Comparison of BC Hydro Subduction GMPE to Data from Recent Large Megathrust Earthquakes

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SUMMARY
As part of a BC Hydro system-wide seismic hazard study that began in 2007, Abrahamson et al. (2012) developed a new ground motion prediction equation (GMPE) for subduction zone earthquakes. The model was based on an updated dataset that also included data used in the development of a number of existing subduction zone GMPEs. Due to the absence of recorded events with magnitudes greater than M_w8.3, the magnitude scaling for M_w>8.3 was guided by numerical simulations and for M_w<8.3 by the empirical data.

Following development of the model, two megathrust events - the 2010 Maule Chile (M_w8.8) and the 2011 Tohoku Japan (M_w9.0) earthquakes occurred and provided an opportunity to evaluate the proposed magnitude scaling for M_w>8.3. Based on a residual analysis of the recorded empirical data, a period-dependent adjustment to the BC Hydro model was recommended to be consistent with the observed empirical data from these two megathrust events.

Keywords: Subduction, GMPE, Megathrust Earthquakes

1. INTRODUCTION

A key requirement of the BC Hydro study was to include ground motions from large (>M_w8.5) Cascadia subduction zone megathrust events in its probabilistic seismic hazard analysis (PSHA). However at the start of the project in 2007, the range in ground motions estimated from current state of practice GMPEs typically used in seismic hazard studies for large interface subduction zone earthquakes was substantial, especially for the larger magnitude range (e.g., M_w>8.5). Both numerical simulation data and empirical data have been used in the development of these GMPEs for large megathrust subduction earthquakes. Driven by the large observed range of predicted ground motions from current GMPEs and the availability of additional subduction empirical ground motion data, Abrahamson et al. (2012) amalgamated databases used to develop existing subduction zone GMPEs, updated it to include more recent events around the world, improved the metadata information, and developed a new ground motion model. Although the updated subduction ground motion database was larger and more diverse, there were no recorded events with magnitude greater than M_w8.3. The magnitude scaling of interface events for this new GMPE was sufficiently constrained by the empirical data for magnitudes as large as M_w8.3 and guided by the results of numerical simulations reported by Gregor et al. (2006) and Atkinson and Macias (2009) for magnitudes larger than M_w8.3.

Following initial development of the BC Hydro GMPE, two large interface earthquakes with magnitudes greater than M_w8.3 occurred. In 2010, the Maule Chile (M_w8.8) earthquake was recorded at 31 stations followed by the 2011 Tohoku Japan (M_w9.0) earthquake that was recorded at more than 360 stations. The availability of recordings from these two giant interface earthquakes provided an opportunity to ascertain how well the BC Hydro model predicts the empirical data. Based on an analysis of residuals of the empirical data from these two earthquakes, a period-dependent adjustment was recommended for the BC Hydro model for consistency with the data from this pair of megathrust events. The adjustment affects the large magnitude interface events only.

2. 2010 MAULE CHILE (M_w8.8) EARTHQUAKE

The February 27th, 2010 Maule Chile earthquake occurred off the western coast of Chile. The hypocenter was located approximately 115 km NNE of Concepcion and 335 km SW of Santiago. A total of 31 strong motion stations, each with a tri-axial strong motion accelerograph, at distances between 35 km and 680 km recorded the main event. For each station, the time histories were manually processed following a standard time history processing technique: mean removal, selection of filter corners based on Fourier amplitude spectra (FAS), bandpass filtering, and baseline correction. Horizontal acceleration response spectra and the corresponding geometric mean spectrum were computed for each pair of horizontal components of motion. Two stations located at rupture distances greater than 500 km to the north of the fault plane were excluded from the analysis based on their low signal to noise ratios observed in the original time histories.

Rupture distances were computed based on the finite fault plane listed in Table 1 (USGS, 2010). Estimates of site-specific V_{s30m} values for a third of the stations were obtained from either the BC Hydro database (Abrahamson et al., 2012) or the Arango et al., 2011 database. The V_{s30m} values for the remaining stations were based on an inverse distance weighting of the four closest data points given in the database on the Global USGS Slope Topography web site (USGS, 2011a). Figure 1 shows the distribution of V_{s30m} as a function of rupture distance for the stations used in the analysis. Most of the stations, which are all in the forearc region, have V_{s30m} and rupture distances less than about 800 m/s and 100 km, respectively.

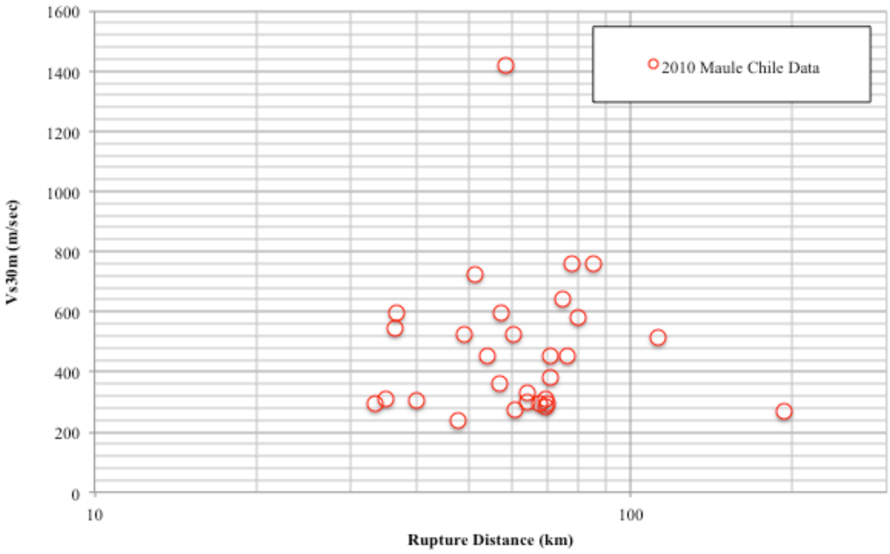

Figure 1. Distribution of V_{s30m} and rupture distances of selected stations in Chile used in the analysis.

Table 1. Finite Fault Parameters for the 2010 Maule Chile Earthquake (USGS, 2010).

Parameter	*Value*
Hypocenter Longitude	72.73 West
Hypocenter Latitude	35.909 South
Hypocenter Depth (km)	35
Fault Strike	17.5
Fault Length (km)	540
Fault Width (km)	200
Dip Angle	18

Comparisons of the 2010 Chile data with predictions of the BC Hydro model for PGA and T=1.0 sec spectral acceleration are shown in Figures 2a and 2b respectively for rock sites (blue diamonds) with V_{s30m}>360 m/s and soil sites (red circles) with V_{s30m}<360 m/s. The attenuation curves in each figure correspond to a V_{s30m} = 500 m/s for rock conditions (blue lines) and a V_{s30m} = 270 m/s for soil conditions (red lines) for a magnitude M_w8.8 event recorded at forearc sites. Overall the distance attenuation is similar between model predictions and the data. The observed average shift between the GMPE attenuation curves and the empirical data will be estimated based on the average event terms from the residuals presented in a later section.

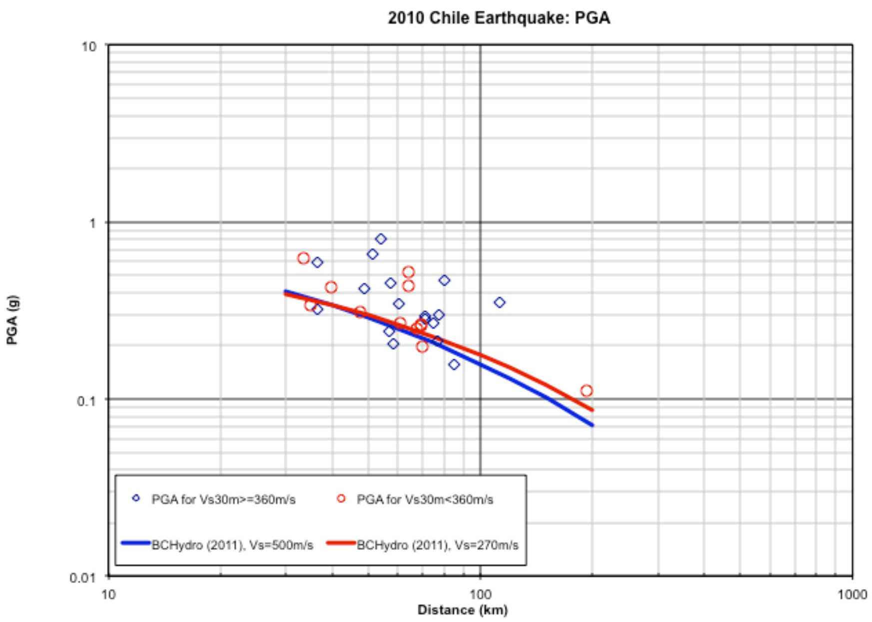

Figure 2a. Comparison of PGA attenuation from the 2010 Chile earthquake and the BC Hydro GMPE.

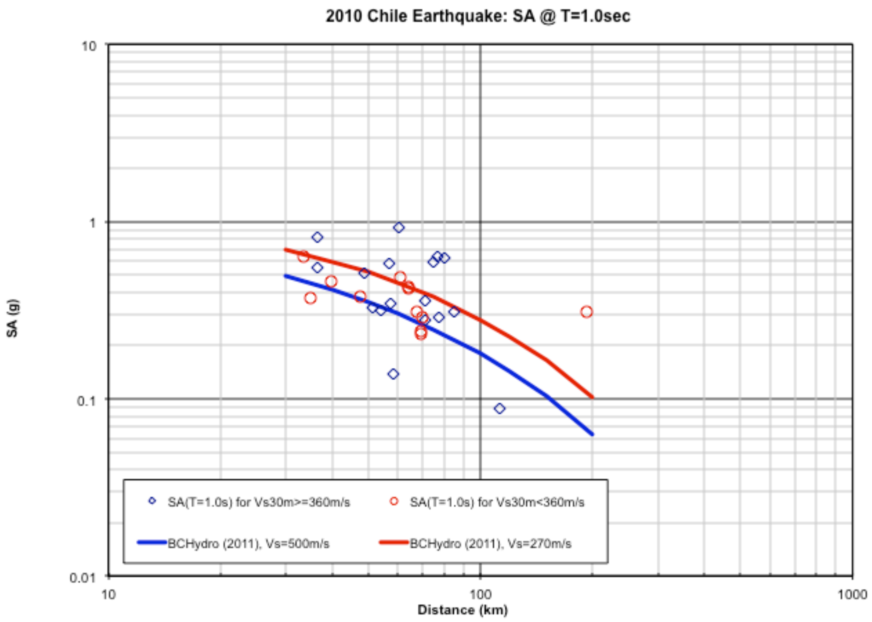

Figure 2b. Comparison of the T=1.0 sec spectra acceleration attenuation from the 2010 Chile earthquake and the BC Hydro GMPE model.

3. 2011 TOHOKU JAPAN (M_w9.0) EARTHQUAKE

The March 11th, 2011 Tohoku Japan earthquake was located off the eastern shore of Japan with the hypocenter located approximately 130 km east of Sendai and 375 km northeast of Tokyo (USGS, 2011b). With more than 360 stations recording the event as part of the KNET (http://www.k-net.bosai.go.jp/) and Kik-Net (http://www.kik.bosai.go.jp/) arrays in Japan, the Tohoku earthquake is the best well-recorded large megathrust subudction earthquake. The Kik-net array consists of surface and downhole instruments. For this analysis, only the surface recordings were analyzed.

Based on the finite-fault parameters listed in Table 2, rupture distances of 44 km to almost 1,000 km were computed for the 369 strong motion stations used in the analysis. Site-specific V_{s30m} values of the stations were taken from the BC Hydro database (Abrahamson et al., 2012). The distribution of V_{s30m} and rupture distance is shown in Figure 3. Similar to the data from the 2010 Maule Chile event, the majority of stations have a site-specific V_{s30m} value less than 800 m/s. The distribution of rupture distance is fairly uniform between distances of 50 – 500 km. Japanese sites were also classified as being located in the forearc or backarc region based on a dividing line following the line of volcanoes on the islands of Japan. This same boundary was used for the database associated with the BC Hydro GMPE (Abrahamson et al., 2012).

Table 2. Finite Fault Parameters for the 2011 Tohoku Japan Earthquake (USGS, 2011b and Shao et al., 2011).

Parameter	*Value*
Hypocenter Longitude	142.369 East
Hypocenter Latitude	38.322 North
Hypocenter Depth (km)	32
Fault Strike	198
Fault Length (km)	475
Fault Width (km)	200
Dip Angle	10

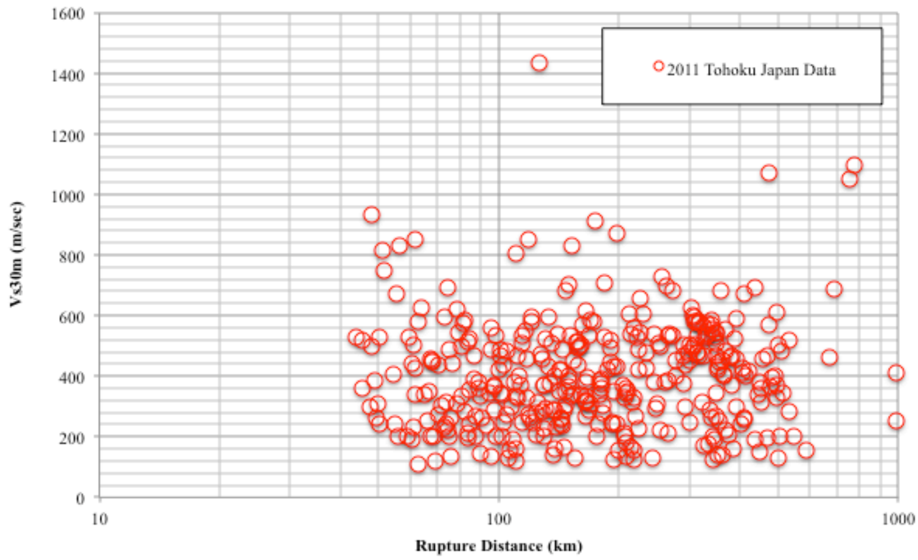

Figure 3. Distribution of selected stations from the 2011 Tohoku Japan earthquake used in the analysis.

A similar time history processing technique was used for Tohoku data. This processing consisted of a mean removal and the application of a high-pass 6th order Butterworth filter with a corner frequency frequency of 0.1 Hz (Dawood and Rodriquez-Marek, 2011).

A comparison of the Tohoku data for PGA and T=1.0 sec are shown in Figures 4 and 5. The data points are coded based on simplified rock and soil classification with the rock sites (blue diamonds) having V_{s30m}>360 m/s and the soil sites (red circles) with V_{s30m}<360 m/s. The attenuation curves plotted in each figure correspond to V_{s30m} = 500 m/s for rock conditions (blue lines) and V_{s30m} = 270 m/s for soil conditions (red lines) for a magnitude M_w9 event. The epistemic ΔC_1 terms for the GMPE (Abrahamson et al., 2012) are shown as dashed lines. Based on these plots, the PGA distance attenuation for forearc sites is stronger in the empirical data than currently modelled in the BC Hydro GMPE. However, for PGA from backarc sites and at T=1.0 sec for both forearc and backarc sites, the distance attenuation rates observed in the empirical data and predicted by the model are similar.

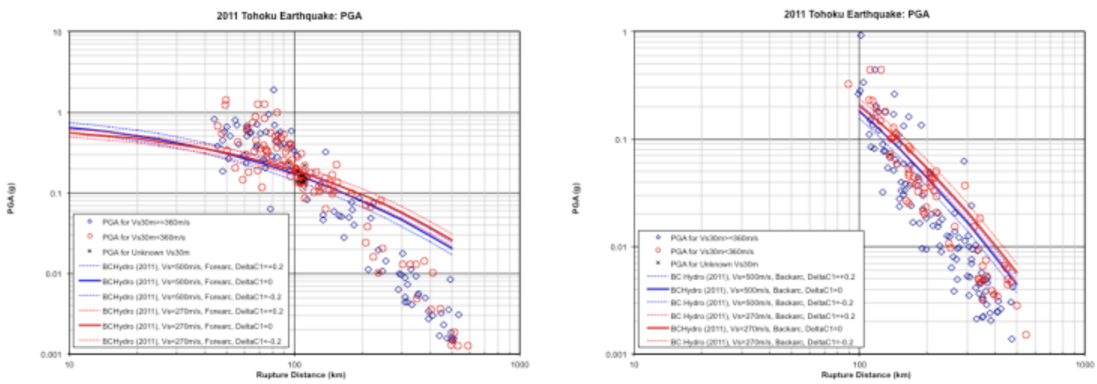

Figure 4. Comparison of PGA attenuation from the 2011 Tohoku earthquake and the BC Hydro GMPE. Forearc sites are shown on the left and backarc sites are shown on the right.

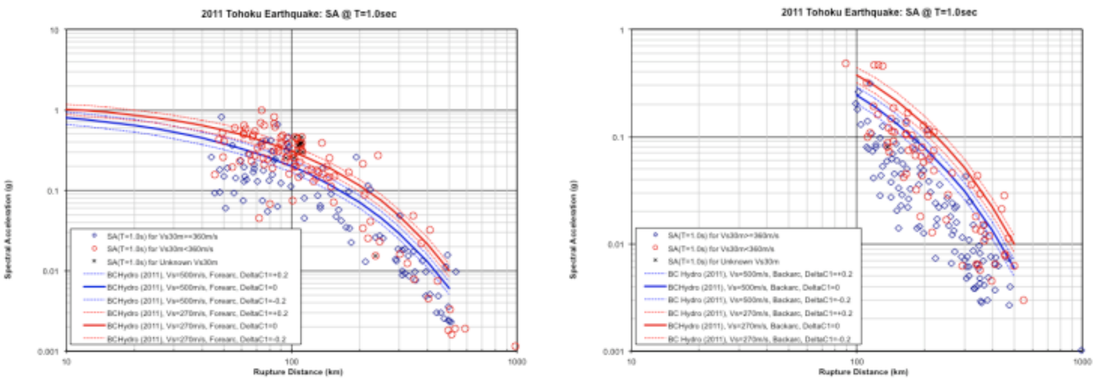

Figure 5. Comparison of the T=1.0sec attenuation from the 2011 Tohoku earthquake and the BC Hydro GMPE. Forearc sites are shown on the left and backarc sites are shown on the right.

4. RESIDUAL ANALYSIS

Residuals were computed between the empirical data from both events and the BC Hydro GMPE. For each residual calculation, the site-specific distance, V_{s30m}, and forearc/backarc classification values were used. Residuals were computed for a suite of 10 spectral periods between PGA and 3.0 seconds. For each earthquake, the event term and standard errors were computed at all ten spectral periods. For the Tohoku earthquake, the event terms were grouped using distance bins of 0 – 100 km and 100 – 200 km based on the observed different attenuation rates with distance (see Figures 4 and 5). The resulting event terms with their standard errors are shown in Figure 6.

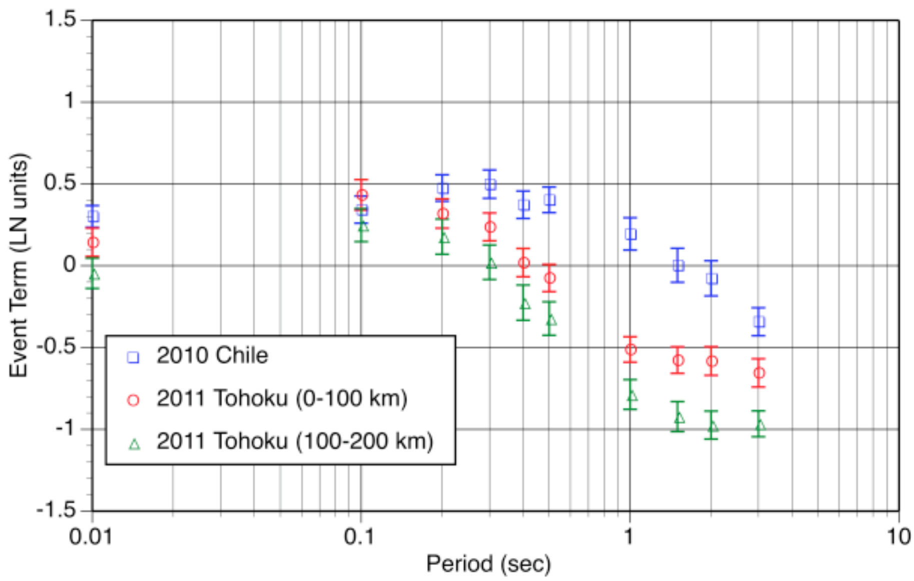

Figure 6. Event terms and standard errors as functions of spectral period from the 2010 Chile and 2011 Tohoku earthquakes.

The event terms computed from these two earthquakes are compared in Figure 7 with the event terms from the other earthquakes in the BC Hydro database (Abrahamson et al., 2012). Results for PGA and T=0.2 sec are shown in Figure 7a and the longer period results for T=1.0 and 3.0 sec spectral acceleration are shown in Figure 7b. Overall, these new event terms fall within the observed range of event terms from the entire dataset. However, a consistent pattern of positive event terms for short periods and negative event terms for longer periods are noted from the results of these two large magnitude events.

A hypothesis test was performed to test if the average of the event terms from the two earthquakes at the 10 spectral periods for a given distance range was from a distribution with zero mean and a standard deviation of 0.48 (smoothed τ from the BC Hydro subduction model). For this testing the known correlation between spectral periods was not considered and each of the 10 spectral periods was treated independently. In addition the standard deviation was divided by the square root of 2 based on having observations from the two earthquakes. The probability of observing a mean greater than or equal to the absolute value of the average event terms from the two earthquakes is given by:

$$P(|Mean\,Event\,Term| > x) = 1 - \Phi\left(\frac{x}{\tau}\right) \tag{4.1}$$

where x is the mean event term and Φ is the cumulative standard normal distribution. The results are presented in Table 3 for the Chile data and the two different distance bins from the Tohoku earthquake.

For the smallest distance bin of 0 – 100 km from the Tohoku event, the average confidence level across all spectral periods was about 13% whereas for the other distance bin of 100 – 200 km this average was closer to 25-30%. Based on these results, a change to ΔC_1 term of the BC Hydro GMPE was proposed (Abrahamson et al., 2012) to account for the observed differences between the median predictions and the empirical data from these two large interface earthquakes.

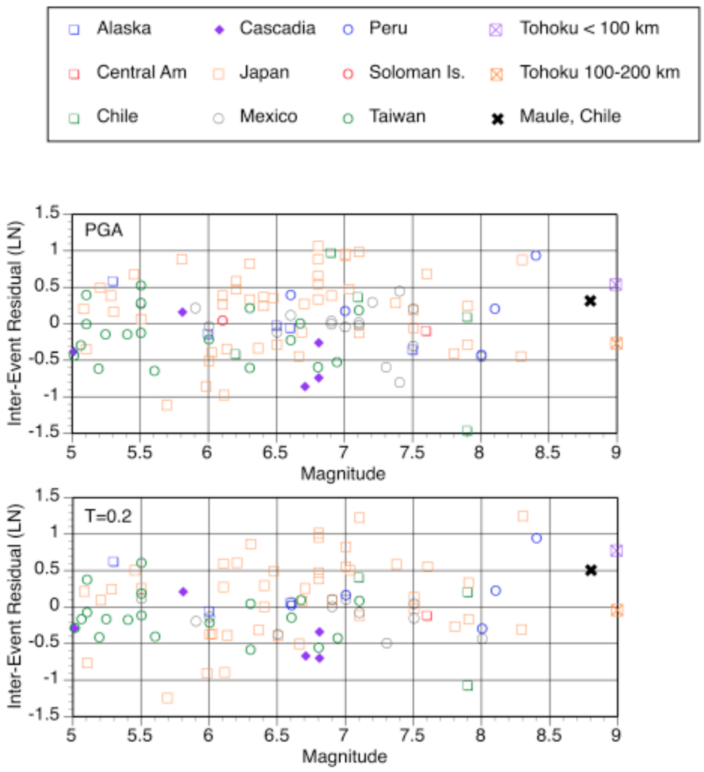

Figure 7a. Inter-event residuals for PGA and T=0.2 sec spectral acceleration from the BC Hydro dataset regression and the 2010 Chile and 2011 Tohoku events which were not used in the regression analysis for the BC Hydro GMPE.

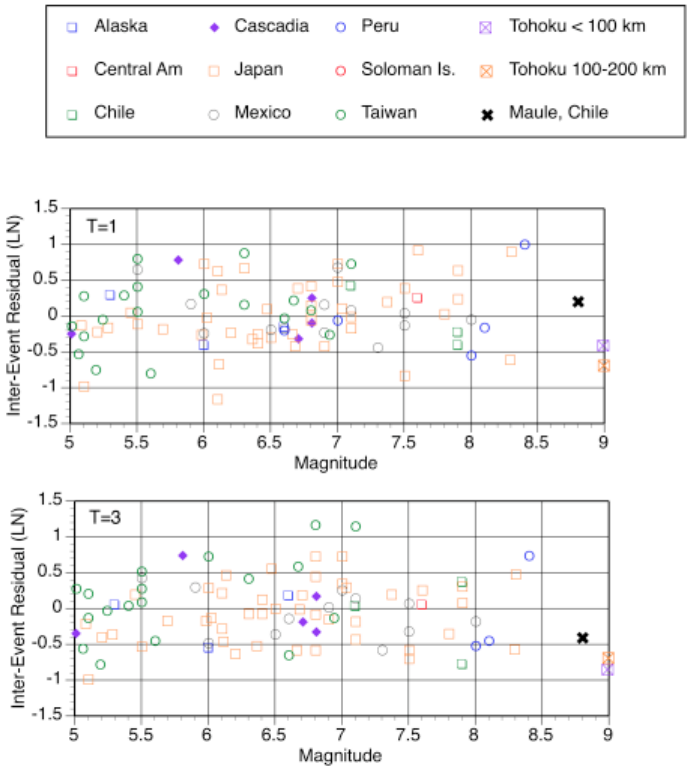

Figure 7b. Inter-event residuals for T=1.0 and T=3.0 sec spectral acceleration from the BC Hydro dataset regression and the 2010 Chile and 2011 Tohoku events which were not used in the regression analysis for the BC Hydro GMPE.

Table 3. Probability of observing a mean greater than average event terms from Chile and Tohoku earthquakes.

Chile Data and Tohoku Data (Distances Less than 100 km)		
Period (sec)	Average Event Term	Probability of average event term >= |observed|
PGA	0.4214	10.72%
0.1	0.6150	3.50%
0.2	0.6251	3.28%
0.3	0.5457	5.40%
0.4	0.3716	13.68%
0.5	0.3052	18.43%
1.0	-0.1112	37.17%
1.5	-0.2963	19.14%
2.0	-0.3751	13.45%
3.0	-0.5964	3.94%
Chile Data and Tohoku Data (100<Distances<200 km)		
Period (sec)	Average Event Term	Probability of average event term >= |observed|
PGA	0.0178	47.91%
0.1	0.1690	30.93%
0.2	0.2168	26.15%
0.3	0.1897	28.82%
0.4	0.0132	48.45%
0.5	0.0033	49.62%
1.0	-0.2496	23.11%
1.5	-0.3813	13.07%
2.0	-0.4104	11.33%
3.0	-0.5195	6.30%

5. CONCLUSION AND RECOMMENDATIONS

An analysis of residuals between strong ground motion data from two large megathrust earthquakes and the BC Hydro GMPE (Abrahamson et al., 2012) has been performed. The magnitude scaling for large interface earthquakes in the BC Hydro GMPE was constrained by numerical simulations for magnitudes greater than M_w8.3 due to a lack of empirical data for events larger than this upper magnitude for the time period of earthquakes contributing to the empirical database. Following the development of the empirical database, however, two recent large megathrust events have provided empirical data for M_w>8.3. Based on the residual analysis of these data, a period-dependent adjustment to the ΔC_1 model is recommended for the BC Hydro GMPE (Abrahamson et al., 2012). This adjustment results in an increase in the short period ground motions and a decrease in the longer period ground motions from the initial BC Hydro GMPE. As an example, the median acceleration response spectra from a magnitude M_w9.0 earthquake at a rupture distance of 60 km with a V_{s30m} = 800 m/s are shown in Figure 8. The red and blue lines are based on the proposed adjusted and current ΔC_1 values respectively. The results of this study do not change the predicted median ground motions from intraslab events.

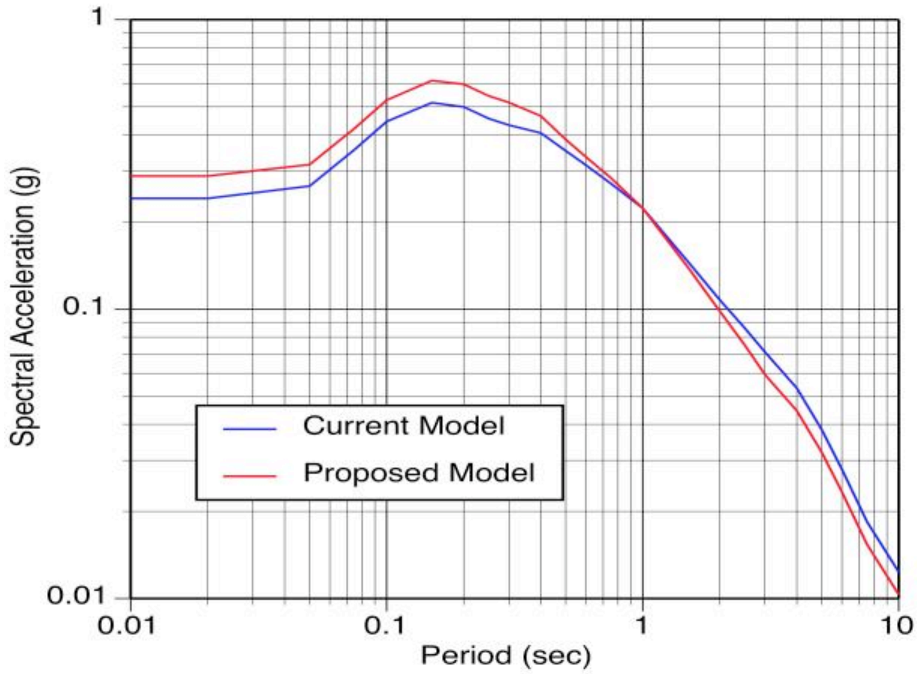

Figure 8. Median spectra for a M_w9 event at a rupture distance of 60 km with a V_{s30m} = 800 m/s using both the BC Hydro GMPE (blue line) and the recommended ΔC_1 adjusted spectra (red line) based on the residual analysis results.

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