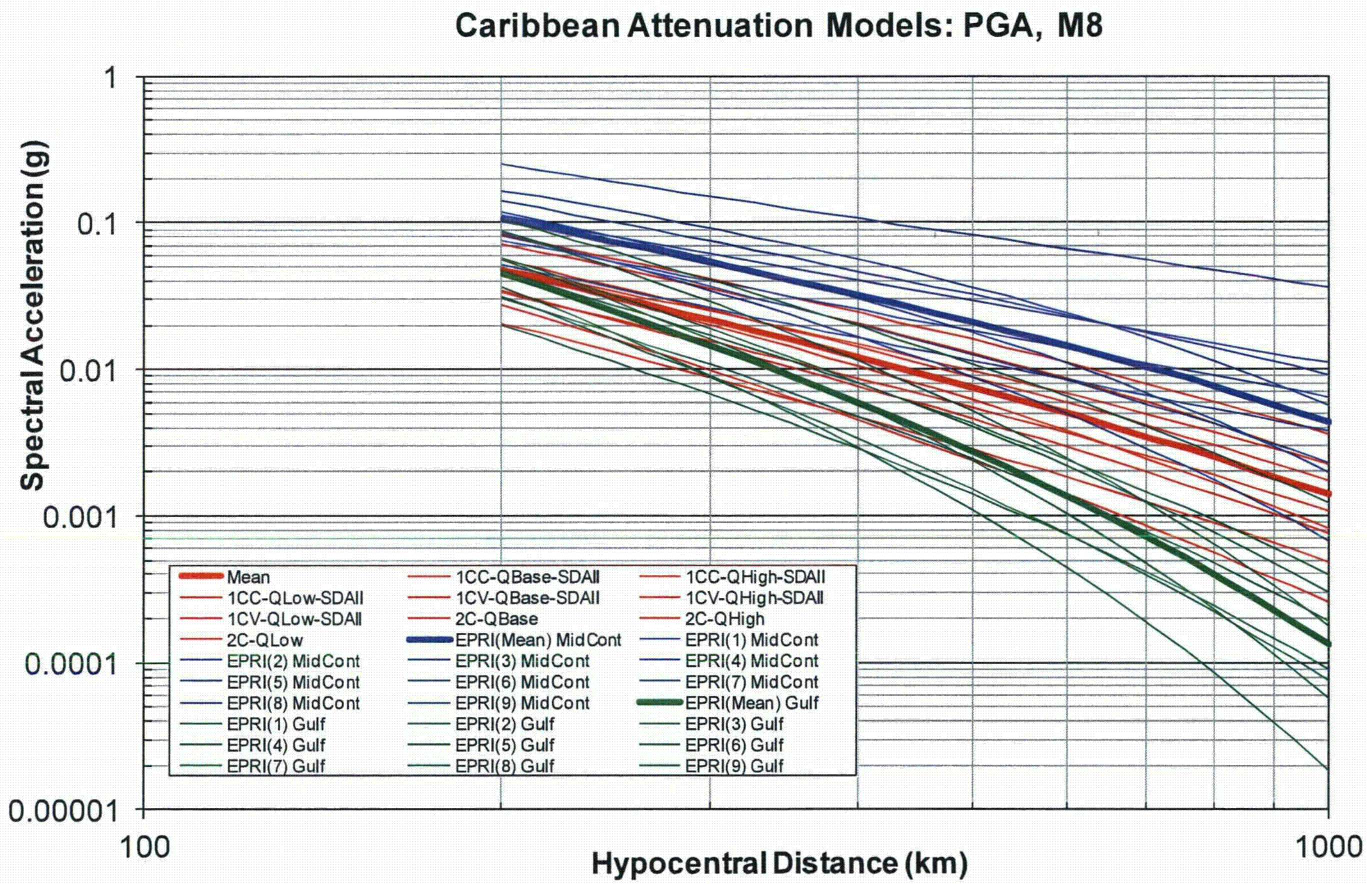

Figure 1b. Magnitude 8 attenuation curve for PGA for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

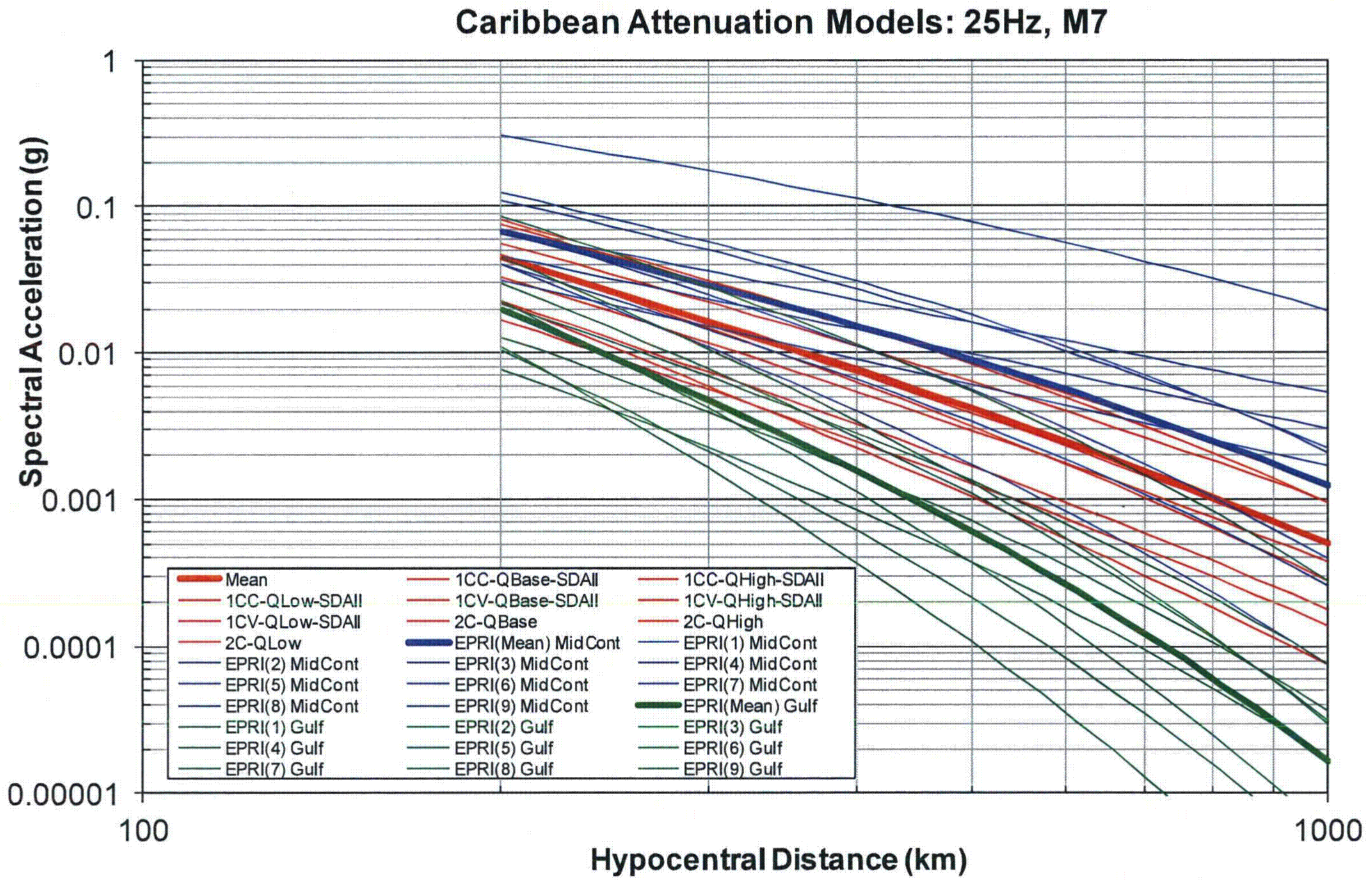

Figure 2a. Magnitude 7 attenuation curve for 25 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

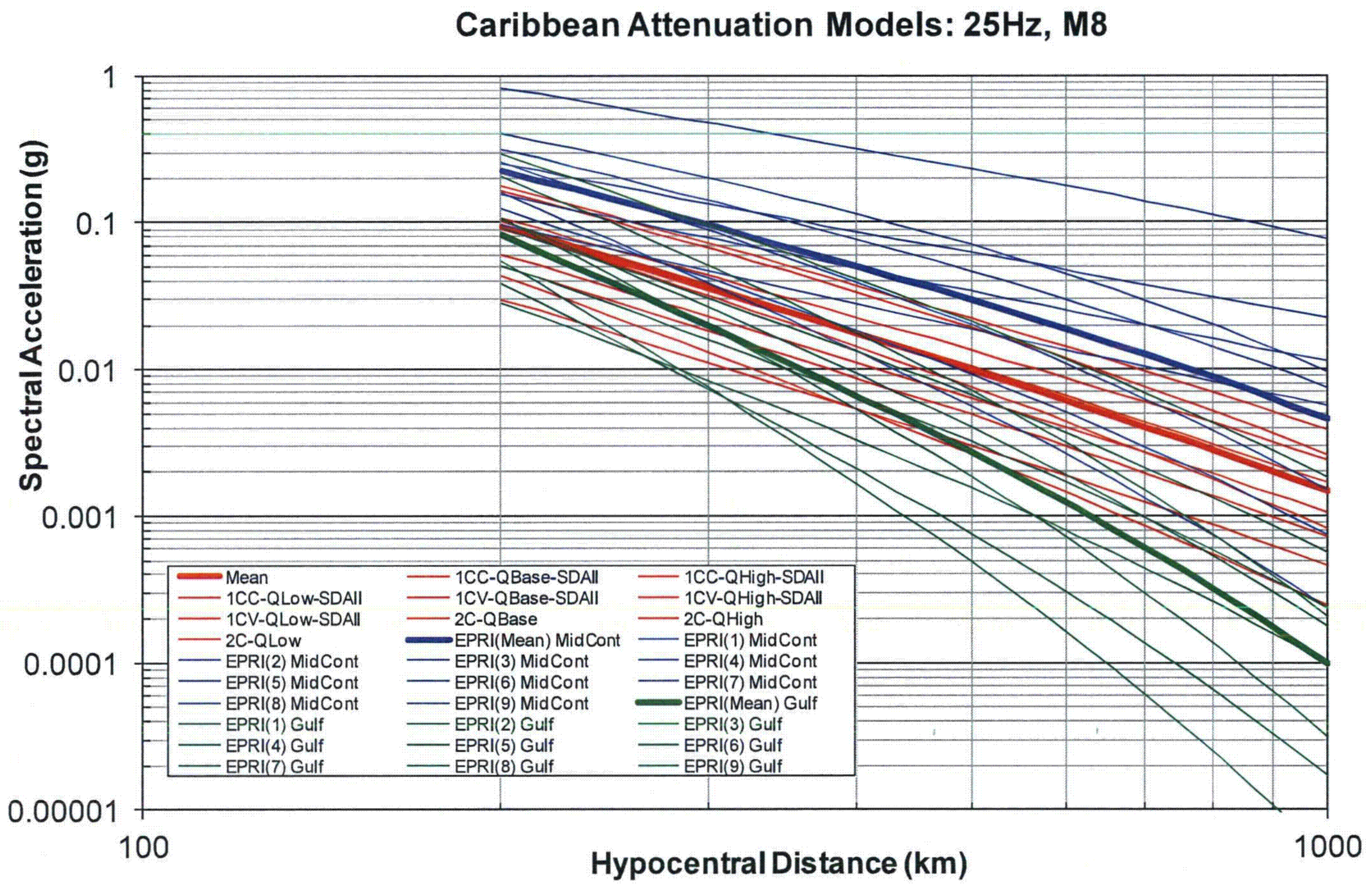

Figure 2b. Magnitude 8 attenuation curve for 25 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

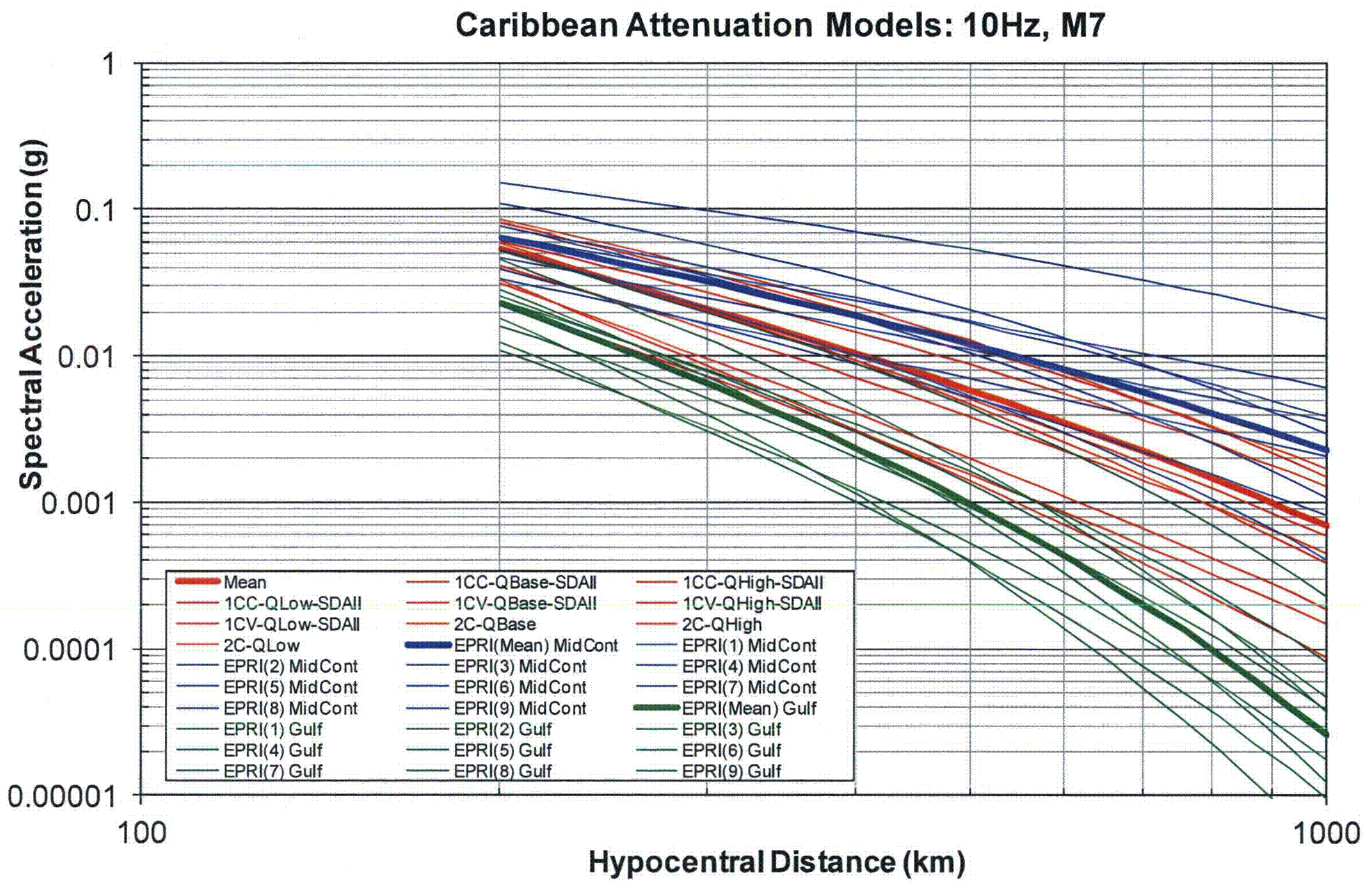

Figure 3a. Magnitude 7 attenuation curve for 10 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

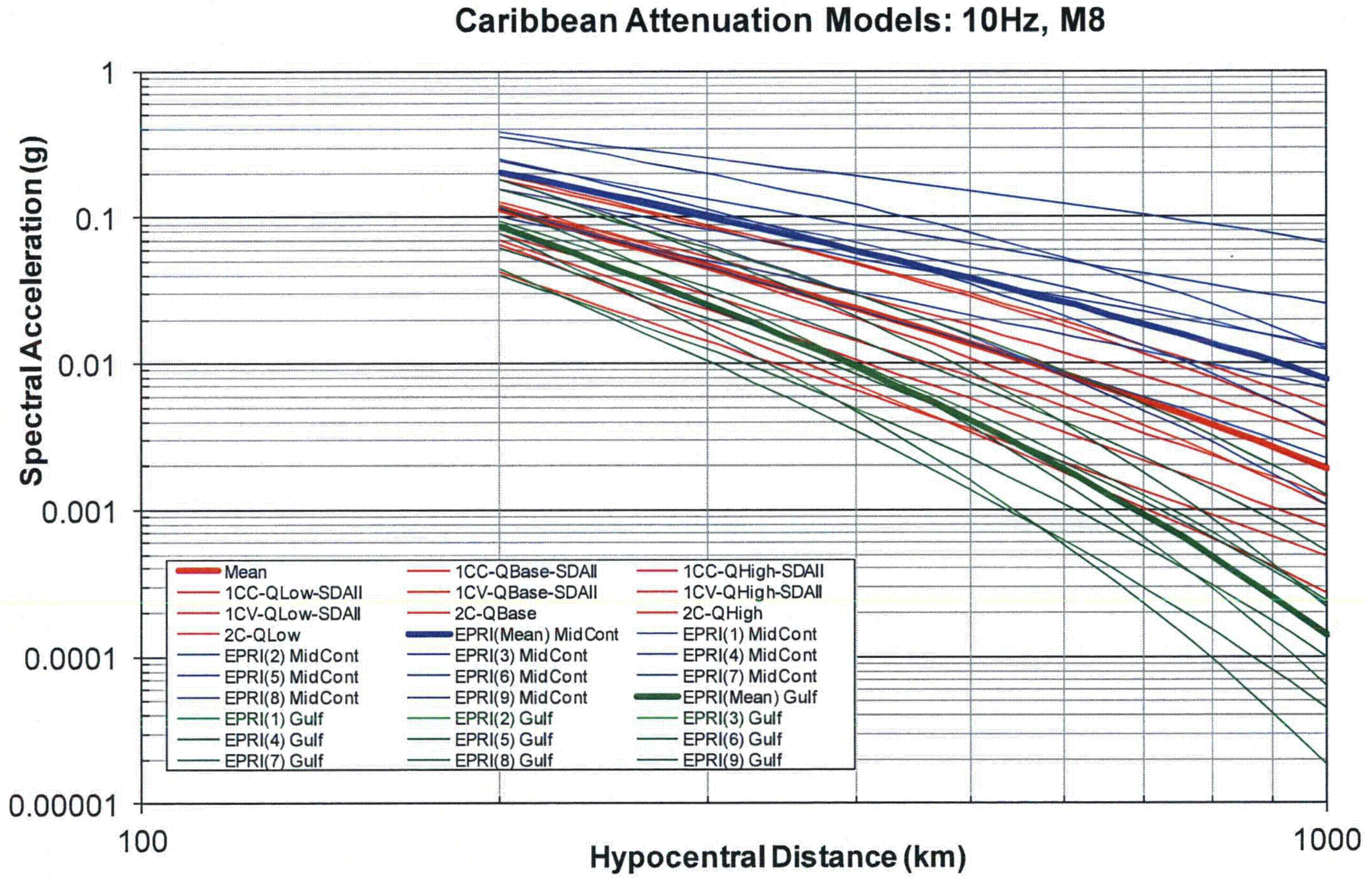

Figure 3b. Magnitude 8 attenuation curve for 10 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

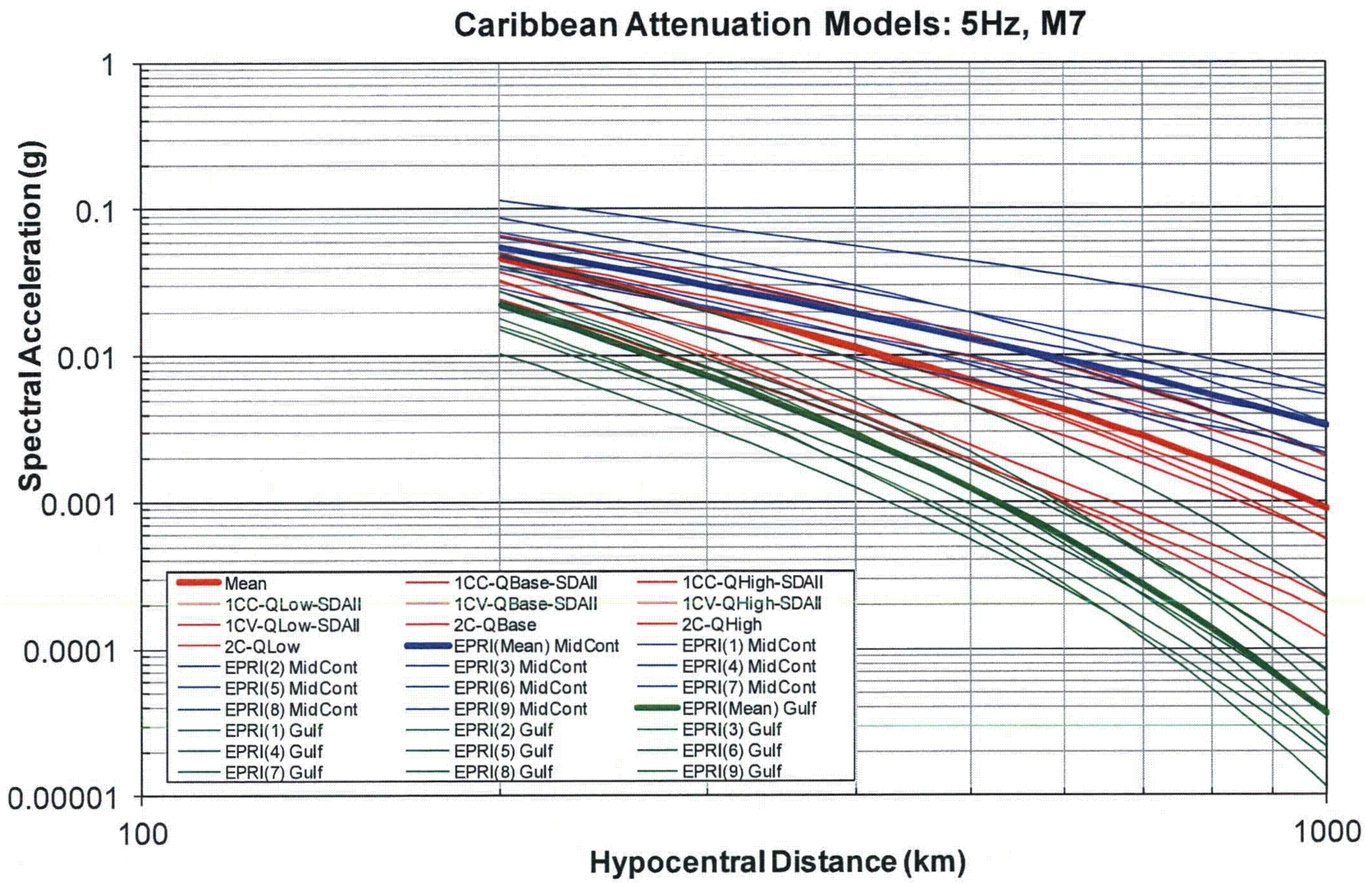

Figure 4a. Magnitude 7 attenuation curve for 5 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

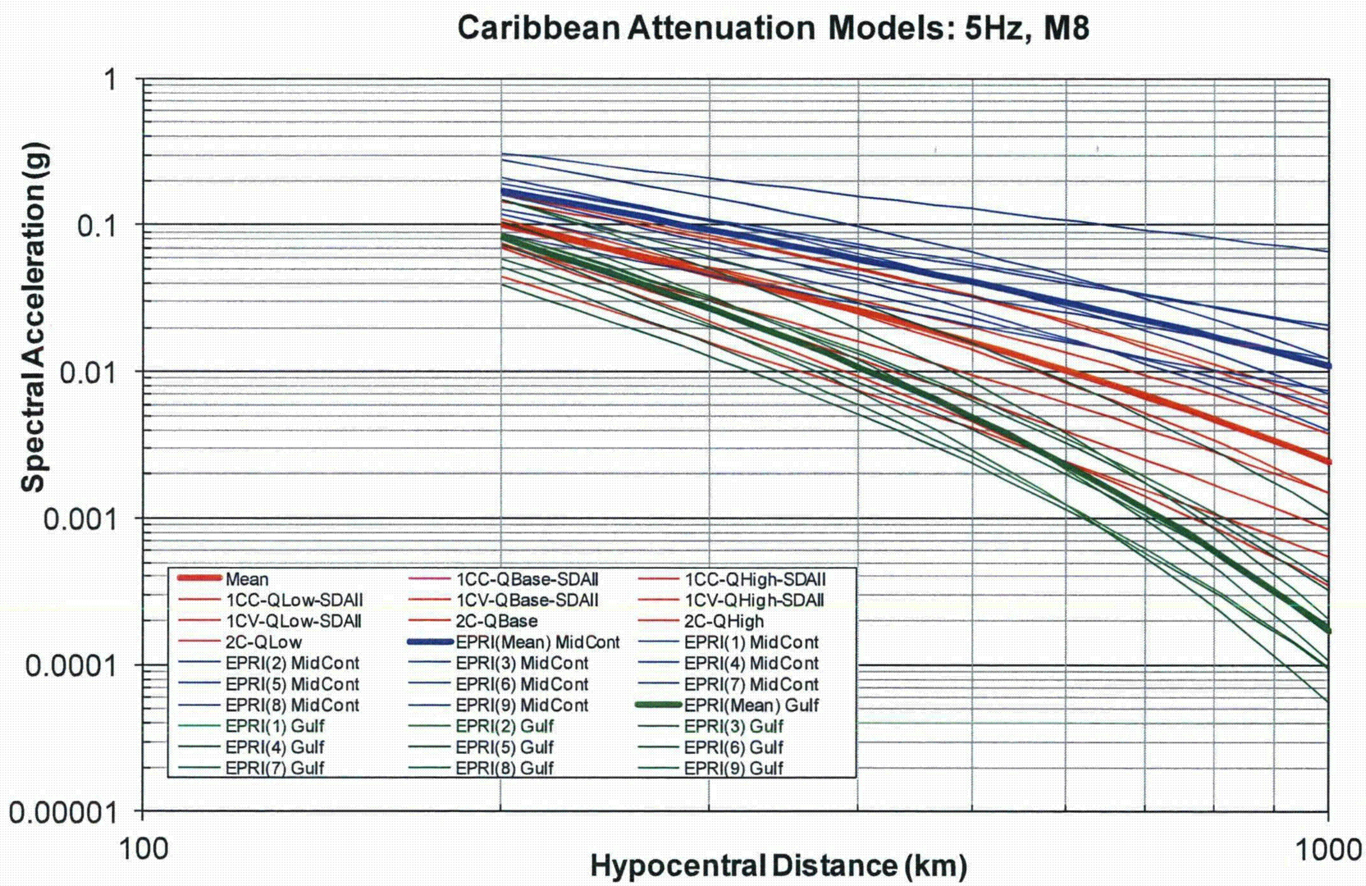

Figure 4b. Magnitude 8 attenuation curve for 5 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

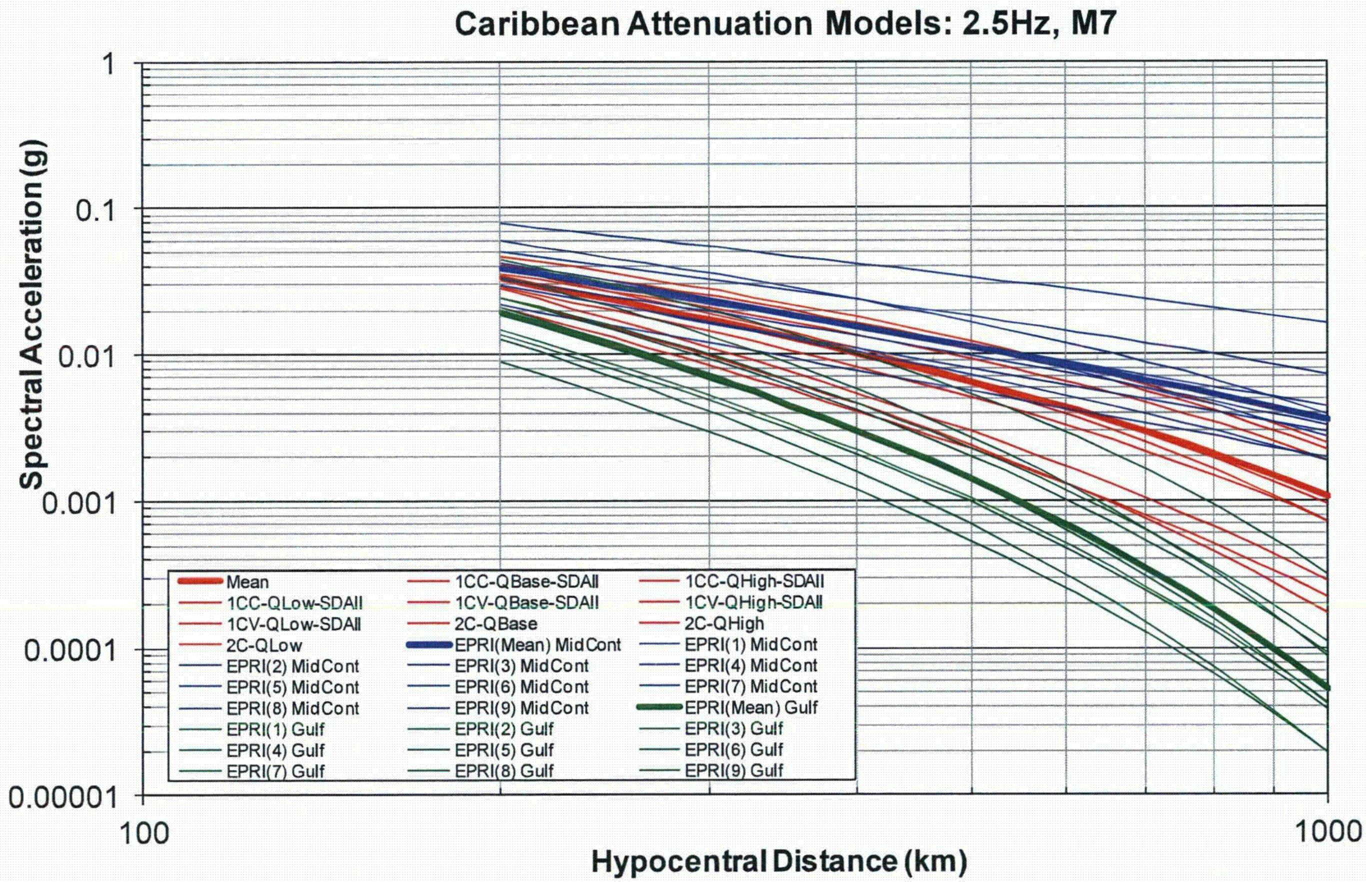

Figure 5a. Magnitude 7 attenuation curve for 2.5 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

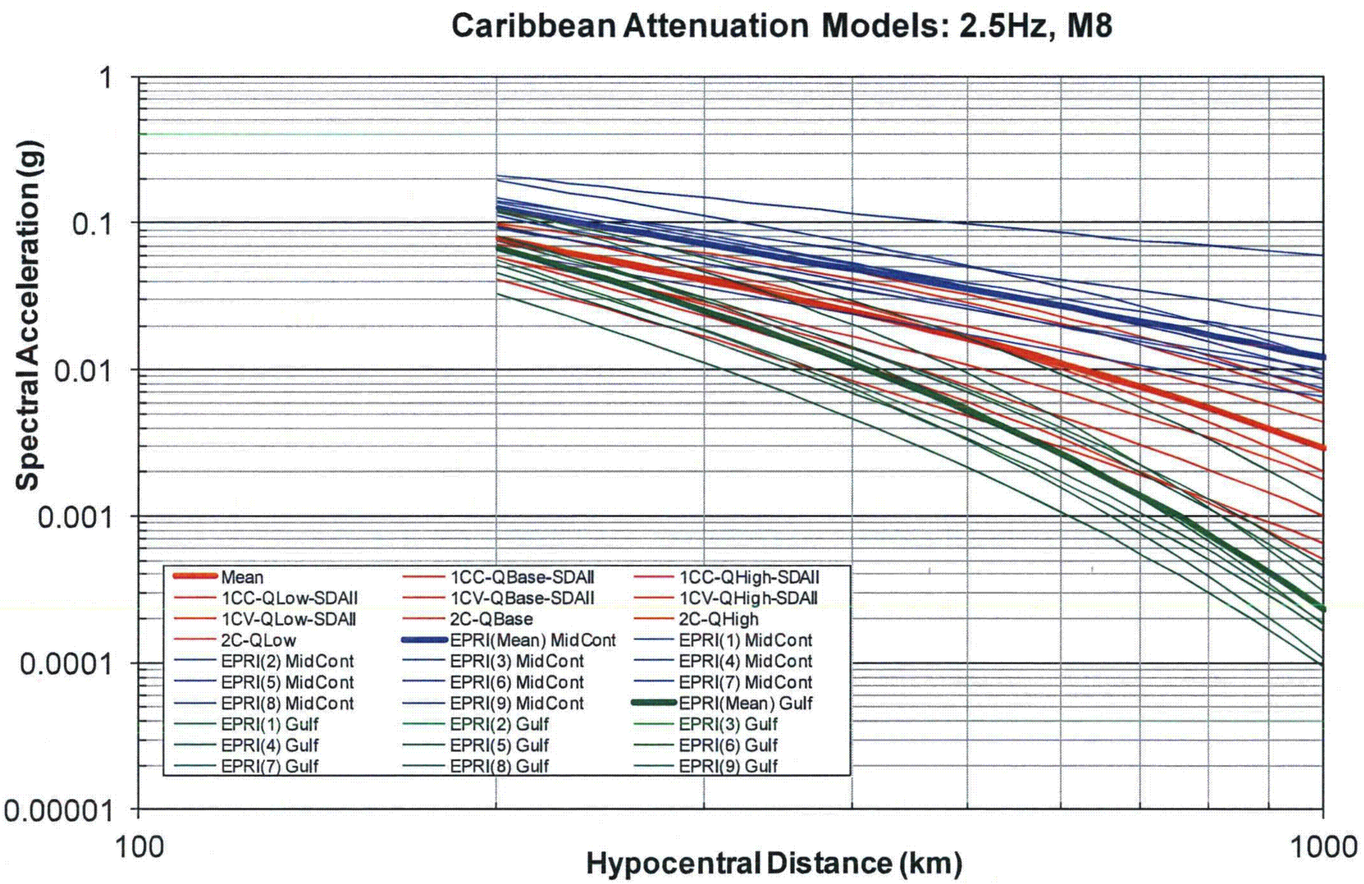

Figure 5b. Magnitude 8 attenuation curve for 2.5 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

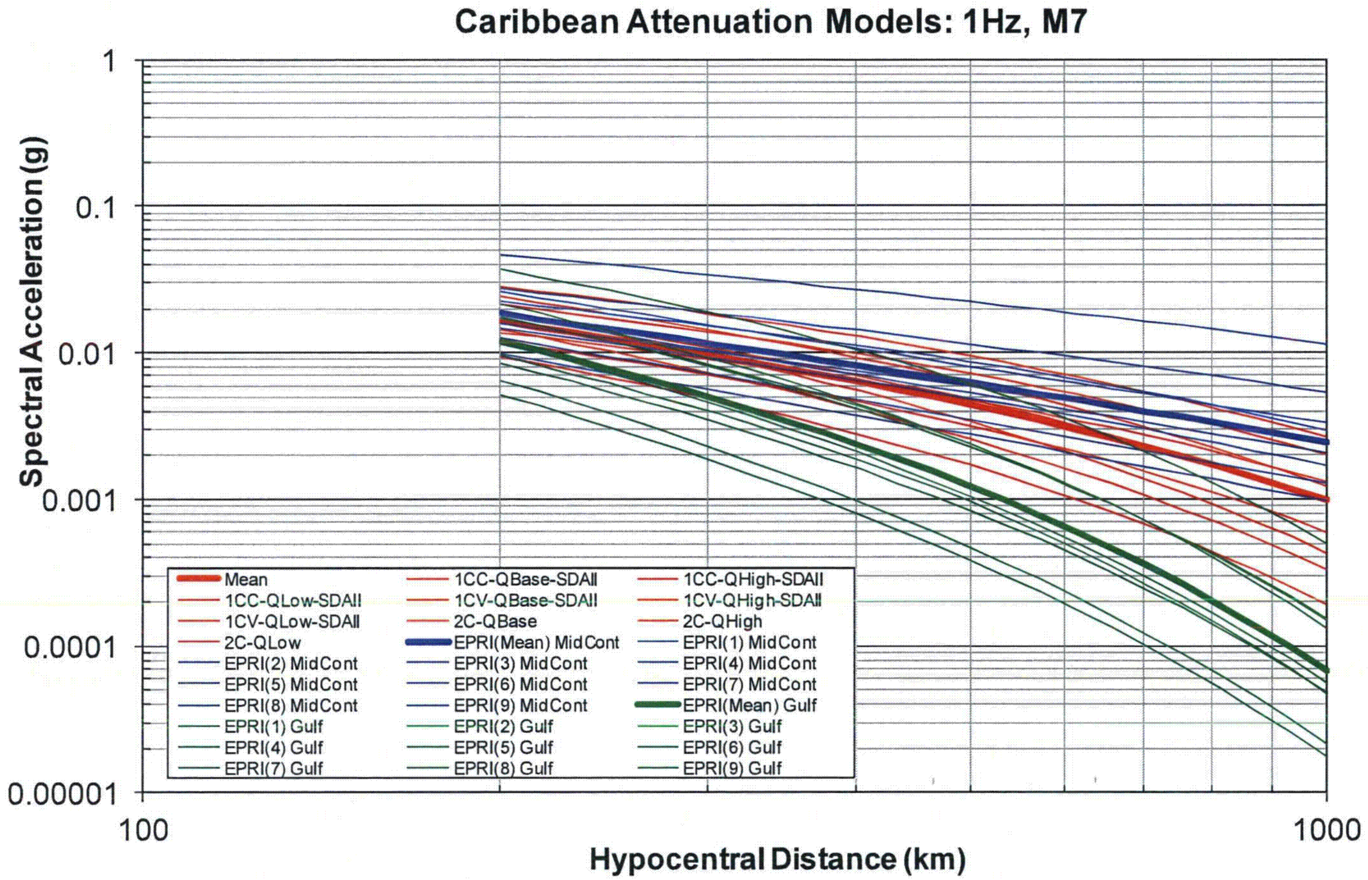

Figure 6a. Magnitude 7 attenuation curve for 1 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

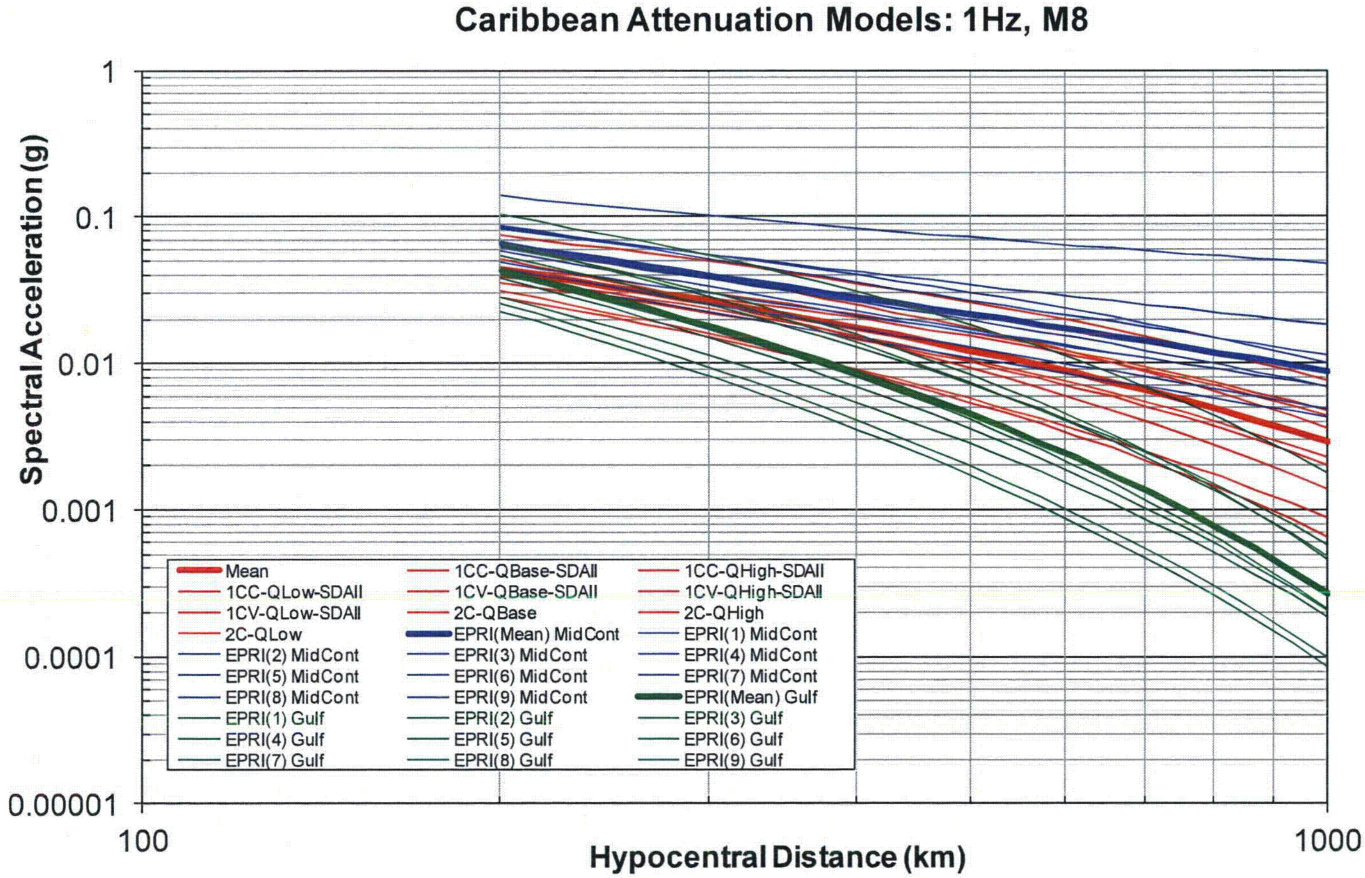

Figure 6b. Magnitude 8 attenuation curve for 1 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

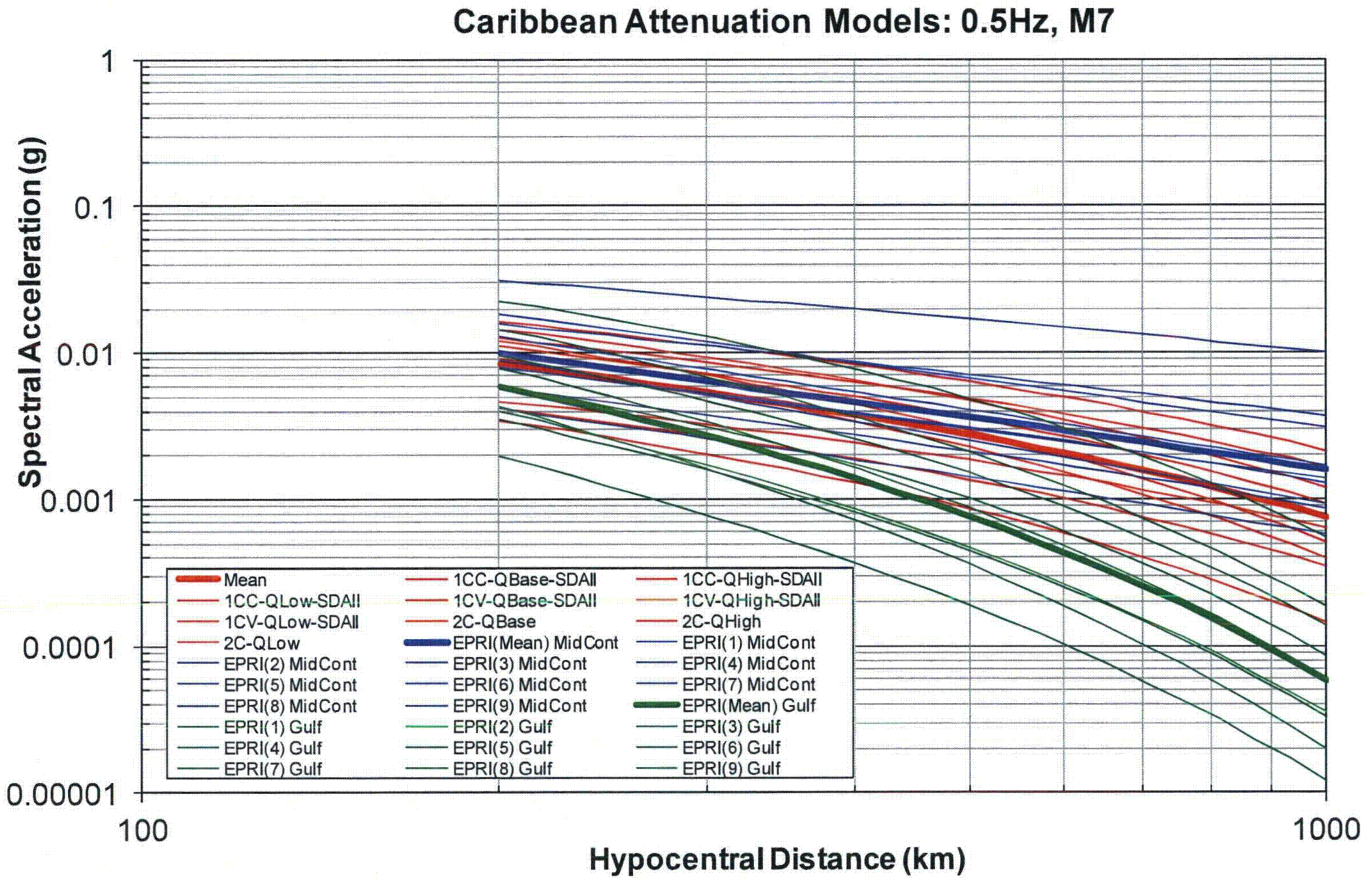

Figure 7a. Magnitude 7 attenuation curve for 0.5 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

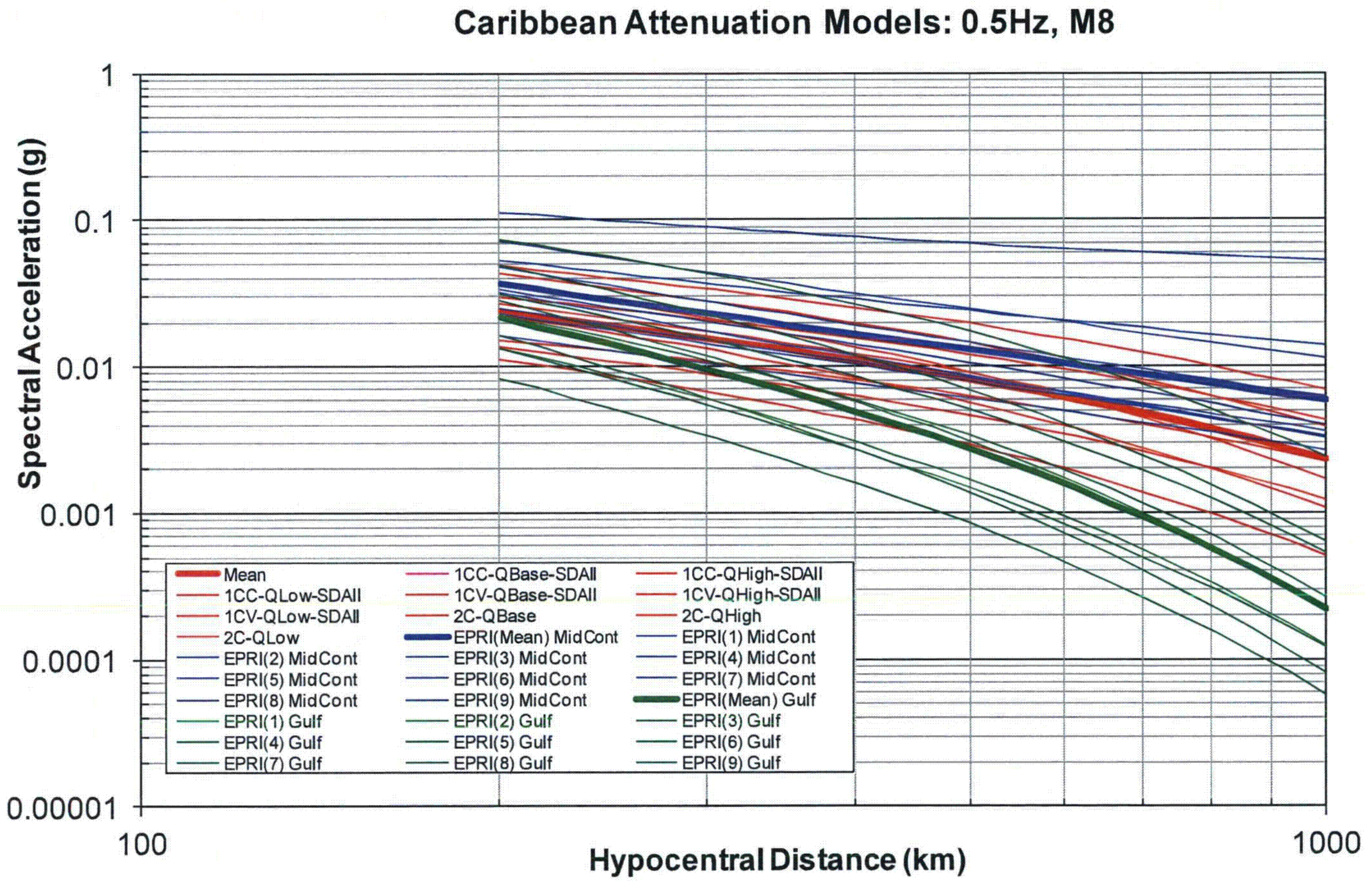

Figure 7b. Magnitude 8 attenuation curve for 0.5 Hz for the Caribbean (red curves), Mid-Continent (blue curves), and Gulf Coast (green curves) region GMPE models.

Following the development of the 9 Caribbean GMPE models, an additional sensitivity analysis was performed to assess the applicability of the GMPE models for the modeling of ground motion attenuation for the Caribbean region. Summary results of this analysis are presented below.

The sensitivity analysis compares the GMPEs developed for the project with empirical ground motion data from five regional earthquakes that have occurred since 2004 in the Gulf of Mexico and Caribbean region. Regional broadband empirical data from selected IRIS stations were obtained, processed, and compared with the suite of Caribbean GMPE models and with both the Mid-Continent and Gulf Coast suite of EPRI (2004) GMPE regional models.

In this comparison all of the GMPE attenuation curves are for the assumed CEUS hard rock site conditions with Vs=2.83 km/sec, whereas the empirical IRIS data are for the whatever individual site conditions exist at each station, which were not obtainable at this time. Based on simplified site response analysis it would be expected that adjustments for the station-specific site conditions to the more stable CEUS hard rock site condition would result in some reduction in the observed empirical ground motion values.

The current deaggregation of seismic hazard at the project site from all sources, Cuban, Caribbean, and southeast United States, is shown in Figure 8 for longer period motions (for which the relative contribution of the larger, more distant Cuban and Caribbean sources would be expected to have their greatest contribution) and for the 10^{-4} and 10^{-5} mean annual frequency of exceedance probabilities used to develop design ground motions under current NRC regulatory guidance. The relative contribution for the higher frequency case (not shown) of 5 and 10 Hz from the more distant Caribbean sources is significantly reduced compared to the contribution to hazard from the closer local seismic sources. For this sensitivity comparison, the empirical ground motions for 1 and 2.5 Hz are presented for each of the five regional earthquakes and ground motion prediction equations.

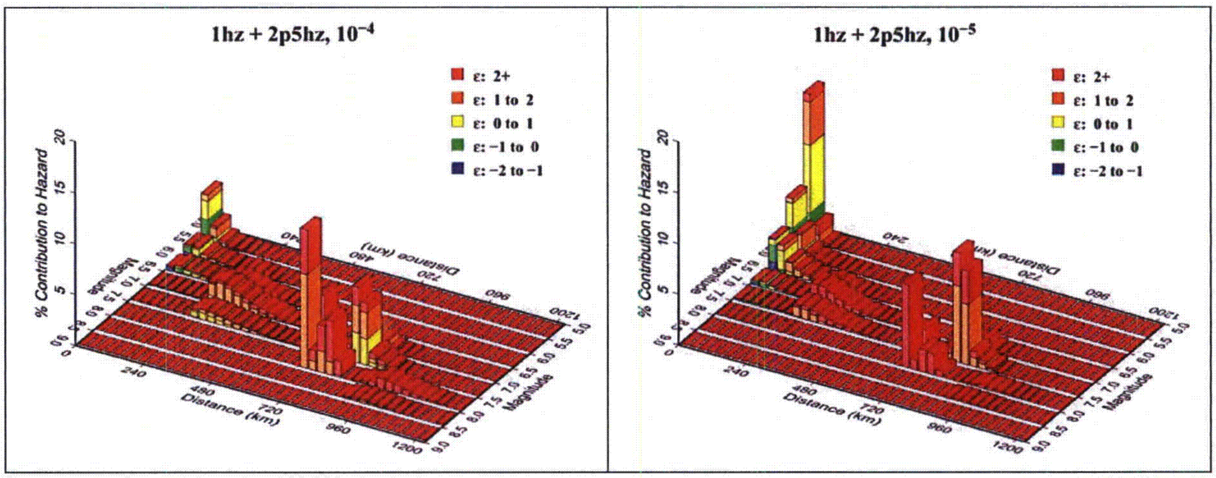

Figure 8. Magnitude and Distance Deaggregation for 1 and 2.5 Hz at 10^{-4} and 10^{-5} Annual Frequencies of Exceedance.

The five regional earthquakes that have been analyzed are:

- 12/14/2004 – Caribbean Sea Region (Mw6.8)
- 09/10/2006 – Gulf of Mexico (Mw5.9)
- 02/04/2007 – Cuba Region (Mw6.2)
- 05/28/2009 – North of Honduras (Mw7.3)
- 01/12/2010 – Haiti (Mw7.0)

For each event, a standard time history processing methodology was applied with the final results being a dataset of the acceleration response spectra for a spectral damping of 5% at each station. The geometric mean of the two horizontal components was computed and comparison plots for the 1 and 2.5 Hz spectral frequencies were generated showing the empirical data and the suite of GMPE models (i.e both of the EPRI, 2004 GMPE models and the Caribbean GMPE models). Both the individual attenuation curves and the weighted mean attenuation curve for a given set are shown in the comparison plots for each spectral frequency and earthquake.

Caribbean Sea Region (Mw6.8), 12/14/2004:

This event occurred in the Caribbean Sea region and its epicenter is shown in Figure 9a along with the FPL project site location, and the location of the IRIS stations that recorded this earthquake. Based on the observed station distribution, the IRIS station DWPF located in central Florida has the most applicable source to site path for this comparison. The large majority of stations located in central America have the opposite travel path azimuth and may show different attenuation properties based on these different tectonic travel paths. The attenuation curves and empirical data are shown in Figures 9b and 9c for the 1 and 2.5 Hz spectral frequencies. The data point from the DWPF station is highlighted as a solid blue circle. Overall the empirical data falls below the median Caribbean attenuation curve (heavy red line) and has values which are in the lower distribution of range of Caribbean attenuation curves. In addition, the observation from the DWPF station is lower than the entire range of the Caribbean attenuation curves.

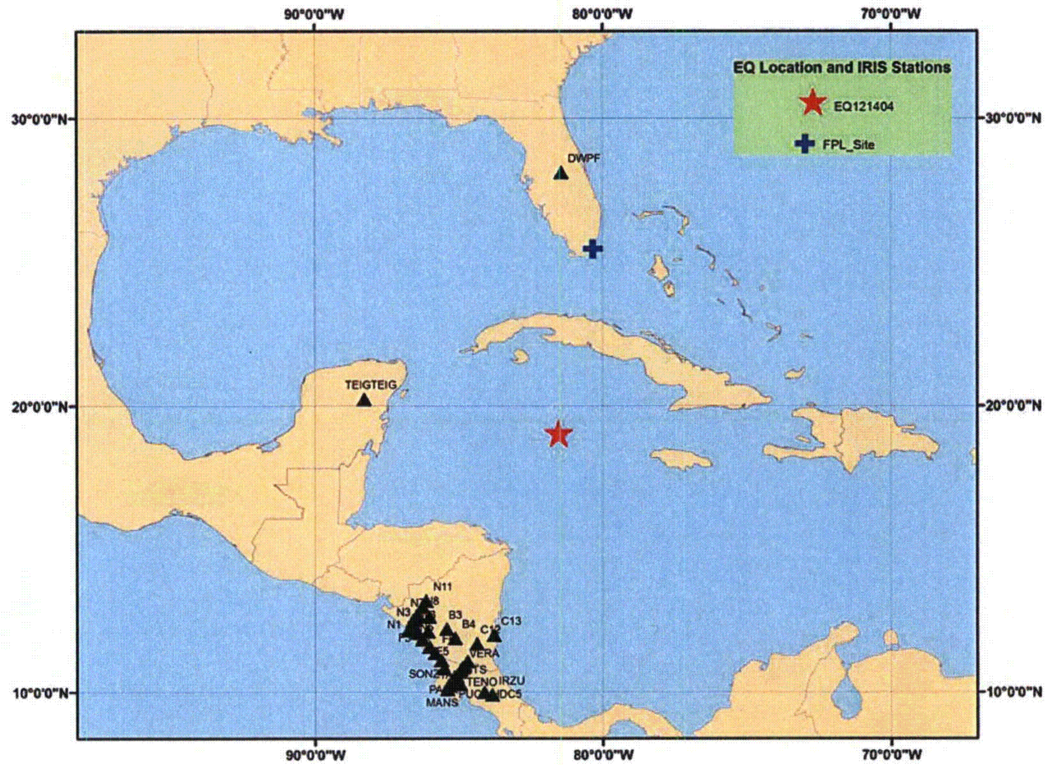

Figure 9a. Map showing the earthquake location for the 12/14/2004 Caribbean Sea Region earthquake (Mw6.8), the IRIS station locations used in the analysis and FPL project site location.

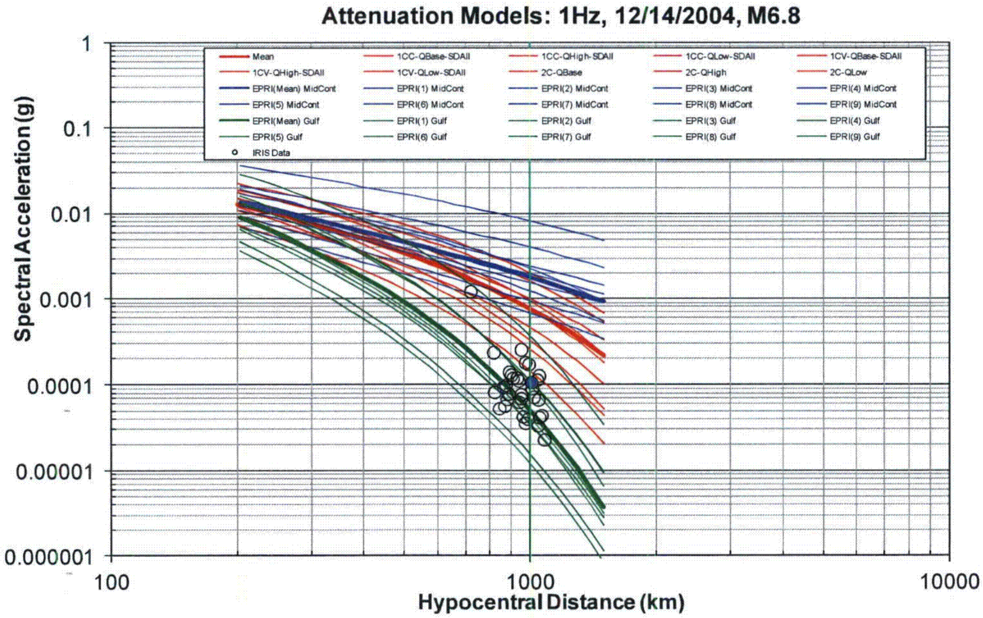

Figure 9b. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 1 Hz. The DWPF data point is shown as a blue-filled circle.

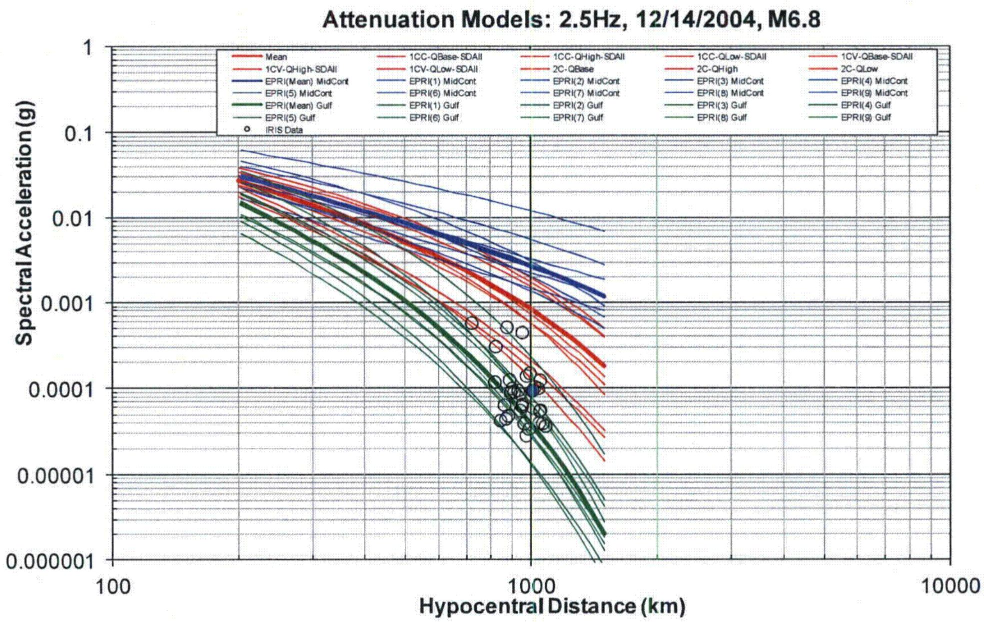

Figure 9c. Comparison of Caribbean GMPE (red lines), EPRI MidContinent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 2.5 Hz. The DWPF data point is shown as a blue-filled circle.

Gulf of Mexico (Mw5.9), 09/10/2006:

This event occurred in the Gulf of Mexico and its epicenter is shown in Figure 10a along with the FPL project site location, and the location of the IRIS stations that recorded this earthquake. Based on the observed station distribution, the IRIS station DWPF located in central Florida has the most applicable source to site path for this comparison. The distribution of stations in the central United States have a less applicable travel path azimuth and may show different attenuation properties based on these different tectonic travel paths. The attenuation curves and empirical data are shown in Figures 10b and 10c for the 1 and 2.5 Hz spectral frequencies. The data point from the DWPF station is highlighted as a solid blue circle. In general the empirical observations fall within the range of the Caribbean attenuation curves with the single except of station LRAL (i.e., at a distance of about 750km) for 2.5 Hz in which the empirical data exceeds the highest Caribbean attenuation curve. As noted earlier, the empirical observation has not been adjusted to a common site condition of Vs=2.83km/sec and it could be expected that this empirical data point could possibly be reduced if a site amplification adjustment were to be applied. It can also be concluded from the comparison plots in Figures 10b and 10c, that the distribution of the current Caribbean attenuation curves adequately captures the range of the empirical data. In addition, the observation from the DWPF station is in the lower range of the Caribbean attenuation curves.

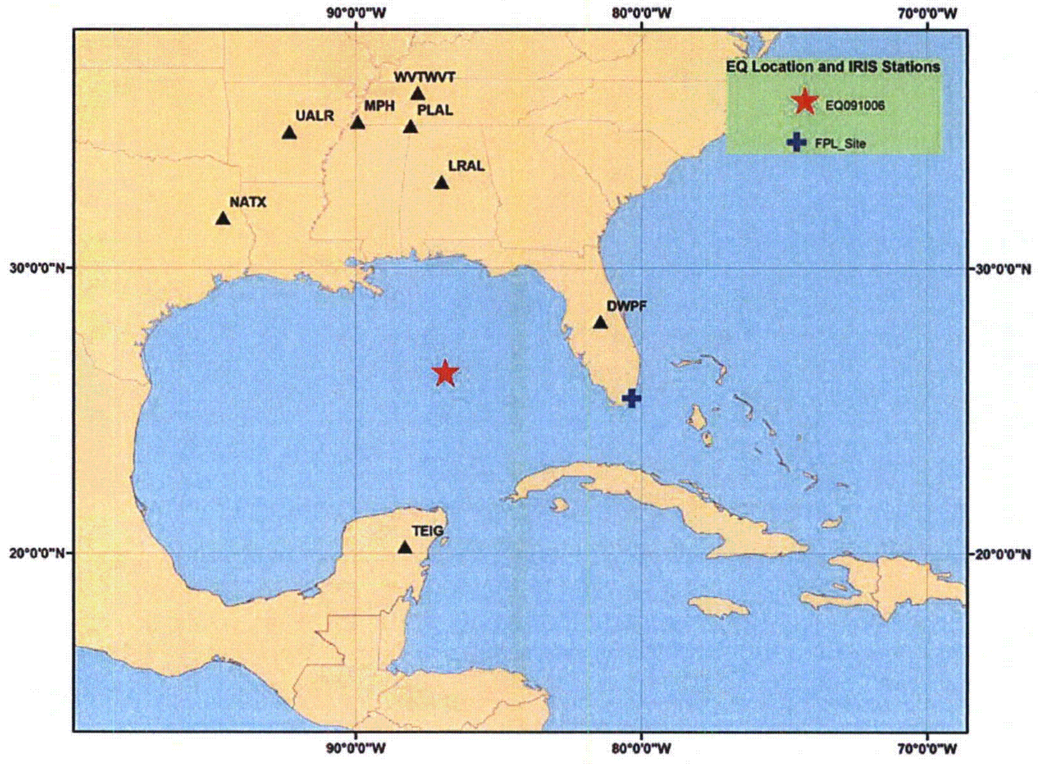

Figure 10a. Map showing the earthquake location for the 09/10/2006 Gulf of Mexico earthquake (Mw5.9), the IRIS station locations used in the analysis and FPL project site location.

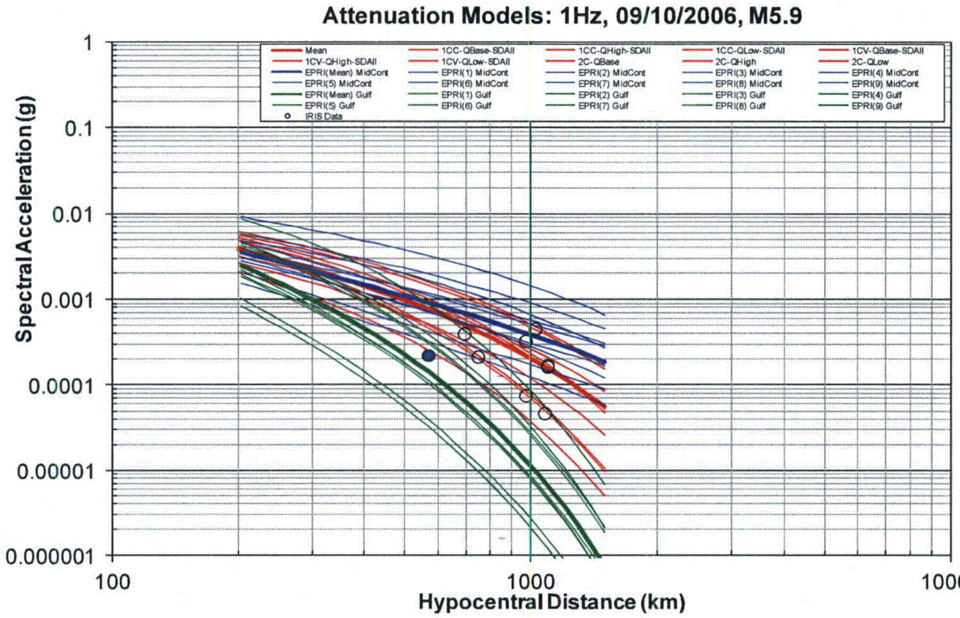

Figure 10b. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 1 Hz. The DWPF data point is shown as a blue-filled circle.

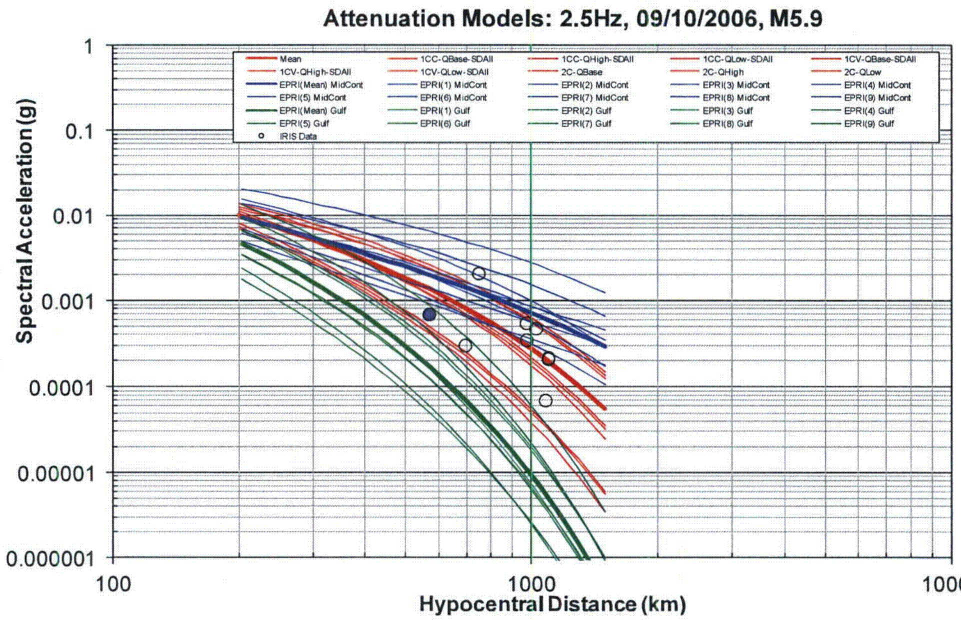

Figure 10c. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 2.5 Hz. The DWPF data point is shown as a blue-filled circle.

Cuba Region (Mw6.2), 02/04/2007:

This event occurred south of the island of Cuba and its epicenter is shown in Figure 11a along with the FPL project site location, and the location of the IRIS stations that recorded this earthquake. Only three IRIS stations were analyzed from this. Based on the observed station distribution, the IRIS station DWPF located in central Florida has the most applicable source to site path for this comparison. The attenuation curves and empirical data are shown in Figures 11b and 11c for the 1 and 2.5 Hz spectral frequencies. The data point from the DWPF station is highlighted as a solid blue circle. Overall the empirical data falls below the median Caribbean attenuation curve (heavy red line) and has values which are in the lower distribution of range of Caribbean attenuation curves. In addition, the observation from the DWPF station is similar to the lowest Caribbean attenuation curve or lower.

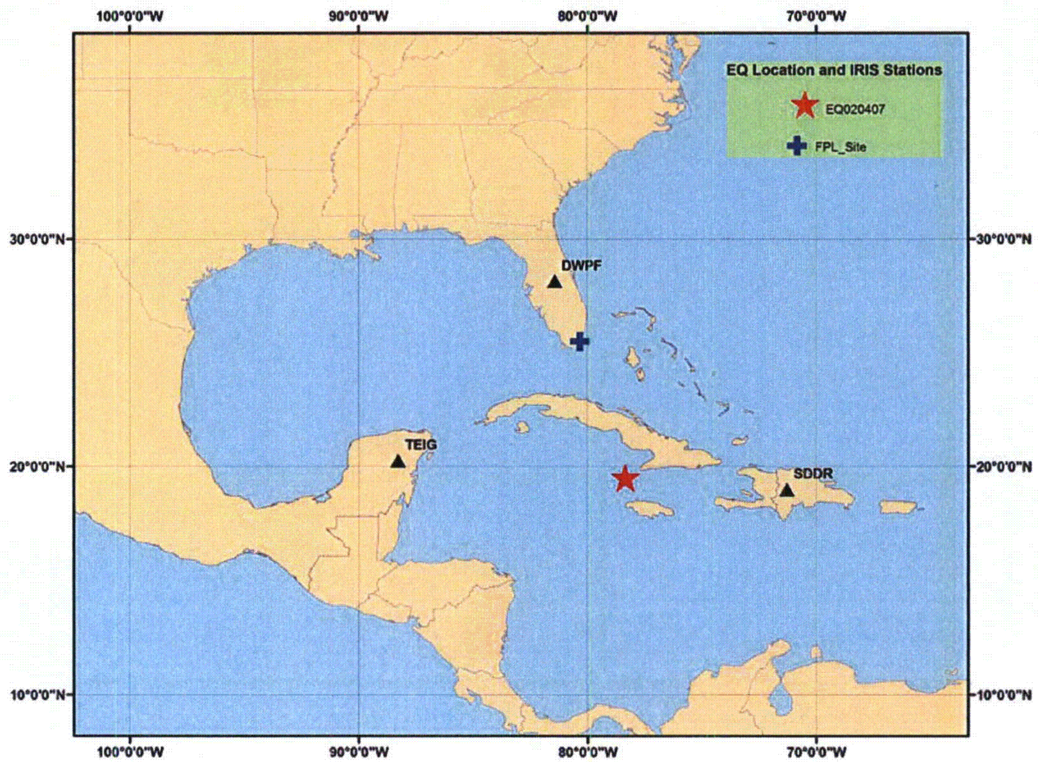

Figure 11a. Map showing the earthquake location for the 02/04/2007 Cuba Region earthquake (Mw6.2), the IRIS station locations used in the analysis and FPL project site location.

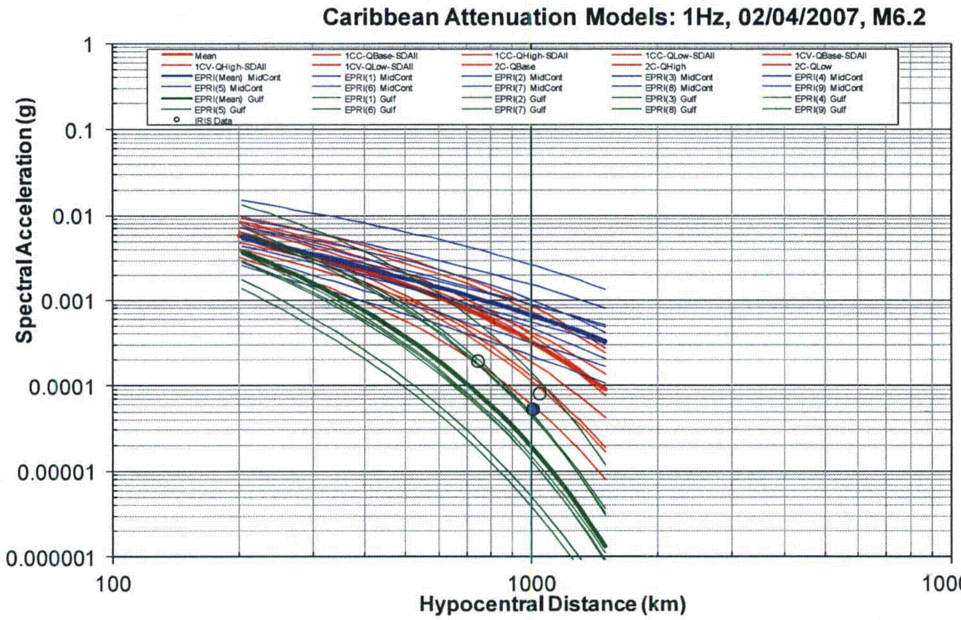

Figure 11b. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 1 Hz. The DWPF data point is shown as a blue-filled circle.

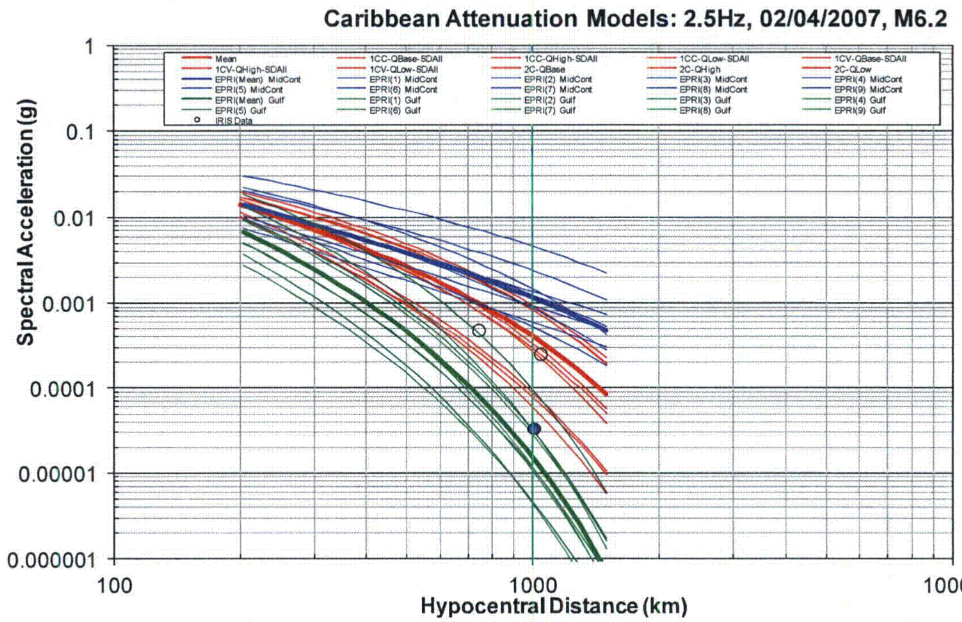

Figure 11c. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 2.5 Hz. The DWPF data point is shown as a blue-filled circle.

North of Honduras (Mw7.3), 05/28/2009:

This event occurred north of Honduras in Central America and is the largest earthquake in the suite of five events analyzed in this sensitivity study. The location of its epicenter is shown in Figure 12a along with the FPL project site location, and the location of the three IRIS stations that were analyzed. Based on the azimuths from the earthquake to the three IRIS stations, none of the associated seismic ray travel paths are ideal for this comparison study. The attenuation curves and empirical data are shown in Figures 12b and 12c for the 1 and 2.5 Hz spectral frequencies. The comparisons provided in the figures indicate that the empirical data from this earthquake are lower than any of the Caribbean attenuation curves.

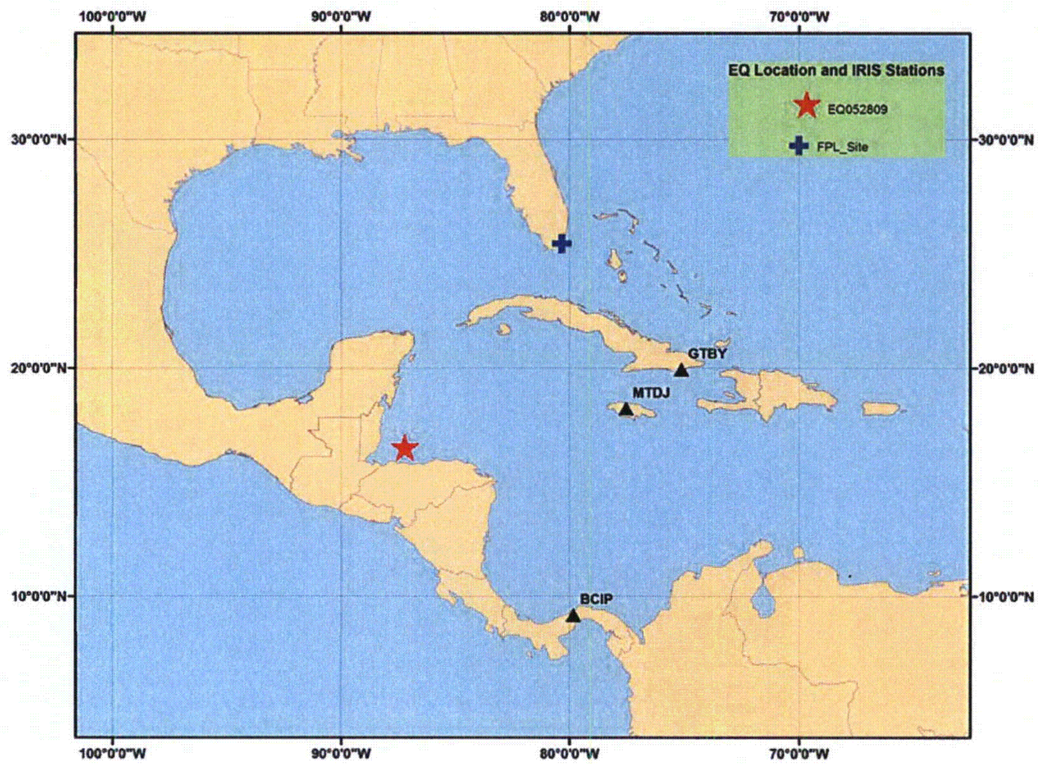

Figure 12a. Map showing the earthquake location for the 5/28/2009 Caribbean Sea Region earthquake (Mw7.3), the IRIS station locations used in the analysis and FPL project site location.

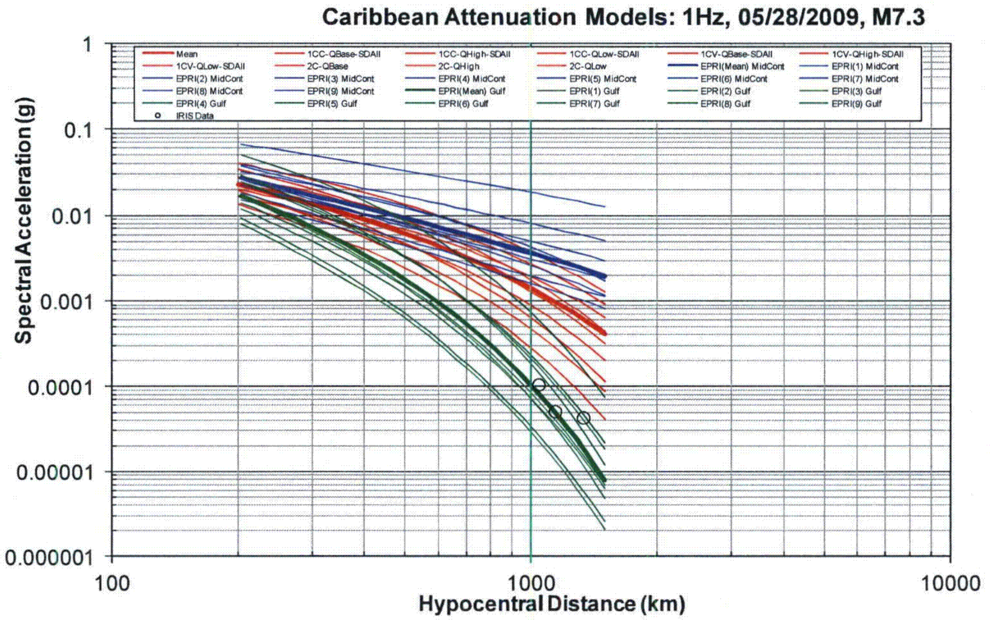

Figure 12b. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 1 Hz.

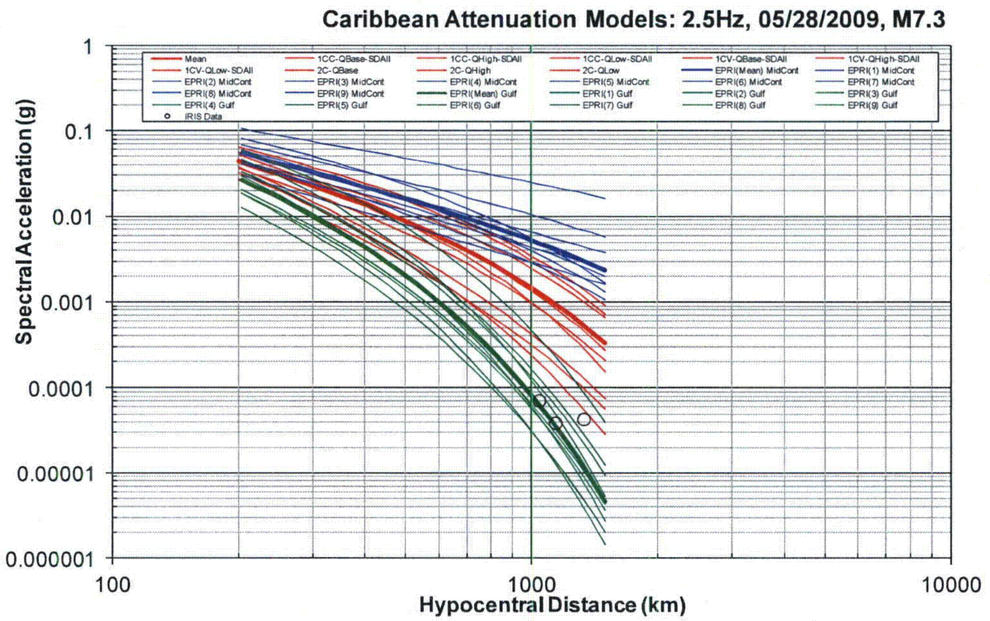

Figure 12c. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 2.5 Hz.

Haiti (Mw7.0), 01/12/2010:

The Haiti earthquake is the most recent event in this suite of five earthquakes analyzed. The epicentral location and the suite of IRIS stations analyzed are shown in Figure 13a. Based on the observed station distribution, the IRIS station OTAV located in between the south part of Florida and the island of Cuba has the most applicable source to site path for this comparison. Note that the data from the DWPF was not available for this earthquake. The attenuation curves and empirical data are shown in Figures 13b and 13c for the 1 and 2.5 Hz spectral frequencies. The data point from the OTAV station is highlighted as a solid blue circle. Overall the empirical data falls in the lower range or lower than the Caribbean attenuation curves. In addition, the observation from the OTAV station is significantly lower than the entire range of the Caribbean attenuation curves.

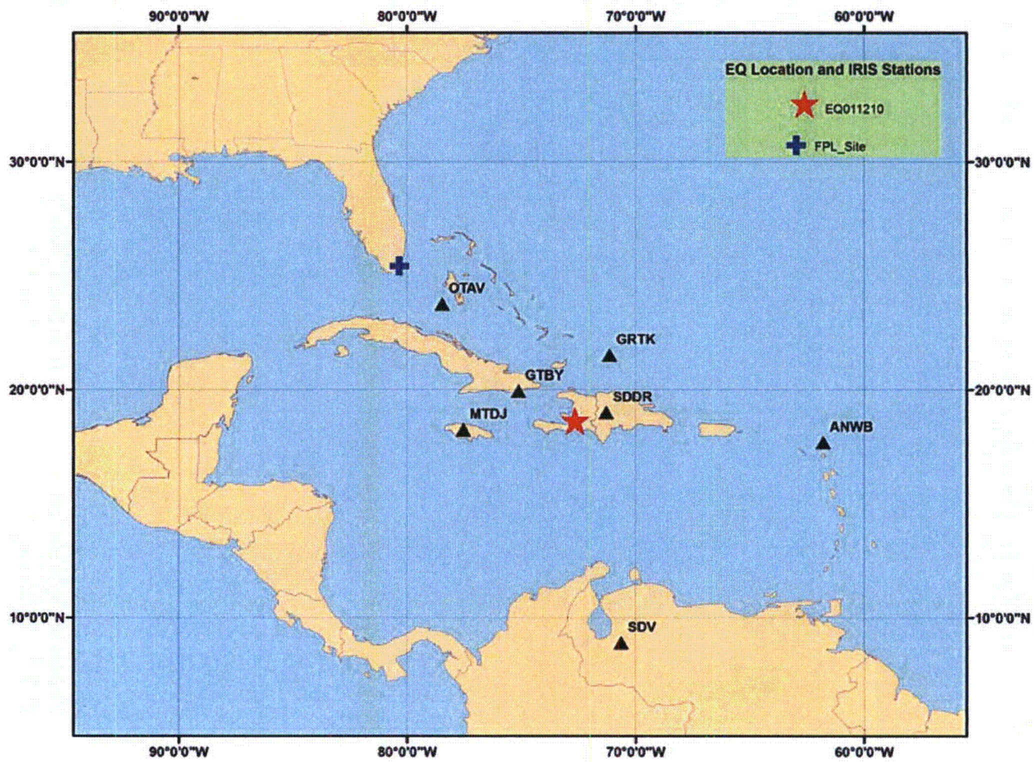

Figure 13a. Map showing the earthquake location for the 01/12/2010 Haiti earthquake (Mw7.0), the IRIS station locations used in the analysis and FPL project site location.

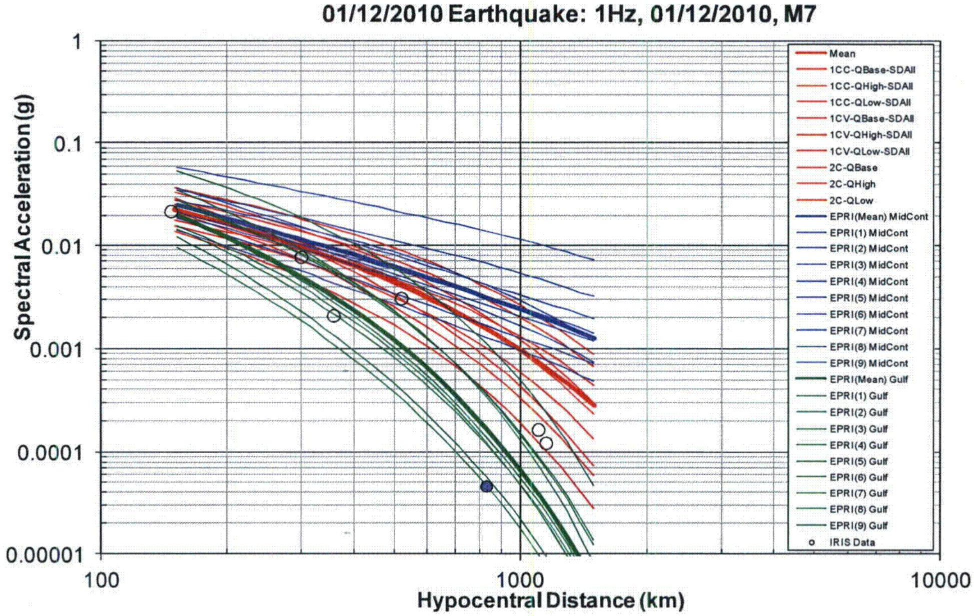

Figure 13b. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 1 Hz. The OTAV data point is shown as a blue-filled circle.

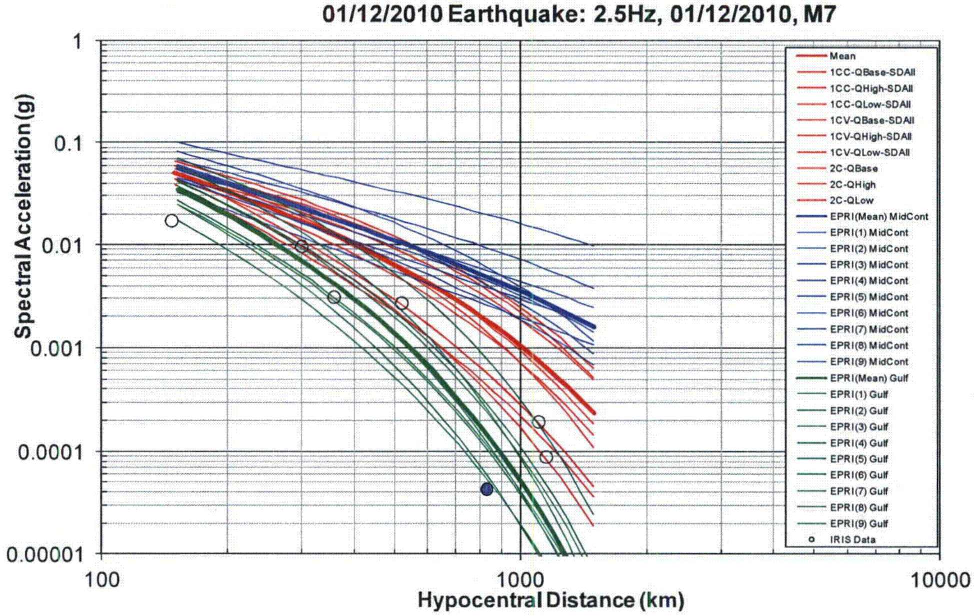

Figure 13c. Comparison of Caribbean GMPE (red lines), EPRI Mid-Continent (blue lines) and Gulf Coast region (green lines) GMPE and empirical IRIS processed data for a spectral frequency of 2.5 Hz. The OTAV data point is shown as a blue-filled circle.

Based on this sensitivity analysis, we conclude that the suite of Caribbean GMPE models used in the current PSHA predicts larger ground motions on average than the observed empirical data from these five earthquakes for the spectral frequencies of 1 and 2.5 Hz. In addition, given the subset of data from just those stations which have a more appropriate source to path seismic ray path this conclusion can be extended to state that the use of the Caribbean GMPE models should provide conservative (i.e., higher) ground motion predictions compared to the observed empirical data from the region.

The sensitivity analysis indicates to us that the suite of GMPEs developed for the FPL FSAR to characterize contributions to hazard at the southern Florida site from Caribbean earthquakes is more like the EPRI Gulf Coast GMPEs than the EPRI Mid-Continent GMPEs and that the contribution to design ground motions from Caribbean earthquakes of a given magnitude and distance is conservatively represented by incorporation of the developed project-specific GMPEs.

References

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Questions

1. Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?
2. Are the selected input parameters acceptable for their use?
3. Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?
4. Is the recommended weighting based on the EPRI (2004) class weights acceptable?
5. Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?
6. Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to PSHA at a site in southern Florida from Caribbean seismic sources?
7. Do you have any other comments?

Gregor, Nicholas

From: Litehiser, Joe
Sent: Tuesday, October 30, 2012 8:18 AM
To: norman abrahamson
Cc: Gregor, Nicholas; Tavakoli, Behrooz
Subject: FPL Questionnaire.
Attachments: CaribbeanGMPE_Questionaire.pdf

Norm – My brief take-away from our conversation last Friday: I heard that you believed that Nick's IRIS empirical data was the most convincing and relevant part of our argument overriding any concern or uncertainty about model parameters. Further, you said that uncertainty about subsurface conditions on IRIS results would not amount to more than a factor of about two – small relative to other uncertainties. Finally, you said that the earthquakes we used for IRIS data are all shallow crustal earthquakes and that this point needs to be emphasized in our response. Given this and the seven questions below, I hope to call you at 7 PM Eastern time this evening. If there is anything, however brief, you can sketch in for the specific questions that would be very helpful. You have the original questionnaire but here it is again for your convenience.

Thanks - Joe

Question 1: Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?		
N. Abrahamson	*Response*	
	Notes	
	Action Item	
Question 2: Are the selected input parameters acceptable for their use?		
N. Abrahamson	*Response*	
	Notes	
	Action Item	
Question 3: Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?		
N. Abrahamson	*Response*	
	Notes	
	Action Item	
	Action Item	
Question 4: Is the recommended weighting based on the EPRI (2004) class weights acceptable?		
Question 5: Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?		
N. Abrahamson	*Response*	
	Notes	
	Action Item	
Question 6: Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to the PSHA at a site in southern Florida from Caribbean seismic sources?		
N. Abrahamson	*Response*	
	Notes	
	Action Item	
Question 7: Do you have any other comments?		
N. Abrahamson	*Response*	
	Notes	
	Action Item	

Review of Bechtel Caribbean GMPE Report

By: Yousef Bozorgnia

August 2, 2012

I reviewed the Bechtel report on development of the Caribbean GMPEs for use for Southern Florida. Below are the specific questions stated in the report and my reply.

1. Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?

Based on the review of the materials submitted by Bechtel, the newly developed GMPEs are acceptable, and the process of developing the GMPEs is rational and logical.

2. Are the selected input parameters acceptable for their use?

Yes, especially considering the work of Motazedian and Atkinson (2005). Also, using Kappa=0.006 sec for the reference rock is consistent with the latest preliminary findings of NGA-East project.

A word of caution: Chen and Atkinson (2002) have a table of site amplifications for CEUS Hard Rock that lists both Amp(f) and Amp(f)*exp(-pi*Kappa*f). For the CEUS Hard Rock, Chen and Atkinson used Kappa=0.002 sec. If in the Caribbean study, values of Amp(f)*exp(-pi*Kappa*f) were directly taken from Chen and Atkinson (2002), theses values should be adjusted for Kappa=0.006 sec.

3. Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?

This value is based on Motazedian and Atkinson (2005) that stated: *"The standard deviation of the distribution of the residuals for intermediate frequencies on average is ~0.28 in log10 units."* (which is equivalent of 0.645 on natural log units). As stated in Motazedian and Atkinson (2005), this sigma is an average standard deviation for intermediate frequencies. On average sense, this number is a reasonable number; however, the standard deviation of GMPEs can be a function of frequency. A simple approximate sensitivity analysis can be performed to estimate a frequency-dependent sigma and its impact on the results.

4. Is the recommended weighting based on the EPRI (2004) class weights acceptable?

The explanation on the assigned weights in Table 3 is reasonable.

5. Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?

Not that I know of.

6. Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to PSHA at a site in southern Florida from Caribbean seismic sources?

Based on the sensitivity analysis of five regional events reported in the Bechtel report, it seems that EPRI Gulf Coast GMPEs are more appropriate. However, it should be noted that the recorded empirical data were not corrected for local site effects to correspond the spectral ordinates of the recorded motions to Vs=2.83 km/sec.

7. Do you have any other comments?

(a) In the sensitivity analysis, the site corrections at the recording sites to correspond the spectral ordinates to Vs=2.83 km/sec should be carried out. Due to lack of specific soil date at the recording site, the site correction needs to be done in an approximation manner. There are different methods of approximating site correction that may be employed.

(b) In the sensitivity analysis, it would be useful to show the residual plots rather than the predicted curves superimposed over the recorded data. In this process, it would be also useful to estimate the "event terms" (and their uncertainties) for the earthquakes examined in the report.

Response to SSHAC Caribbean GMPE Questionnaire

Kenneth W. Campbell, Ph.D.
Kenneth W Campbell Consulting

QUESTIONS AND ANSWERS:

Q1. *Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?*

A1. Yes, it is my opinion that the newly developed Caribbean GMPEs are generally acceptable, albeit possibly conservative at very large distances, for modeling ground motions in the Caribbean region for a site located in Southern Florida for the PSHA study. However, without seeing the functional form, it is not possible to comment on the model itself, which appears to be a very simple functional form, possibly lacking the "hinged-trilinear" geometric attenuation term that was included in the stochastic simulations. This term could be important at large distances. Only a plot of residuals would indicate whether this apparent simple functional form is appropriate. If the term was included in the GMPEs, then this statement can be ignored. Because of the large degree of epistemic uncertainty in the model parameters, travel path, and types of sources (tectonic regime), it would be better if uncertainty was applied to all of the model parameters and not just Q and source spectra type (e.g., "kappa," in which EPRI (1993) included three alternative values for this parameter). I am also somewhat confused regarding how uncertainty in stress drop was treated. It appears that it was included as aleatory modeling uncertainty based on the description in the text (which is not used in capturing aleatory uncertainty in the model), instead of being modeled as epistemic uncertainty. If so, perhaps it would be better to include it as epistemic uncertainty to be consistent with my previous comment.

Q2. *Are the selected input parameters acceptable for their use?*

A2. Yes, I am not aware of any other parameters that might be more acceptable for use in deriving a GMPE for the Caribbean region. However, as mentioned above, it would be more appropriate to include uncertainty in more of these parameters considering the large degree of uncertainty involved in their estimation and current application to a site in southern Florida. I am a bit concerned that Motazedian and Atkinson (2005) used a stress drop from a calibration with California earthquakes and not derived from the data. However, the generally good comparison with the Puerto Rico data would seem to indicate that their 130-bar median value is generally acceptable. The assumption by Motazedian and Atkinson (2005) that site response at site SJG, which appears to represent a shallow soft-rock site, is the same for all of the recording sites in Puerto Rico, is of some concern, since systematic differences in site response could "bleed" into other parameters. However, there is no way of knowing if this is the case and this possibility must instead be captured as epistemic uncertainty

Q3. *Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?*

A3. Yes, I believe that the recommended sigma value of 0.645 natural log units (0.28 common log units) is acceptable as long as sufficient epistemic uncertainty is captured in the model.

Q4. *Is the recommended weighting based on the EPRI (2004) class weights acceptable?*

A4. Yes, the weighting scheme based on class weights seems reasonable. There should be an explanation why the third class of models defined by EPRI (hybrid empirical models) was not considered. It is simply stated as a fact without explanation.

Q5. *Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?*

A5. None of the earthquakes used to compare recorded ground motions with the Caribbean GMPEs developed in this study appeared to be subduction earthquakes. However, most recordings from subduction earthquakes represent continental travel paths and, at large distances, paths in the backarc region, which have been shown to show greater attenuation than paths in the forearc region. Therefore, subduction GMPEs are not appropriate for the primarily oceanic travel paths to the southern Florida site. To show that this is the case, it would be beneficial to compare predictions from the current set of empirical subduction GMPEs with the Caribbean GMPEs developed in this study for large earthquakes at distances of relevance to the southern Florida site to show that these subduction GMPEs would predict smaller ground motions. However, if they don't, then they should be considered for predicting ground motions from subduction sources.

Q6. *Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to PSHA at a site in southern Florida from Caribbean seismic sources?*

A6. Although the limited amount of data appears to suggest that the Gulf Coast region GMPE developed by EPRI (2004) might be more appropriate at large distances, the one earthquake that occurred in the Gulf of Mexico (the closest earthquake to the site) showed relatively good agreement with the Caribbean GMPE developed in this study (ignoring differences in site response). Therefore, I would not suggest that the Gulf Coast region GMPE is more appropriate, but instead suggest that it be captured in the epistemic uncertainty model with by using it as an alternative model or insuring that the epistemic uncertainty in the model parameters include it. I would not recommend that the Mid-Continent region GMPE of EPRI (2004) be used for Caribbean earthquake sources.

Q7. *Do you have any other comments?*

A7a. The Puerto Rico data used by Motazedian and Atkinson (2005) to estimate the model parameters were recorded at distances of 500 km and less. Therefore, use of these parameters

beyond 500 km represents an extrapolation and must be adequately captured as epistemic uncertainty. Presumably, this is accomplished by included epistemic uncertainty in the Q term. Since 8 years has passed since the Motazedian and Atkinson study, there is no doubt many more recordings that could be used to update the model. It might be worthwhile to contact Gail Atkinson and Dariush Motazedian to see if they have any more information or would suggest the use of different parameters from their 2005 study.

A7b. The terms "GMPE" and "attenuation curve" are used interchangeably. This latter term is no longer considered to be acceptable in the engineering seismology community, except when describing actual attenuation properties, such as Q and geometrical spreading. I would suggest that either the terms "GMPE," "distance scaling" or "median prediction" be used as appropriate when describing the distance-scaling characteristics of the GMPE model.

A7c. The statement on Page 18 that "Based on simplified site response analysis it would be expected that adjustments for the station-specific site conditions to the more stable CEUS hard rock site condition would result in some reduction in the observed empirical ground motion values" might be true for relatively low frequencies but might not be true for relatively high frequencies, where a very small kappa at the southern Florida site might actually result in higher ground motion.

A7d. The deaggregation histograms show that the Caribbean sources are important to (and possibly even dominating) the seismic hazard at relatively low structural and exceedance frequencies. How about at higher structural frequencies? For completeness, I would like to see deaggregation plots at the higher structural frequencies.

SSHAC Caribbean Ground Motion Prediction Equation Questionnaire

RESPONSE TO QUESTIONS
By
Shahram Pezeshk

Question 1. Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?

My general comment is that the newly developed Caribbean GMPEs are acceptable and possibly conservative for modeling ground motions in the Caribbean region.

I will elaborate on my answer in much detail through answering the remaining questions.

Question 2. Are the selected input parameters acceptable for their use?

The point-source stochastic method will be a reasonable approach in concept to simulate ground motions as a function of earthquake magnitudes and distances, if the selected input seismological parameters for the simulations are validated using available instrumental seismic data, and are compared to ground-motion relations for other tectonically similar regions. Because of its success and simplicity, the point-source stochastic method is now widely used to predict ground motion in many regions of the world where the number of strong ground-motion recordings is limited and no empirical ground-motion relations are available. This approach has been successfully validated and applied for other regions such as western United States (WUS) and central and eastern United States (CEUS), and on average reproduces similar empirical ground-motion attenuation relationships that can be obtained by direct use of ground-motion recordings.

In the Caribbean-Cuba region, where the number of ground-motion recordings is limited, and except for the Motazedian and Atkinson [MA05] (2005) relation, there are no empirical ground-motion relations available, it is possible to derive simple source models (e.g., 1CC, 1CV, 2C) and to evaluate the variation of seismological parameters (e.g., stress parameter, kappa, and Q factor) using the seismological network data. These parameters are used to scale ground-motion amplitudes with the earthquake magnitude and the source-to-site distance. However, the empirical ground-motion relations estimated from the simulated records should be compared to those calculated from the actual seismographic records in the region, and the applicability of the ground motion prediction equations (GMPEs) should be assessed by the data from other tectonically similar regions.

When I started reviewing the March 5, 2012 report, I was going to recommend that the resulting GMPEs to be superimposed with some selected actual earthquakes in the Cuba and Caribbean region that were recorded by the broadband CEUS stations, Global Seismic Network (GSN), IRIS broadband data, Regional Seismic Network, and other cooperative stations in the Caribbean

region (see McNamara *et al.*, 2012). Now, I am glad that this has been done in the most recent report that has been provided to me (the SSHAC Caribbean GMPE Questionnaire). Therefore, the comparison of the developed Caribbean GMPEs with the EPRI (2004) Mid-Continent and Gulf Coast GMPEs has provided a good way to show the appropriate ranges of input parameters such as stress parameter that scales high frequency of ground motions have been selected. The Gulf of Mexico (M_w 5.9) event is possibly a good representative of ground motions between the Cuba area and the FPL project site location that could be used to validate the selected parameters. This event shows that the selected seismological parameters are acceptable to capture the recording ground motion data (see Figures 10a and 10b).

<u>Source models and stress parameters</u>

McNamara *et al.* (2012) have provided valuable broadband dataset from the earthquakes in the Caribbean region (table of earthquakes and station parameters) to determine the *Q*-factor relations in the region. The McNarama *et al.* (2012) study, which has been published after the development of the Caribbean GMPEs, sheds lights on some of the modeling parameters. Boore *et al.* (2009) have also provided a procedure for estimating stress parameters using an updated dataset and a revised point source stochastic model.

It should be noted that the stress parameter is strongly dependent on the source model used. For instance, Atkinson *et al.* (2009) and Boore (2009) have explained why a stress parameter of about 250 bars is needed in **SMSIM** [point-source simulation] to approximately match the predictions of Atkinson and Boore (2006), which is based on **EXSIM** [finite-fault simulation] with 140 bars, when all other model parameters are set to be equal (Campbell, 2008). The MA05 article has used a source model corresponding to an input stress parameter of 130 bars for the Puerto Rico region based on the calibrated source parameters for **EXSIM**. This is the **EXSIM** source model and the stress parameter of 130 bars may be modified based on the **SMSIM** source model to match the predictions of Atkinson and Silva (2000) in their stochastic ground-motion model.

The earthquake ground motions in the Caribbean region is similar to the WUS region, and attenuates faster with epicentral distance than comparable-sized earthquakes in the CEUS region (see *Q* factor below). The stress parameters in the Caribbean region can be calibrated by the California strong-motion dataset or by the new generation of ground-motion attenuations in WUS. As a result, the stress parameters used in the Caribbean region may not capture the appropriate changes in the stress parameter. However, it is difficult to confirm them with the insufficient information provided in this report.

According to Atkinson and Boore (2006), it should be noted that the effect of the stress parameter on the simulated ground-motion values is approximately independent of distance. The frequency range over which the increase in amplitudes will occur depends on earthquake magnitude (Atkinson and Boore, 2006). Increasing the stress parameter has almost no effect on amplitudes at low frequencies (long periods). Then, the amplitude will increase and reach a constant factor at high frequencies (see *Aleatory and Epistemic Uncertainties*).

Q factor

The instrumental seismic recordings in the different tectonic environments typically show that areas of active tectonics, like the Caribbean region and the WUS region, have higher attenuation of seismic waves than the stable continental regions such as the CEUS region (Aki, 1980; Singh and Herrmann, 1983; Frankel *et al.*, 1990; Benz *et al.*, 1997; Erikson *et al.*, 2004; McNamara *et al.*, 2012). According to the McNamara *et al.* (2012) article, possible reasons to explain these observations in notably different tectonic environments are a highly fractured crust in tectonically active regions that effectively absorb high-frequency seismic waves, differences in crustal temperature, and variations in crustal structures that control elastic wave propagation.

Therefore, the earthquake ground motions in the Caribbean region- similar to the WUS region- are attenuated faster with distance than comparable-sized earthquakes in the CEUS region. In fact, it has been observed throughout the world that *Lg*-phase attenuation (regional surface-wave phase observed as the dominant phase on broadband seismograms at regional distances) is higher for regions with active tectonic than for stable continental interiors (McNamara *et al. 2012*).

Recent studies in the Caribbean region using digital broadband seismic instruments show that both direct *S* and *Lg*-phase attenuation results are most similar to the results obtained for the WUS region. Figure 1 (similar to Figure 9 of McNamara *et al., 2012*) illustrates the *Q* models in the Caribbean region and the adjacent region ranging from Jamaica and Cuba in the west to Puerto Rico and Lesser Antilles in the east compared to those in the WUS and CEUS regions. The results indicate that the local attenuation properties of the Caribbean region are consistent with values estimated for the WUS region, which is likely to be characterized by a lower *Q* factor (higher attenuation) than the CEUS region.

Hough and Anderson (1988) as well as McNamara *et al.* (2012) have pointed out that the attenuation properties of *Lg*-phase differ from those of the direct *S* wave because the *Lg*-phase samples the entire crust including the "deeper crust," which is likely to be characterized by the lower attenuation (higher *Q* factor), while the direct *S* waves are more controlled by the "upper crust" (lower *Q* factor). Therefore, the *Q*-factor model developed by MA05 for the Puerto Rico region using local earthquakes as deep as 200 km might give higher *Q* factor (lower attenuation) than the shallow crustal attenuation models in the Caribbean region. As a result, the MA05 *Q*-factor model and the range of uncertainties for the simulation of ground motions in the Caribbean region implies that *Q* factor adopted for the Caribbean crust has captured conservatively the epistemic uncertainty in *Q* factor.

Note that the focal mechanism and the depth of actual earthquakes in the Caribbean region are significant, especially for their use to validate the Caribbean GMPEs. This information should be addressed in the report.

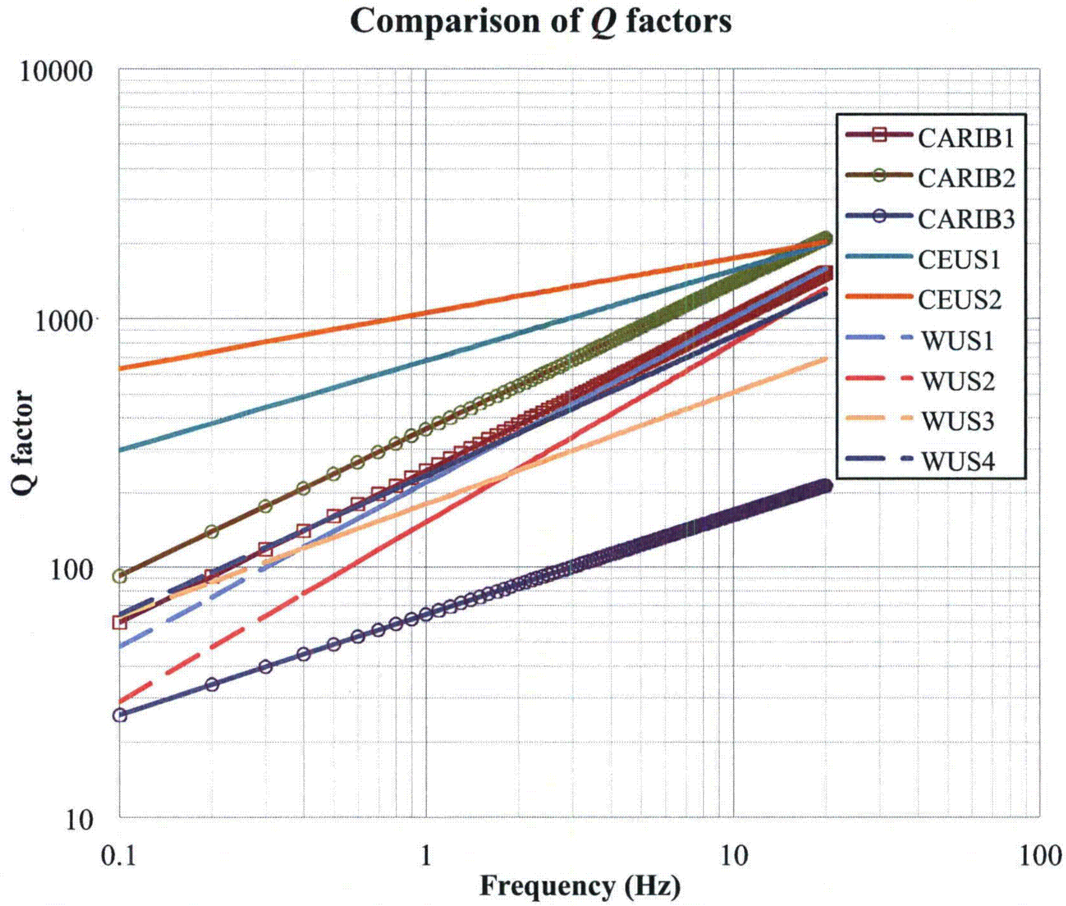

Figure 1. Comparison of Q-factors for three different tectonic regions; 1) Caribbean, 2) CEUS, and 3) WUS regions.

Kappa Filter

The effect of kappa on ground motions is negligible for hard-rock sites at large distances, since high frequency amplitudes are reduced through the kappa operation and are filtered at large distances. Figure 2 shows the comparison between *Q*-factor and kappa of 0.006 at a distance of about 100 km for the Puerto Rico area in the Caribbean region. Using the site attenuation of 0.006 (kappa), which models the near surface attenuation, there is no significant effect on the ground-motion scaling at large distances for hard-rock site compared to *Q* factor.

Geometrical spreading

In developing attenuation models, the *Q* factor is often determined by assuming a hinged-trilinear functional form for the geometrical spreading, in which amplitude decay varies as a function of epicentral distance. This is interpreted as reflecting the seismic waveform in the different layers of crustal structure (Atkinson and Mereu, 1992; Atkinson and Boore, 1995). At large distances, the crustal waveguide L_g-phase control seismic records, and the attenuation rate changes to $R^{-0.5}$ form (Frankel, 1991; McNamara *et al.*, 1996; Benz *et al.*, 1997; McNamara *et al.*, 2012). This fixed exponent of -0.5 has a main role to scale ground-motion amplitudes at large distances. MA05 and McNamara *et al.* (2012) found the same distance-dependent geometrical spreading and adopted a hinged-trilinear functional form specific to Caribbean region. McNamara *et al.* (2012) have observed that beyond 200–250 km, body waves consist of small amplitude mantle head waves and crustal L_g dominates the ground-motion records. Based on these observations, they have confirmed the attenuation rate is changed by $R^{-0.5}$ at distances of 100 km and greater in the Caribbean region compared to the 130 km in the CEUS region. This difference in hinge point at large distances reflects regional differences in the crustal structures between two regions. Therefore, using a constant rate of -0.5, the ground-motion attenuations are strongly controlled not only by region-specific *Q*-factor relations at large distances, but also by the hinge points (Figure 3).

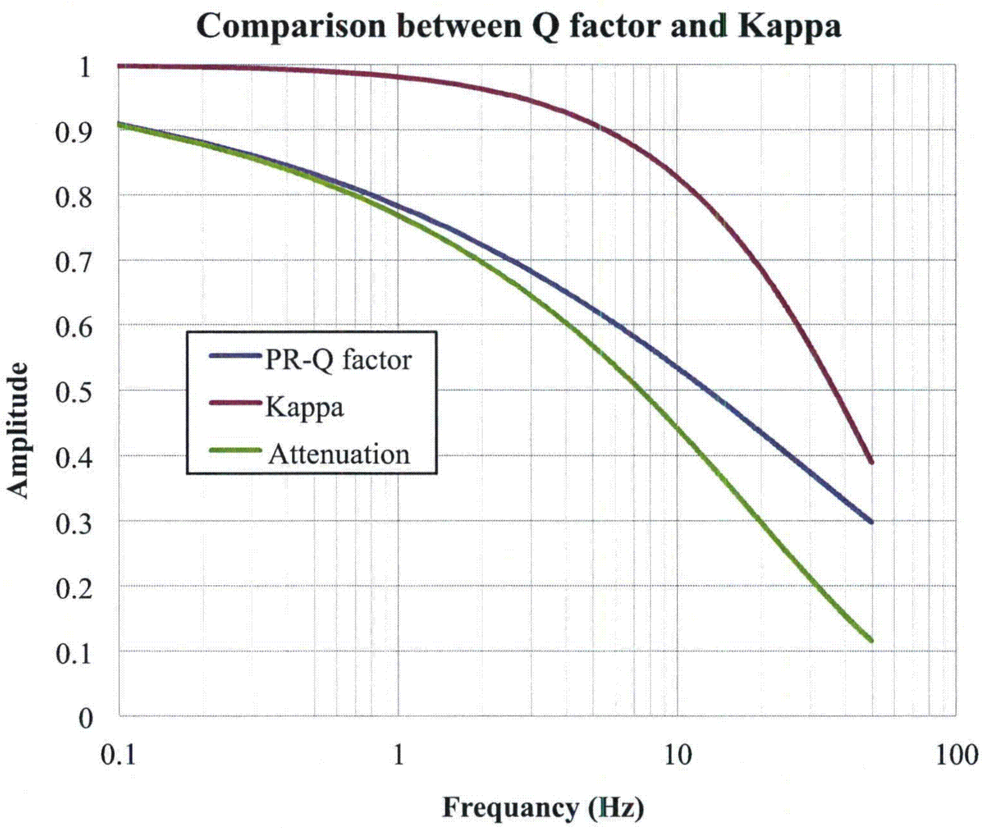

Figure 2. Comparison between *Q*-factor and kappa relations at a distance of about 100 km for the Puerto Rico area in the Caribbean region.

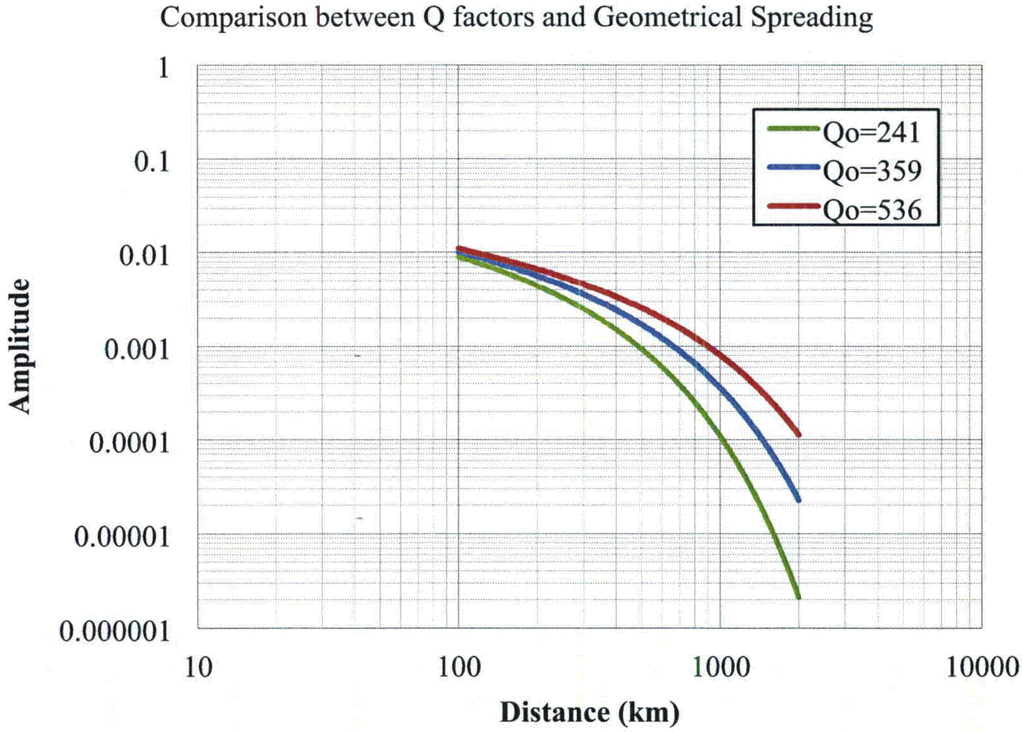

Figure 3. Comparison between Q-factor and Geometrical spreading at frequency of 1Hz and distances between 100 km and 2000 km for the Caribbean region.

Comparison between the attenuation model (*Q*-factor and Geometrical spreading) and the resulting Caribbean GMPEs at frequency of 1 Hz (see Figures 1 through 7 of the SSHAC Caribbean GMPE Questionnaire) indicates that the *Q*-factor relations have strongly controlled the ground-motion amplitudes at large distances. Therefore, selection of the appropriate regional-specific *Q*-factor plays the main role to scale ground-motion amplitudes at large distances in the Caribbean region.

As it was discussed earlier and as it is plotted in Figure 1, the *Q* factors have been selected conservatively. This may conclude that the observed earthquake ground-motion data in the Caribbean region should be located lower than the mean Caribbean GMPEs for the same site conditions - especially at large distances. Data provided in Figures 9b, 9c, 12b, 12c, 13b, and 13c of the SSHAC Caribbean GMPE Questionnaire show that in fact the observed earthquake ground-motion data in the Caribbean region is lower than the mean Caribbean GMPEs. It is also important to note that the observed ground motion data have not been modified for the site amplification.

Question 3. Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?

Aleatory Uncertainties

Atkinson and Boore (2006) has pointed out that the aleatory uncertainty due to the natural random variability in earthquake source, path and site effects is independent of magnitude and distance, with an average value of 0.30 log units for all frequencies in CEUS. This calculated variability, based on the simulation parameters, is slightly larger than typically observed values for the GMPEs in California (e.g., Boore *et al.*, 1997; Abrahamson and Silva, 1997). The MA05 study has also calculated the residuals of the recorded Puerto Rico data versus the Puerto Rico ground motion attenuation relations, and has suggested a standard deviation of the relations of 0.28 log(10) units for all frequencies. This standard deviation is typical for ground-motion relations in many regions and should be relatively independent of region.

Comparison of the variability of ground motions between eastern North America (ENA) and the California or Caribbean region show that the simulated variability may slightly overestimate the actual variability. However, the variability issue will require further earthquake data in ENA.

In response to question 3, the aleatory uncertainty with an average value of 0.645 in natural log units is reasonable to capture the uncertainties in input seismological parameters discussed above for all frequencies in the Caribbean region.

Epistemic Uncertainties

Epistemic uncertainty is modeled by examining the influence of epistemic uncertainty in stress parameter and *Q* factor, which are the largest source of epistemic uncertainty. It is also evaluated through comparisons of the results of the Caribbean GMPEs with other ground motion prediction equations in the other tectonically similar regions.

The Caribbean GMPEs have been developed for a stress of 130 bars based on the **EXSIM** model (see *Question 2 – Source models and stress parameters*) for the problem issue with **SMSIM** stress parameter matching), and the epistemic uncertainty in this value has been considered to be an order of a factor of 2.

According to Atkinson and Boore (2006), it should be noted that the effect of the stress parameter on the simulated ground-motion values is approximately independent of distance. The frequency range over which the increase in amplitudes will occur depends on the earthquake magnitude. As shown in Figure 4, increasing the stress parameter has almost no effect on the amplitude at low frequencies. Then, the amplitude will increase and reach a constant factor at high frequencies. Furthermore, the effect of epistemic uncertainty in stress parameter is illustrated in Figure 4, which plots the amount by which the log amplitudes predicted by the GMPEs would need to be increased to accommodate a factor of 2 increases in stress parameter (Atkinson and Boore, 2006, personal communications with Atkinson).

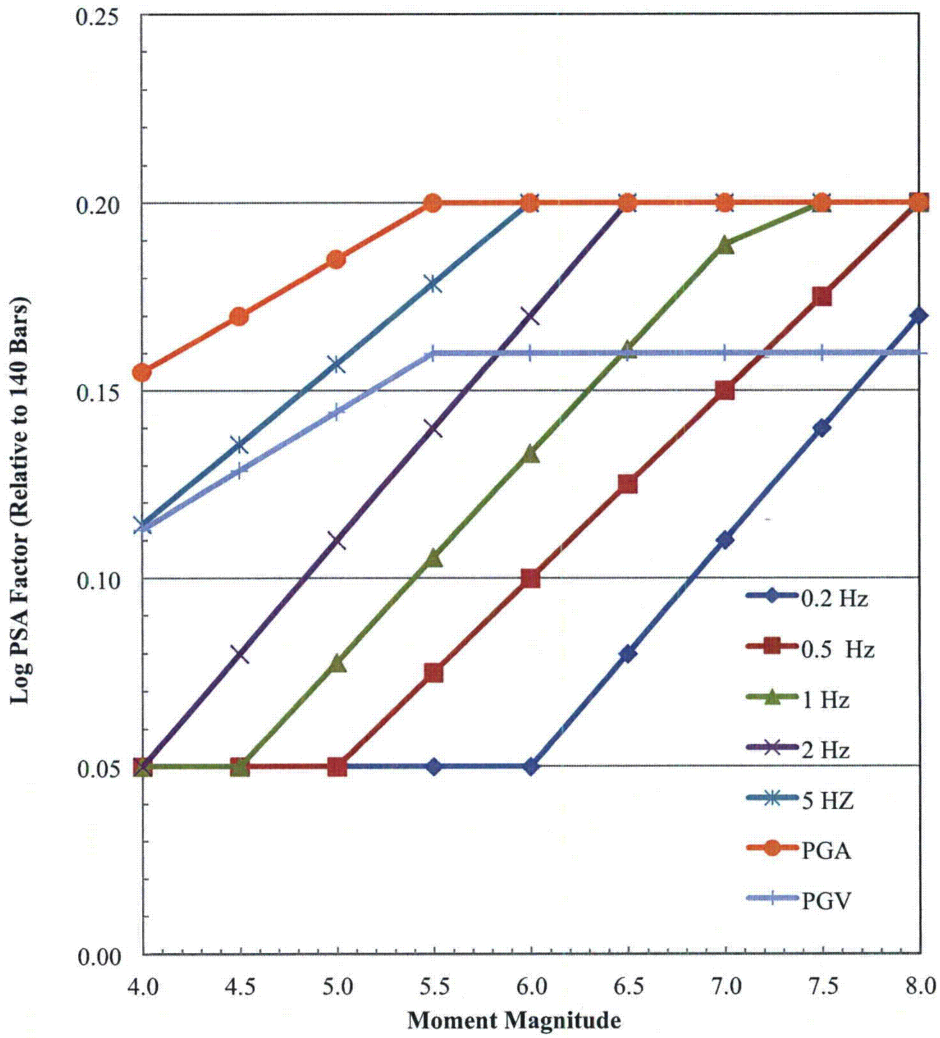

Figure 4. Effect on predicted ground-motion amplitudes of increasing the stress parameter by a factor of 2 (relative to predicted values for 140 bars), adopted from Atkinson and Boore (2006).

The effect of the *Q*-factor on the simulated ground motion values is strongly dependent of distance. As mentioned above, the MA05 *Q*-factor model and the range of epistemic uncertainties for the simulation of ground motions in the Caribbean region implies that *Q*-factor adopted for the Caribbean crust has captured conservatively the epistemic uncertainty in *Q*-factor (see Figures 2 and 3 and its related discussions). According to McNamara *et al.,* 2012, while the *Q*-factor relations in the Caribbean region are relatively low and indicative of an active tectonic environment, L_g-phase amplitudes are considerably higher than might be expected in an oceanic region. Therefore, because of the complicated nature of the crust, the *Q*-factor is expected to be

highly variable throughout other parts of the Caribbean region, and then the appropriate ranges of Q factors used in the Caribbean region are acceptable.

In addition, seismic hazard assessments for the Caribbean region should use a variety of ground motion prediction equations (GMPEs) obtained for other tectonically similar regions to capture the large epistemic uncertainty observed on earthquake ground-motion predictions.

Question 4. Is the recommended weighting based on the EPRI (2004) class weights acceptable?

The recommended weighting based on the EPRI (2004) class weights is reasonable and acceptable.

Question 5. Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?

The resulting Caribbean GMPEs should be similar to stochastic ground-motion relations obtained for other parts of United States. Differences are attributable to regional variations in ground-motion parameters and crustal structures.

The Q-factor relations in the Caribbean region and the WUS region show that areas of active tectonics have higher attenuation of seismic waves than the stable continental regions such as the CEUS region. Therefore, I would recommend that the shallow crustal ground-motion attenuation relations in WUS (NGA 2008) as well as the ground-motion model of MA05, which was developed for Puerto Rico, are also plotted to provide a better estimation of ground motions in the Caribbean region for comparison.

The intermediate earthquakes (M_w 5-6), in particular near the north of Cuba can be added to the actual data plots (see USGS and IRIS datasets) to better understand the variability of ground motions between the Cuba and the FPL project site.

Question 6. Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to PSHA at a site in southern Florida from Caribbean seismic sources?

The Q-factor relations in the different tectonic environments (Figure 1) show that areas of active tectonics, like the Caribbean region and the WUS region, have higher attenuation of seismic waves than the stable continental regions such as the CEUS region. Therefore, it is possible that the ground-motion attenuation relations developed in the CEUS Mid-continental region may not be applicable for the estimation of ground motions in the Caribbean region. This is shown considering the observed ground-motion data in the region (see Figures 9 through 12 of the SSHAC Caribbean GMPE Questionnaire).

In my opinion, as discussed earlier, the main parameter that controls the behavior of ground motions, especially at large distances, is the region-specific Q-values. As shown in Figure 1, the Q-values used in the development of ground motions in the Caribbean region lie between those

of the CEUS and WUS regions. Therefore, the comparison of the developed Caribbean GMPEs with the EPRI (2004) Mid-Continent and Gulf Coast GMPEs implies that the ground motion attenuation curves adopted for the Caribbean region are between those EPRI cases (see Figures 1 through 7 of the SSHAC Caribbean GMPE Questionnaire). However, the actual earthquakes show that the Caribbean GMPEs are closer to the Gulf Coast GMPES than EPRI (2004) Mid-Continent GMPEs.

Another parameter that makes the ground motions in the Caribbean GMPEs deviate from the EPRI (2004) ground motion relations is differences in the hinge points of the attenuation curve that reflect regional differences in crustal structure between two regions (see Geometrical Spreading section). Assuming all parameters being equal, shifting the hinge point to 100 km -- compared to 130 km for the CEUS region- leads to reduce the ground motions in the Caribbean region at large distances.

***Question** 7.* Do you have any other comments?

Four minor comments:

- Table 1 of the SSHAC Caribbean GMPE Questionnaire suggests that a value of 3.6 km/sec was used to represent the shear-wave velocity at the source. Similarly, this table suggests that site amplification factors provided in Chen and Atkinson (2002) have been used. It should be noted that Chen and Atkinson (2002) used a shear-wave velocity of 3.8 km/sec; therefore, the site amplifications need to be adjusted accordingly.
- I am not clear how data for Table 2 were generated. An explanation would be needed.
- More recording events, especially between Cuba and the FPL project site, should be superimposed to the empirical ground-motion attenuation curves for the intermediate magnitude ranges between 5 and 6, if the records are available to process.
- The focal mechanism and depth of the actual earthquakes should be addressed in the report.

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SSHAC Caribbean GMPE Questionnaire

Response to Questionnaire

Paul Somerville URS July 11, 2012

1. Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?

From a regulatory viewpoint I expect that they are acceptable because they are conservative when compared with the data. From a scientific viewpoint they do not have a sound physical basis and therefore lack predictive power, as suggested by their overprediction of the data. See Comments on Q1 and Q5 below.

2. Are the selected input parameters acceptable for their use?

Not relevant; see Comment on Q5 below

3. Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?

Yes

4. Is the recommended weighting based on the EPRI (2004) class weights acceptable?

Not relevant; see Comment on Q5 below

5. Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?

None exist now; it is preferable to develop an empirically calibrated model. See Comment on Q5 below.

6. Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to PSHA at a site in southern Florida from Caribbean seismic sources?

The Gulf Coast region GMPE is more appropriate; see Comment on Q5 below

7. Do you have any other comments?

Comment on Q1. Motazedian and Atkinson (2005) and the Caribbean Model

Motazedian and Atkinson (2005), page 77, state that:

"the ***Puerto Rico*** relations are based on the combination of events of all types. Crustal events have contributions to the Puerto Rico relations ***as well as interface and in-slab events***. Due to the limited data precision for Puerto Rico events, it is not feasible to distinguish between event types in most cases. Thus, the Puerto Rico ground motions are ***region-specific***, but the attenuation is averaged over all types of events." The in-slab events have depths as large as 200 km.

The bold italics are my emphasis, and I interpret Puerto Rico as not including the whole Caribbean region per Figure 1 and my Comments on Q5. I think that this statement renders the Motazedian and Atkinson (2005) model unsuitable for use in representing Caribbean earthquake ground motions at the Florida site. This unsuitability is manifested in its large degree of overprediction of most of the recorded ground motions (see Table 1).

Comment on Q5. Alternative Empirically Calibrated Model from Recorded Ground Motion Data

The need for an alternative empirically calibrated model is suggested by the following analysis of the source characteristics of the earthquakes (listed in Table 1 and derived from source parameters provided by Nick Gregor in Appendix 1) whose recorded ground motions were used for comparison with the candidate models. The path continuity is inferred from Figure 1, in which dark blue regions indicate oceanic crust and paler blue offshore regions indicate continental crust. The path continuity is relevant because, for distances beyond about 70 km, physics-based ground motion prediction equations for crustal earthquakes are based on the propagation of waves that are trapped in the crustal waveguide; in ENA these waves are called Lg waves. Discontinuity in the waveguide due to crustal thinning or thickening can lead to drastic reduction in the efficiency of the waveguide. If the earthquake occurs below the crust (i.e. in the mantle), then the crustal waveguide is not primarily involved in controlling the seismic wave propagation to the site. In that case, the attenuation of ground motion would instead be controlled by the seismic velocity gradient of the upper mantle (the gradient returns the seismic waves back to the surface through critical reflection phenomena). I am not aware of any ground motion prediction models that address mantle earthquakes (other than ones for slab earthquakes in subduction zones, which would seem to be too deep and tectonically different to be suitable here).

Table 1. Tectonic Environment of Recorded Earthquakes

Event	**Depth (km)**	**Mechanism / Tectonic Environment**	**Path Continuity**	**Recorded /Model ground motion:**	
				Gulf Coast	**Caribbean**
Caribbean Sea	12	Strike-slip on transform fault in oceanic mantle	Very low	Consistent	Lower
Gulf of Mexico	29.6	Intraplate thrust in oceanic mantle	Low	Higher	Consistent
South of Cuba	12.6	Strike-slip on transform fault in oceanic mantle	Very low	Consistent	Lower
N. of Honduras	12.0	Strike-slip on transform fault in continental - oceanic transition	Very low	Consistent	Lower
Haiti	12.0	Strike-slip in continental crust	Very Low	Consistent	Lower

* recorded ground motions with respect to Gulf Coast model

From Table 1 we can see that none of the five earthquakes is a crustal earthquake with a continuous crustal path to Florida, which is the condition on which all of the considered GMPE's is based. The first three earthquakes almost certainly occurred within the mantle, all with low or very low path continuity. The fourth occurred near a continental - oceanic transition with very low path continuity. Only the fifth, the Haiti earthquake, occurred in continental crust but it also has very low path continuity.

I infer that, for four of the events, the combination of very low path continuity and occurrence below the crust (except for the Haiti event) and causes the rapid rate of attenuation of their ground motions, consistent with the Gulf Coast ground motion model. Only the Gulf of Mexico event, which has low (but not very low) path continuity, has ground motions whose rate of attenuation is consistent with the Caribbean model, and even for that event, the recording in Florida is consistent with the higher of the Gulf Coast models. The relatively high ground motions of this event may reflect the high strength of the intraplate upper mantle, and may not be representative of the lower strength of the shallow upper mantle of the other three mantle events, which are all on or near plate margins.

We have thus shown that the physical basis of the Motazedian and Atkinson (2005) model renders it unsuitable for predicting the ground motions of earthquakes that occur in the mantle or whose waves propagate across path discontinuities or both, and that this lack or predictive power seems to be manifested in their overprediction of the ground motions recorded from at least four of the five earthquakes.

In view of the lack of predictive power of the Motazedian and Atkinson (2005) model and the Caribbean model derived from it, I think it would be preferable to select a model that is consistent with the recorded ground motion data. The Gulf Coast region model seems to form the best starting point for such a model.

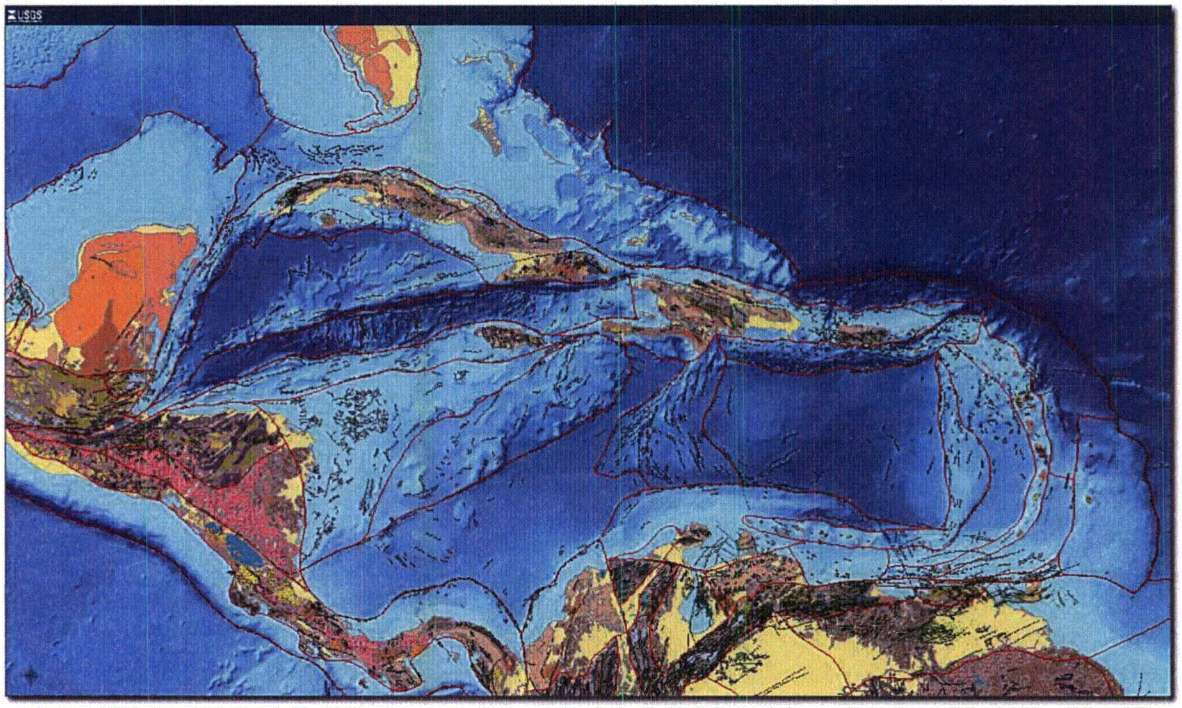

Figure 1. Tectonics and Crustal Structure of the Caribbean Sea Region. Source: http://escweb.wr.usgs.gov/share/mooney/training%20courses.html#Caribbean; http://escweb.wr.usgs.gov/?attach_external_tab&99960320&4&0&0&0&0&Google%20Chrome%20Frame

Appendix 1. Inference of Tectonic Environment of Analyzed Earthquakes

12/14/2004 (M6.8)-Harvard Caribbean Sea
Latitude: 19.050
Longitude: -81.520
Depth = 12.0 km
Fault Plane 1 (Strike, Dip, Rake): 258.0, 84.0, -2.0
Fault Plane 2 (Strike, Dip, Rake): 349.0, 88.0, -174.0

Tectonics: Strike-slip on transform fault in Oceanic mantle?

09/10/2006 (M5.9)-GCMT Gulf of Mexico
Latitude: 26.32
Longitude: -86.84
Depth = 29.6 km
Fault Plane 1 (Strike, Dip, Rake): 324.0, 28.0, 117.0
Fault Plane 2 (Strike, Dip, Rake): 114.0, 65.0, 77.0

Tectonics: Thrust in oceanic mantle?

02/04/2007 (M6.2)-GCMT South of Cuba
Latitude: 19.490
Longitude: -78.340
Depth = 12.6 km
Fault Plane 1 (Strike, Dip, Rake): 257.0, 76.0, -9.0
Fault Plane 2 (Strike, Dip, Rake): 349.0, 81.0, -166.0

Tectonics: Strike-slip on transform fault in Oceanic mantle?

05/28/2009 (M7.3)-GCMT North of Honduras

Latitude: 16.500
Longitude: -87.170
Depth = 12.0 km (Fixed)
Fault Plane 1 (Strike, Dip, Rake): 63.0, 60.0, -7.0
Fault Plane 2 (Strike, Dip, Rake): 156.0, 84.0, -150.0

Tectonics: Strike-slip on transform fault in continental – oceanic crust transition?

01/12/2010 (M7.0)-GCMT Haiti
Latitude: 18.610
Longitude: -72.620
Depth = 12.0 km (Fixed)
Fault Plane 1 (Strike, Dip, Rake): 250.0, 71.0, 22.0
Fault Plane 2 (Strike, Dip, Rake): 152.0, 69.0, 159.0

Tectonics: Strike-slip in Continental crust?

Response to Caribbean GMPE Questions by Robert Youngs

1. Are the newly developed Caribbean GMPEs acceptable for modeling ground motions in the Caribbean region for the project site located in Southern Florida for the PSHA study?

Response: The models developed from simulation appear to be reasonable. The comparisons with recorded motions indicate that they may slightly over estimate ground motions, which is OK.

2. Are the selected input parameters acceptable for their use?

A comparison of the Chen and Atkinson (2002) amplification functions with those used to develop CEUS models should be made to confirm their consistency. You want the model to be predicting ground motions for site conditions similar to those of EPRI (2004)

3. Is the recommended sigma value (i.e., 0.645 natural log units) acceptable?

Response: There does not appear to be a strong basis for the 0.645 and it is intended for use in Puerto Rico. A more preferable model with a stronger basis may be the EPRI (2006) model for CENA or some simplification of that model, perhaps using the final NGA (2008) results.

4. Is the recommended weighting based on the EPRI (2004) class weights acceptable?

Yes, roughly equal weight for 1 versus 2 corner is reasonable

5. Are there any other GMPE models which should be considered for the PSHA contribution from Caribbean sources?

Response: The USGS uses WNA GMPEs for modeling ground motions in Puerto Rico. It may be useful to compare the predictions from the NGA models adjusted to CEUS hard rock conditions using published factors (e.g. Atkinson and Boore, BSSA 2011) with the developed models at least in a distances of about 200 evaluate whether they predict higher or lower ground motions.

6. Is either the Mid-Continent or Gulf Coast region GMPE from EPRI (2004) more appropriate for use in the evaluation of the contribution to PSHA at a site in southern Florida from Caribbean seismic sources?

Response: I do not see any reason to consider the EPRI (2004) models to be more appropriate than the Caribbean model developed for the Turkey Point study. The comparisons with data shown in the figures confirms that.

7. Do you have any other comments?

Response:

Yes, see below

(a) The presentation of the comparisons on Figures 1-7 makes it very difficult to distinguish among the various relationships. It would perhaps be more useful to compare the median models of the EPRI (2004) clusters with the three base case Caribbean relationships.

(b) It is not stated why the EPRI (2004) Cluster 4 model is not included in the comparisons. It is appropriate for large magnitude earthquakes, which are the type of earthquakes from the Caribbean sources that contribute to the hazard at Turkey Point.

(c) Some description of the site conditions at the Florida DWPF station should be included. This station has the appropriate path for Caribbean earthquakes recorded in Florida, but what about site conditions or expected amplification from hard rock?

NRC RAI Letter No. PTN-RAI-LTR-037

SRP Section: 02.05.02 - Vibratory Ground Motion

Question for Geosciences and Geotechnical Engineering Branch 1 (RGS1)

NRC RAI Number: 02.05.02-3 (eRAI 5896)

FSAR Subsection 2.5.2.4.4.3.1 describes summary information related to the SSHAC Level 2 study on new seismic source models for the Cuba and northern Caribbean region. In accordance with NUREG-0800, Standard Review Plan, Chapter 2.5.2, "Vibratory Ground Motion", and Regulatory Guide (RG) 1.208, "A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion," please provide the complete SSHAC documentation detailing specifically:

a. Procedures and any assumptions made in developing the Caribbean seismic sources,

b. The questionnaire used in obtaining expert opinions,

c. The TI any advisory groups and/or peer reviewers used,

d. How the experts' opinions were integrated into the development of the final models. Discuss expert opinions and/or suggestions that were left out of the final model and justifications for doing so,

e. How conflicting opinions among the experts were dealt with,

f. How the final models represent the consensus of the informed community

FPL RESPONSE:

a) Procedures and any assumptions made in developing the Caribbean seismic sources

A seismic source characterization of Cuba and the northern Caribbean region for use in the Turkey Point Units 6 & 7 project was developed through the use of the Senior Seismic Hazard Analysis Committee (SSHAC) Level 2 process, defined in SSHAC (1997) (FSAR Reference 318). The SSHAC developed a formal process for conducting expert assessments and the use of expert judgment to incorporate uncertainties in probabilistic seismic hazard analysis (PSHA) (SSHAC 1997). The goal of the SSHAC process is to "represent the center, the body, and the range of technical interpretations that the larger informed technical community would have if they were to conduct the study" (SSHAC 1997, p. 21) (FSAR Reference 318). The SSHAC process also identifies a clear definition of ownership of the input parameters into the PSHA, and hence, ownership of the PSHA results. Ownership means intellectual responsibility such that the regulator will know the individuals who are responsible for developing the PSHA.

SSHAC (1997) (FSAR Reference 318) defines four levels of effort for capturing the range of uncertainty by the informed technical community (ITC). These are termed Levels 1 through 4. With each increasing level, there is increasing direct involvement of the ITC and, thus, increasing confidence and documentation that the center, body, and range of uncertainty in the ITC have been captured. Regardless of level of study, however, the goal of the SSHAC process is "to provide a representation of the informed scientific community's view of the important components and issues and, finally, the seismic hazard" (SSHAC

1997, p. 26) (FSAR Reference 318). Moreover, "regardless of the scale of the PSHA study, the goal remains the same: to represent the center, the body, and the range that the larger ITC would have if they were to conduct the study" (SSHAC 1997, p. 21) (FSAR Reference 318).

FSAR Subsection 2.5.2.4.4.3 describes the seismic source characterization for Cuba and the northern Caribbean region developed for the Turkey Point Units 6 & 7 project. Development of this seismic source characterization followed the SSHAC Level 2 process. According to SSHAC (1997, p. 23) (FSAR Reference 318), a Level 2 study is appropriate for issues with "significant uncertainty and diversity," and for issues that are "controversial" and "complex." The use of the SSHAC Level 2 process for the Turkey Point Units 6 & 7 project is consistent with other COL applications and regulatory guidance.

The SSHAC Level 2 process utilizes an individual, team, or company to act as the Technical Integrator (TI). In a SSHAC Level 2 study, the TI is responsible for reviewing data and literature and contacting experts who have developed interpretations or who have specific knowledge of the seismic sources. The TI interacts with these resource experts to identify issues and interpretations and to assess the center, body, and range of informed expert opinion. In other words, the role of the TI is to "evaluate the viability and credibility of the various hypotheses with an eye toward capturing the range of interpretations, their credibilities, and uncertainties" (SSHAC 1997, p. 27) (FSAR Reference 318).

The SSHAC Level 2 process performed for the Turkey Point Units 6 & 7 project began with a comprehensive literature search and review performed by the TI team. Based on this literature review, the TI team developed an initial straw man seismic source characterization. Also based on this literature review, the TI team identified resource experts with specialized knowledge of the region. These resource experts span a wide range of disciplines, including geology, seismology, geodesy, and geophysics. FSAR Table 2.5.2-216 provides a list of the resource experts contacted as part of this process. The TI team conducted interviews with resource experts regarding seismic sources in Cuba and the northern Caribbean. Parts (b), (d), and (e) of this response provide additional discussion of the TI team's interactions with experts. During the course of its development, the seismic source characterization was presented to, and discussed with, the project Technical Advisory Group (TAG). Part (c) of this response provides additional discussion of the TAG and their interactive review of the source characterization.

The seismic source characterization of the northern Caribbean region developed for the Turkey Point Units 6 & 7 project includes a number of assumptions, as described below. This source characterization is designed to include the seismic sources in the northern Caribbean region capable of generating frequent large or great earthquakes that, given the site-to-source distances, are assumed to be the contributors to the site hazard. The seismic source model for the Cuba and northern Caribbean region includes the Cuba areal source and segments of the plate boundary, but does not include background zones for the modern plate boundary region (FSAR Figure 2.5.2-217). At its closest approach, the North America-Caribbean plate boundary lies approximately 420 miles (680 km) from the Turkey Point Units 6 & 7 project site. Segments of the plate boundary were modeled as fault sources. However, it was assumed that distant background sources covering areas of relatively sparse seismicity would not contribute to site hazard. Therefore, with the exception of Cuba, areal background sources were not developed for the Caribbean plate boundary region. This is similar to PSHAs developed for many eastern U.S. sites that

include the distant New Madrid seismic source but exclude some background sources that exist between the site and the New Madrid seismic source.

Additionally, it was assumed that the Phase 2 earthquake catalog is the most appropriate earthquake catalog for use in seismic source characterization, determination of seismicity rates for Cuba, and calculating hazard at the site. As described in FSAR Subsection 2.5.2.1.3, there are many earthquake catalogs covering the Phase 2 seismicity investigation region, but no single published catalog includes everything for assessing earthquake occurrence. Thus, several regional and global catalogs were combined to make a new catalog supplement. These catalogs cover different time, space, and magnitude ranges with varying accuracy.

b) The questionnaire used in obtaining expert opinions

The TI team conducted interviews with resource experts by phone, email, and/or face-to-face discussions. To provide a framework and starting point for these discussions, resource experts were given a standard questionnaire pertaining to the initial straw man seismic source characterization and key issues regarding seismic sources in Cuba and the northern Caribbean. This questionnaire is provided here as Enclosure A. The interviews with resource experts were not a formal process of expert interrogation to obtain from each expert all of the specific parameters and weights to be used in the model. Instead, the resource experts were encouraged to speak to their own areas of expertise.

c) The TI and advisory groups and/or peer reviewers used

The TI team assembled to develop the seismic source characterization for Cuba and the northern Caribbean region for the Turkey Point Units 6 & 7 project comprised four William Lettis & Associates, Inc., geologists:

- Dr. Ross Hartleb
- Mr. Roland LaForge
- Mr. Scott Lindvall
- Dr. Steve Thompson

Peer review for this process was provided by the project TAG. At TAG meetings 1 through 3, TAG members included:

- Dr. Robert Kennedy (RPK Structural Mechanics Consulting)
- Dr. William McCann (Earth Scientific Consultants)
- Mr. Donald Moore (Southern Nuclear Operating Company)
- Dr. J. Carl Stepp (Earthquake Hazards Solutions)
- Dr. Robert Youngs (Geomatrix Consultants, currently AMEC)

Additional guidance and peer review were provided during TAG meeting 4. TAG meeting 4 was convened to discuss issues related to the update to FSAR Sections 2.5.1, 2.5.2, and 2.5.3, including re-evaluation of the seismic source characterization for Cuba and the northern Caribbean region. TAG meeting 4 differed from previous TAG meetings by including members with more specialized knowledge of the tectonics of Cuba, the Caribbean region, and the eastern United States. TAG members for meeting 4 included:

- Prof. Robert Hatcher (University of Tennessee at Knoxville)
- Prof. John Lewis (George Washington University, emeritus)
- Prof. Paul Mann (University of Texas at Austin, currently University of Houston)
- Dr. William McCann (Earth Scientific Consultants)
- Dr. J. Carl Stepp (Earthquake Hazards Solutions)

d) How the experts' opinions were integrated into the development of the final models. Discuss expert opinions and/or suggestions that were left out of the final model and justifications for doing so.

As described above, the TI team developed an initial straw man seismic source model based on information available in the published literature. This initial straw man model and an accompanying questionnaire (Enclosure A) were transmitted to resource experts with specialized knowledge of the region for their review and comment. Based on discussions with, and guidance from, the resource experts regarding the initial straw man seismic source characterization, the TI team performed additional literature review and analysis and critical review of its initial straw man model. This new information was used by the TI team to revise the straw man model and to develop a preliminary seismic source characterization. The TI team then conducted follow-up interviews with some of the resource experts to modify or validate the preliminary seismic source characterization. Following this collection of additional data and information, the TI team conducted additional discussions with TAG reviewers at TAG meetings 1 through 3 to evaluate and finalize the proposed models for use in the PSHA. The TI team was responsible for combining the feedback from resource experts and TAG reviewers with data from the published literature to capture the range of technically defensible interpretations into the final seismic source characterization for Cuba and the northern Caribbean region.

The TI team presented the seismic source characterization, at varying stages of completion, at TAG meetings 1 through 3. The final seismic source characterization implemented in the PSHA was presented at TAG meeting 4 for review and comment. There were few conflicting opinions among resource experts and TAG reviewers involved in this SSHAC Level 2 effort. However, part (e) of this response (below) provides additional discussion of how conflicting opinions among experts were handled.

e) How conflicting opinions among the experts were dealt with

In general, there were few conflicting opinions among resource experts and TAG reviewers involved in this SSHAC Level 2 effort. The decision to model intraplate Cuba as an areal source, however, was a specific focus of interaction between the TI team and some resource experts. Likewise, this decision was an important topic of discussion between the TI team and the TAG, especially at TAG meeting 4.

In the initial straw man source characterization distributed to experts for their comments, Cuba was modeled using two areal sources and no fault sources, except along the modern plate boundary offshore of southernmost Cuba (Enclosure A). These two areal sources included a "West-Central Cuba" zone that covered most of the island and a "Southeast Cuba" zone that was restricted to the area of more concentrated seismicity in the southeastern-most portion of the island near the modern plate boundary (Enclosure A). This two-zone model for Cuba was subsequently revised for use in the FSAR such that

intraplate Cuba was modeled as a single areal source with a uniform seismicity rate based on events listed in the Phase 2 earthquake catalog for that area. The TI team's decision not to retain the separate Southeast Cuba zone is based on the significant distance from the site and that the modern plate boundary south of Cuba is modeled as individual fault sources.

In addition to the single areal source zone for Cuba, the model presented in the FSAR also includes multiple fault sources representing segments of the active North America-Caribbean plate margin south and east of Cuba (FSAR Figure 2.5.2-217). Most resource experts contacted provided little input and feedback regarding these modeling decisions for Cuba, citing lack of personal knowledge and/or the lack of available published information for Cuba.

In his role as a resource expert, Dr. Paul Mann suggested that the TI team consider the Pinar and La Trocha faults in Cuba as potential fault sources in the model. However, he also indicated to the TI team that, to his knowledge, slip rate and paleoseismic data are unavailable for these and other faults in Cuba. Dr. Mann informed the TI team that the Pinar fault is associated with a prominent and linear mountain front, but that he has walked along portions of the Pinar fault and did not observe any recent offsets along this fault zone. Based on this information, the TI team considered including the Pinar and La Trocha faults as seismic sources. Due to the lack of data regarding activity and slip rates for these faults, however, the TI team decided not to model these as independent fault sources.

In email correspondence to the TI team, one expert suggested that the TI team consider: (1) subdividing Cuba into numerous seismogenic zone sources (SZs), as described in Garcia et al. (2003) (FSAR Reference 254) and (2) implementing a smoothed seismicity approach for Cuba as described in Garcia et al. (2008) (FSAR Reference 255). Garcia et al. (2003) (FSAR Reference 254) present seismic hazard maps for Cuba that are based on SZs. Their SZs are elongated, areal seismic sources intended to represent potentially active faults or fault zones. The dimensions of these SZs vary, but are approximately 12–30 miles wide (20–50 km wide), with uncertainty in the boundaries that varies from zone to zone but that ranges from 1–10 km (0.6 to 6 miles) for sources in Cuba. Garcia et al.'s (2003) (FSAR Reference 254) assessments of seismicity rates for their SZs are not based on geologic- or geodetic-based fault slip rates because these data are lacking. Instead, Garcia et al.'s (2003) (FSAR Reference 254) SZs are large enough to envelop sufficient numbers of earthquakes to estimate separate rates of seismicity for each source from the earthquakes observed within that source. Maximum magnitude (Mmax) for their SZs varies from zone to zone and is based on either adding roughly 0.5 magnitude units to the largest observed earthquake in the zone or judgment informed by previous studies.

In all cases, Mmax for their SZs in intraplate Cuba ranges between M 5 and 7. With the exception of three SZs assigned Mmax of M 7, the remaining SZs are assigned only moderate Mmax values that range from M 5 to 6.5. Based on their SZ approach, Garcia et al. (2003) (FSAR Reference 254) present maps of expected levels of ground shaking with a 475-year return period. Garcia et al.'s (2003) (FSAR Reference 254) SZ approach predicts relatively high levels of ground shaking throughout much of southernmost Cuba near the modern plate boundary. In contrast, the "rest of the island is characterized by moderate values that do not represent the possibility of very severe damage at the specified annual probability level" (Garcia et al. 2003, p. 2,588) (FSAR Reference 254).

In a more recent study, Garcia et al. (2008) (FSAR Reference 490) present seismic hazard maps for Cuba that are based on a spatially smoothed seismicity approach, using correlation distances of 18 and 25 miles (30 and 40 km). According to Garcia et al. (2008) (FSAR Reference 490), the rationale for this change in approach is "to avoid drawing seismic sources in a region where the seismogenic structures are not well known" (p. 173) and "to avoid the subjective judgment involved when drawing SZs in a region where [it] is problematic to associate seismicity with tectonic features" (p. 178). Moreover, they state that "since the northern part of the Cuban region lies in an intraplate region and is characterized by a moderate seismicity, the association of earthquakes to faults is problematic and, consequently, the definition of SZs is based, in some cases, on subjective decisions" (p. 174). Garcia et al. (2008) (FSAR Reference 255) compare the results from the smoothed seismicity approach with those based on the Garcia et al. (2003) (FSAR Reference 255) SZ approach. To illustrate the differences between the two approaches, Garcia et al. (2008) (FSAR Reference 255) calculate the residual PGA with a 475-year return period between the smoothed seismicity approach and the SZ approach. The largest differences between the methods are located along the modern plate boundary near Hispaniola and in southernmost Cuba. Relative to the smoothed seismicity approach, the SZ approach yields equivalent or slightly higher values of PGA throughout most of Cuba away from the modern plate boundary, but these differences are "rather limited" (Garcia et al. 2008; p. 192) (FSAR Reference 255).

From this comparison, Garcia et al. (2008) (FSAR Reference 255) conclude that, relative to the smoothed seismicity approach, the SZ approach tends to result in slightly higher PGA values in northwestern Cuba. They indicate that "an improvement of the seismicity data collection would be welcome for a better knowledge of the seismicity in northwestern Cuba" (p. 193). Moreover, they indicate that "although the definition of SZs is positive because it focuses on understanding the regional tectonics, this exercise could be misleading when not supported by data. Consequently, a mixture of the two approaches would probably be the best solution: a seismotectonic approach for the more seismic areas and only seismicity elsewhere" (p. 174). According to Garcia et al. (2008) (FSAR Reference 255), "the northern intraplate region [of Cuba] is related to a moderate to low seismicity" (p. 182). This observation of low to moderate rates of seismicity in northern Cuba is consistent with observations made from the Phase 2 earthquake catalog, which indicate a higher concentration of earthquakes and higher magnitudes in southernmost Cuba at and near the modern plate boundary. Therefore, the Garcia et al. (2003) (FSAR Reference 254) approach of defining SZs may not be applicable to the moderate-to-low seismicity areas of northern Cuba.

As part of the SSHAC Level 2 process, the TI team considered various modeling approaches for intraplate Cuba, including: (1) a seismogenic zone approach like that described in Garcia et al. (2003) (FSAR Reference 254), (2) the characterization of fault sources in Cuba, and (3) the characterization of a large areal zone or zones, with or without a smoothed seismicity approach. The TI team's decision not to implement an SZ approach was based on the recognition of the scant geologic data and few earthquakes in this region. The TI team's decision was also based on the assessment that the level of detail published on faults in Cuba was insufficient to confidently create SZs for the network of faults in intraplate Cuba and have confidence that the poorly located diffuse seismicity can be associated with a fault-like source or large areal sources. The primary reasons why the TI

team did not define individual faults as fault sources are the lack of published slip rate information and the paucity of geologic data that could be used to independently estimate slip rates for fault sources.

Likewise, the TI team considered adopting a smoothed seismicity approach for Cuba as described in Garcia et al. (2008) (FSAR Reference 255). The TI team's decision not to implement the smoothed seismicity approach was based on: (1) the TI team's assessment that a simpler, uniform rate approach is appropriate for Cuba, given that the intent is to quantify seismic hazard at a distant site in southernmost Florida, and (2) the smoothed seismicity approach would isolate the higher rates of seismicity in southeastern Cuba and more distant to the site and could be viewed as a non-conservative modeling assumption.

The decision to model intraplate Cuba in the FSAR as a single areal source zone with a uniform seismicity rate was discussed during TAG meetings 1 through 3. This decision was confirmed by the reviewers at TAG meeting 4. At meeting 4, TAG member Prof. Robert Hatcher suggested that the TI team consider including fault sources for intraplate Cuba away from the modern plate boundary. At that time, Prof. Robert Hatcher indicated that he is neither an expert on source characterization, nor an expert on the earthquake geology of Cuba. In the discussions that followed, the TAG at meeting 4 reached consensus that the single areal source approach is the most defensible, given: (1) the lack of knowledge regarding slip rates, geometries, and maximum magnitudes for individual faults in intraplate Cuba, and (2) the fact that this seismic source characterization is intended for use at a site in southern Florida, as opposed to a site in Cuba.

f) How the final models represent the consensus of the informed community

Through use of the SSHAC Level 2 process, the TI team developed a seismic source characterization of Cuba and the northern Caribbean region that is intended for use at the Turkey Point Units 6 & 7 site in southernmost Florida. The development of this characterization is based on literature reviews and interactions with both resource experts and the project TAG. The intent of this process was to represent the center, body, and range of technical interpretations that the larger ITC would have if they were to conduct the study.

There was general agreement among most of the resource experts, the project TAG, and published literature that the SSHAC Level 2 seismic source characterization presented in the FSAR represents the consensus of the ITC, especially with respect to the characterization of fault sources associated with the modern North America-Caribbean plate boundary. However, this seismic source characterization departs from some earlier published studies that quantify seismic hazard in Cuba from sources within and around Cuba. For example, Garcia et al. (2003) (FSAR Reference 254) and Garcia et al. (2008) (FSAR Reference 255) quantify seismic hazards in Cuba using a seismogenic zone approach and a smoothed seismicity approach, respectively.

The TI team's decision to not model individual faults in Cuba as seismic sources was due to a lack of geologic slip rate information. The TI team also did not choose to model faults as narrow SZs, and establish rates by counting seismicity within those zones, similar to the approach used by Garcia et al. (2003) (FSAR Reference 254). For the portions of northern Cuba within the site region and for much of Cuba well beyond the site region there is little geologic information and seismicity with which to characterize fault or SZ sources. Garcia et al. (2008) (FSAR Reference 255) caution that the SZ approach can be misleading in

areas of scant geologic data and few earthquakes. They also suggest that the SZ approach is more applicable for "more seismic areas" like southernmost Cuba nearest the modern plate boundary. For southernmost Cuba where the SZ approach may be more applicable according to Garcia et al. (2008) (FSAR Reference 255), the TI team retained a single areal source zone and decided not to model fault or SZ sources due to the significant distance from the site. The TI team's characterization of the modern plate boundary south of Cuba as individual fault sources is in agreement with published literature and expert judgment captured by the SSHAC Level 2 process.

This response is PLANT SPECIFIC.

References:

None

ASSOCIATED COLA REVISIONS:

The following COLA changes are identified as a result of this response:

The text in FSAR Subsection 2.5.2.4.4.3.2.1, third paragraph, will be revised as follows in a future update of the FSAR:

Recent peer-reviewed literature provides support for the assessment of the lack of knowledge regarding the state of fault mapping in Cuba. For example, Cotilla-Rodriguez et al. (Reference 321, p. 327) states, "...the detailed association between destructive earthquakes and active tectonic features is extremely complex and not known in depth [...] there is not a close correlation of seismic events with individual faults in Cuba." Furthermore, **Cotilla-Rodriguez** et al. (Reference 321, p. 331) states, "...most [historical, pre-instrumental earthquakes] have scarce data and do not permit a clear association to a seismic zone. There is no uniform knowledge about the historical seismicity of Cuba." ~~Additionally, recent peer-reviewed seismic hazard studies of Cuba describe a shift from a probabilistic approach that defined individual faults and source zones (Reference 254), to newer studies (Reference 255) performed by many of the same researchers that use spatially smoothed seismicity in place of source zones. The rationale for this shift is, "...to avoid drawing seismic sources in a region where the seismogenic structures are not well known" (Reference 255, p. 173). Moreover, "...since the northern part of the Cuban region lies in an intraplate region and is characterized by a moderate seismicity [sic], the association of earthquakes to faults is problematic and, consequently, the definition of [seismic sources] is based, in some cases, on subjective decisions" (Reference 255, p. 174).~~

Garcia et al. (Reference 254) present seismic hazard maps for Cuba that are based on seismogenic zone (SZ) source zones. Their SZs are narrow, elongated, areal seismic sources intended to represent potentially active faults. Seismicity rates for these "fault-like" SZs are not based on geologic- or geodetic-based fault slip rates because these data do not appear to exist. Instead, Garcia et al.'s (Reference 254) SZs are large enough to envelop sufficient numbers of earthquakes to estimate separate rates of seismicity for each source from the earthquakes observed within that source. In a subsequent publication, Garcia et al. (Reference 255) compare the results of their earlier SZ approach with those obtained by their implementation of a

smoothed seismicity approach to hazard. Relative to the results obtained from their smoothed seismicity approach, Garcia et al. (2008) conclude that the seismotectonic zone approach tends to result in slightly higher PGA values in northwestern Cuba. They indicate that "an improvement of the seismicity data collection would be welcome for a better knowledge of the seismicity in northwestern Cuba" (Reference 255, p. 193). Moreover, they indicate that "although the definition of SZs is positive because it focuses on understanding the regional tectonics, this exercise could be misleading when not supported by data. Consequently, a mixture of the two approaches would probably be the best solution: a seismotectonic approach for the more seismic areas and only seismicity elsewhere" (Reference 255, p. 174). According to Garcia et al. (2008) (Reference 255, p. 182), "the northern intraplate region [of Cuba] is related to a moderate to low seismicity." This observation of low to moderate rates of seismicity in northern Cuba is consistent with observations made from the Phase 2 earthquake catalog, which indicates a higher concentration of earthquakes and higher magnitudes in southernmost Cuba at and near the modern plate boundary relative to the rest of the island. Therefore, Garcia et al.'s (Reference 254) seismotectonic zone approach may not be applicable to the moderate to low seismicity areas of northern Cuba.

ASSOCIATED ENCLOSURES:

Enclosure A – SSHAC Caribbean Questionnaire, dated May 19, 2008