

Vertical to Horizontal (V/H) Ratios for Large Megathrust Subduction Zone Earthquakes



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SUMMARY

Vertical design ground motions are typically developed following two different procedures – application of vertical to horizontal (V/H) spectral ratios applied to the horizontal design ground motions or vertical ground motion estimates from vertical component ground motion prediction equations (GMPE). The V/H approach is limited by the lack of V/H spectral ratio models for subduction zone events. However, crustal V/H models have been developed and the applicability of a recent crustal earthquake V/H model is tested with strong ground motion data from two large megathrust earthquakes: 2010 Maule Chile (M_w 8.8) and 2011 Tohoku Japan (M_w 9.0).

A statistical comparison between empirical V/H spectral ratios from these two earthquakes and a V/H spectral ratio model for crustal earthquakes is presented. Based on the comparisons, the V/H model for crustal sources is recommended as an applicable model for estimating vertical motions from large megathrust subduction zone earthquakes (up to M_w 9.0).

Keywords: V/H Ratio, Megathrust, Subduction

1. INTRODUCTION

One key result from seismic hazard ground motion studies for engineering projects is the development of design acceleration response spectra. Typically, horizontal design spectra are developed based on either a probabilistic or deterministic analysis using available models of the significant seismic sources in the project region and appropriate ground motion prediction equations (GMPEs). The availability of numerous empirical GMPEs allows the direct computation of the horizontal component of motion within the framework of a seismic hazard analysis. However, vertical ground motions are typically developed following two different procedures: application of vertical to horizontal (V/H) spectral ratios to horizontal ground motions or computation of vertical spectrum from GMPEs developed for the vertical component. Due to the lack of vertical component GMPEs, the latter approach cannot be used for sites for which the controlling earthquakes are large megathrust subduction zone earthquakes (e.g., in the Pacific Northwest region). Even if vertical component GMPEs were available, this latter approach is not preferred for use in a probabilistic hazard study because the horizontal and vertical ground motions are typically controlled by different earthquake scenarios so that the vertical uniform hazard spectrum (UHS) represents different earthquakes than the horizontal UHS. This poses a challenge in combining horizontal and vertical loads based on separate scenario events.

For locations where large megathrust earthquakes contribute significantly to the hazard, the V/H approach is also limited by the lack of V/H spectral ratio models for subduction ground motions.

During the last several years, both vertical GMPEs (Abrahamson and Silva, 1997; Campbell, 1997; Sadigh et al., 1997; Ambraseys and Douglas, 2003; Bozorgnia and Campbell, 2004; and Ambraseys et al., 2005) and V/H models (Gulerce and Abrahamson, 2011; Bozorgnia and Campbell 2004; Ambraseys and Douglas, 2003) have been developed. These new empirically based vertical and V/H models have lagged behind the development of horizontal component GMPEs and none are based on subduction zone earthquake ground motions. The recently published V/H model by Gulerce and Abrahamson (2011) [referred to as ‘GA2011’ for the remainder of this paper] represents an empirically based model that is consistent with the current state of practice GMPEs developed as part of the Next Generation Attenuation (NGA) study (Power et al., 2008). The GA2011 model was developed using the same crustal ground motion database (Chiou et al., 2008) that was used in the development of the NGA GMPEs and is consistent with the Abrahamson and Silva (2008) NGA GMPE for non-linear site response. The crustal NGA dataset does not contain reverse-faulting events with magnitude greater than 8 and as such the GA2011 model is limited to $M_w < 8$ for reverse events.

The key objective of this paper is to explore the applicability of the GA2011 V/H model not only to subduction earthquakes but also to large ($>M_w 8$) megathrust subduction zone earthquakes. Specifically, empirical recordings from two giant subduction zone earthquakes: 2010 Maule Chile ($M_w 8.8$) and 2011 Tohoku Japan ($M_w 9.0$) earthquake are compared with the predictions of the GA2011 model.

The 2010 Maule Chile ($M_w 8.8$) and 2011 Tohoku Japan ($M_w 9.0$) earthquakes significantly expanded the current database of strong ground motion recordings from large megathrust earthquakes. The Tohoku earthquake alone had 369 three component surface recordings and the Maule Chile earthquake had 31 three component surface recordings. Closest rupture distances for all of the stations were computed based on assumed fault planes for the two earthquakes. Each station in the dataset was assigned a V_{s30m} value based on a recently compiled subduction ground motion dataset (Abrahamson et al., 2012). A standard time history processing methodology was implemented and the empirical V/H spectral ratios were computed based on the geometric mean of the two horizontal components.

2. 2010 MAULE CHILE ($M_w 8.8$) EARTHQUAKE

The February 27th, 2010 Maule Chile earthquake occurred off the western coast of Chile as shown in Figure 1. The hypocenter was located approximately 115 km NNE of Concepcion, Chile and 335 km SW of Santiago, Chile. A total of 31 strong motion stations, each with three components of motion and distances between 35 and 680 km recorded this mainshock event. For each station, the time histories were manually processed following a standard processing technique: mean removal, selection of filter corners based on Fourier amplitude spectra (FAS), bandpass filtering and baseline correction. Using the processed time histories, the geometric mean of the response spectra of each pair of horizontal components of motions was computed. Stations that are located at rupture distances greater than 500 km to the north of the fault plane were removed from the dataset based on their low signal to noise levels observed in the recorded time histories.

Rupture distances were computed based on the finite-fault rupture plane listed in Table 1 (USGS, 2010). Estimates of site-specific V_{s30m} values for nine stations were obtained from either the BC Hydro database (Abrahamson et al., 2012) or the recently published database by Arango et al. (2011). The V_{s30m} values for the remaining stations were obtained from the Global USGS Slope Topography web site (USGS, 2011a) and based on an inverse distance weighting of the four closest data points given in the USGS database. Figure 2 shows the distribution of the recording stations as a function of V_{s30m} and rupture distance. The majority of the data used in the analysis is from stations with V_{s30m} and distances less than about 800 m/s and 100 km, respectively.

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

<i>Parameter</i>	<i>Value</i>
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

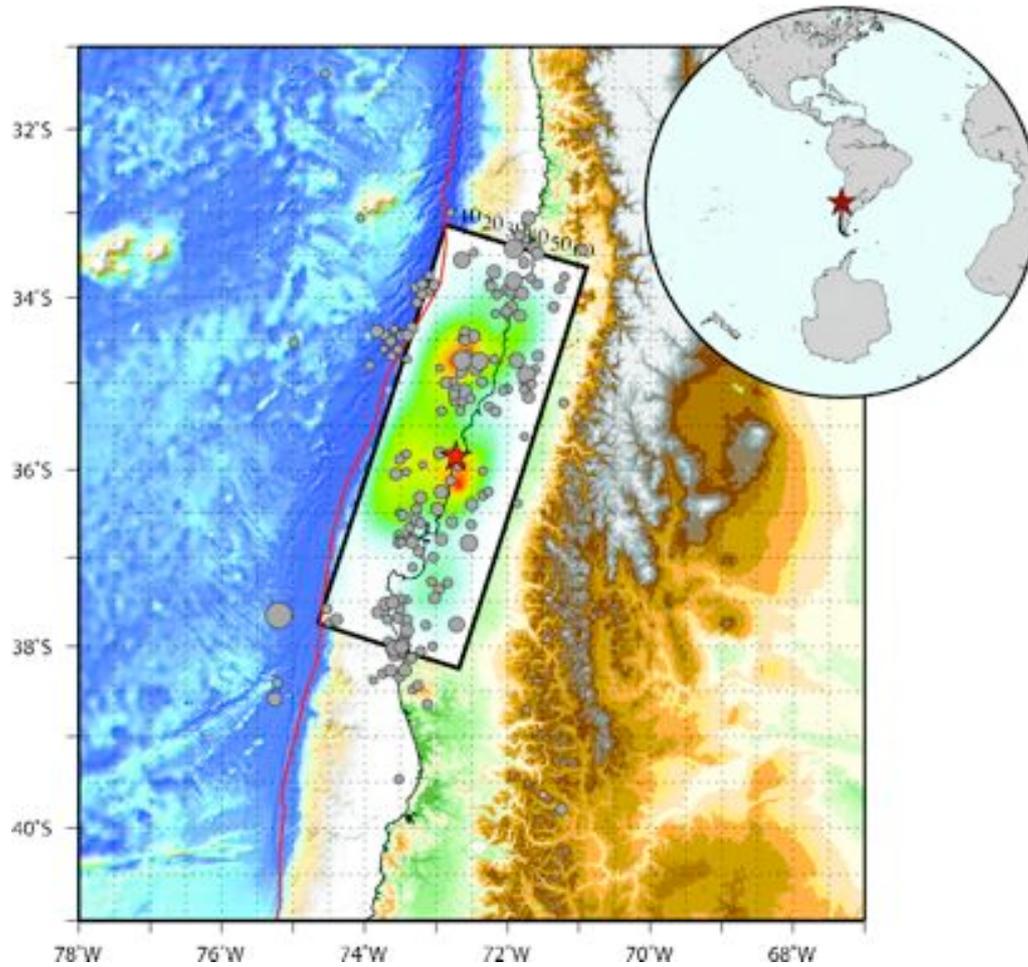


Figure 1. Slip inversion finite fault model from USGS (2010) for the 2010 Maule Chile earthquake. Aftershocks are indicated by grey solid dots and the epicenter is plotted as a red star.

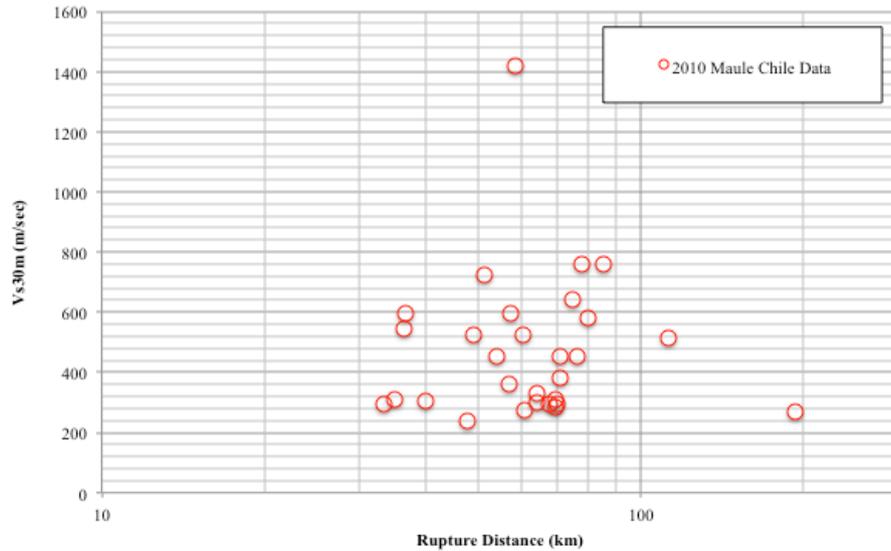


Figure 2. Distribution of selected stations from the 2010 Maule Chile earthquake used in the analysis.

3. 2011 TOHOKU JAPAN (M_w 9.0) EARTHQUAKE

The March 11th, 2011 Tohoku Japan earthquake was located off the eastern shore of Japan as shown in Figure 3. The hypocenter was located approximately 130 km east of Sendai and 375 km northeast of Tokyo (USGS, 2011b). This was the most well-recorded large megathrust subduction earthquake to have occurred 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 Kik-net array consists of both surface instrument and downhole instruments. For this analysis, only the surface recordings from these arrays were used.

The slip inversion (Shao et al., 2011), aftershock locations, and fault plane solutions are shown in Figure 3. Based on the finite-fault parameters listed in Table 2, rupture distances were computed for the 369 stations used in the analysis. These stations range in distances from 44 km to almost 1,000 km. Site-specific V_{s30m} values for recording stations were obtained from the BC Hydro database (Abrahamson et al., 2012). The distribution of V_{s30m} as a function of rupture distance is shown in Figure 4. Similar to the 2010 Maule Chile event, most stations have a site-specific V_{s30m} value of less than 800 m/s. The rupture distance distribution is fairly uniform between 50 km and 500 km.

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

<i>Parameter</i>	<i>Value</i>
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

A similar time history processing technique used for the Maule dataset was also applied to the strong ground motion time histories from the Tohoku event (Dawood and Rodriguez-Marek, 2011). This processing consisted of a mean removal and the application of a high-pass 6th order Butterworth filter with a corner frequency of 0.1 Hz. The geometric mean of the spectral accelerations of the two horizontal components was calculated for the computation of the V/H spectral ratio.

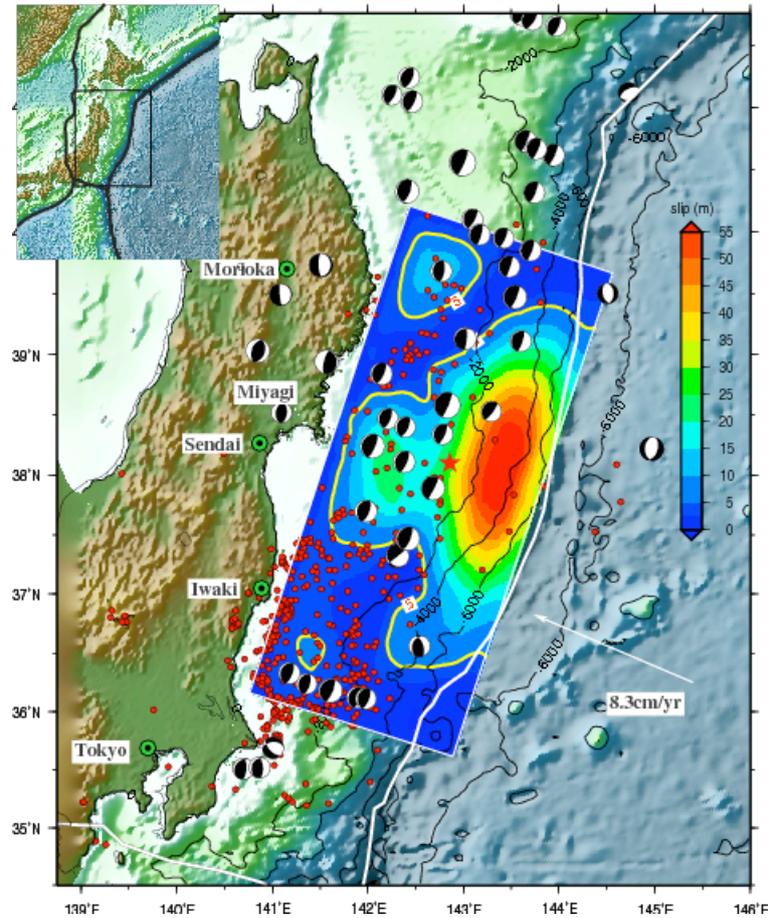


Figure 3. Slip inversion finite fault model from Shao et al. (2011) for the 2011 Tohoku Japan earthquake. Aftershocks are indicated by grey solid dots and the epicenter is plotted as a red star.

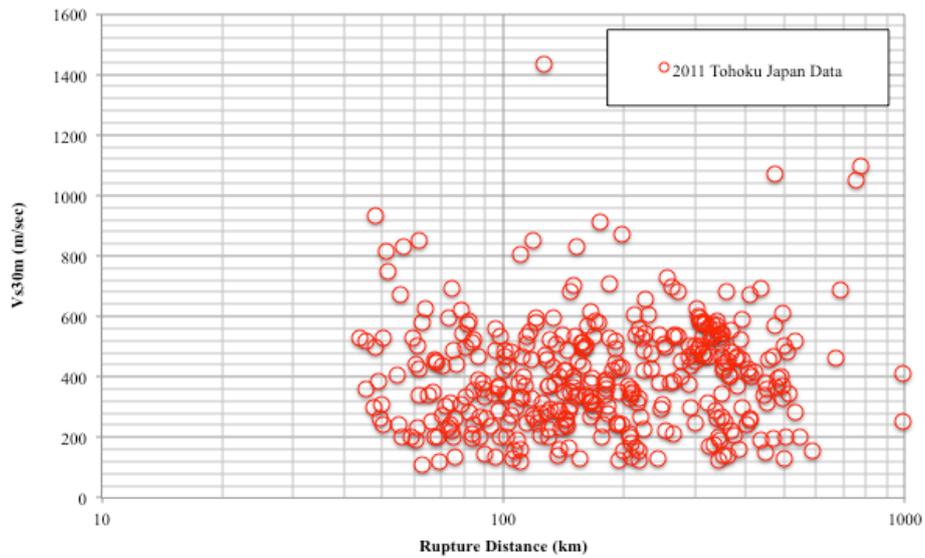


Figure 4. Distribution of selected stations from the 2011 Tohoku Japan earthquake used in the analysis.

4. V/H RATIO MODEL COMPARISON

The GA2011 V/H model was developed using the same dataset of crustal earthquakes used in the NGA project (Chiou et al., 2008) and is consistent with the Abrahamson and Silva (2008) NGA GMPE. The crustal dataset contained reverse mechanism events with magnitudes less than 8 and as such the GA2011 model is limited to $M_w < 8$ for reverse events. The goal of this study is to perform a statistical analysis on the applicability of the GA2011 V/H model to large megathrust subduction ground motion data, and more specifically for events with magnitudes larger than magnitude 8. In both cases, results are presented based on an upper magnitude value of 8 and the respective magnitudes of the two earthquakes. The latter implies an extrapolation of the GA2011 model to a magnitude beyond its stated applicability.

Based on the processed response spectra data from the two earthquakes, empirical spectral V/H ratios were computed for a suite of spectral periods. The mean residuals and standard errors for these spectral periods are shown in Figure 5a for the 2010 Chile earthquake using an upper magnitude limit of 8 for the GA2011 model. Similar results are shown in Figure 5b but with the event specific magnitude of 8.8 for the 2010 Chile earthquake. Also shown on these residual plots are the plus and minus inter-event values (i.e., tau) from the GA2011 model. Overall, the use of the event specific magnitude of 8.8 gives a better fit to the empirical data. It is noted that for spectral periods longer than about 2 seconds, the GA2011 underpredicts the V/H ratio (i.e., positive residuals with values larger than the inter-event terms from the GA2011 model) for both magnitude values.

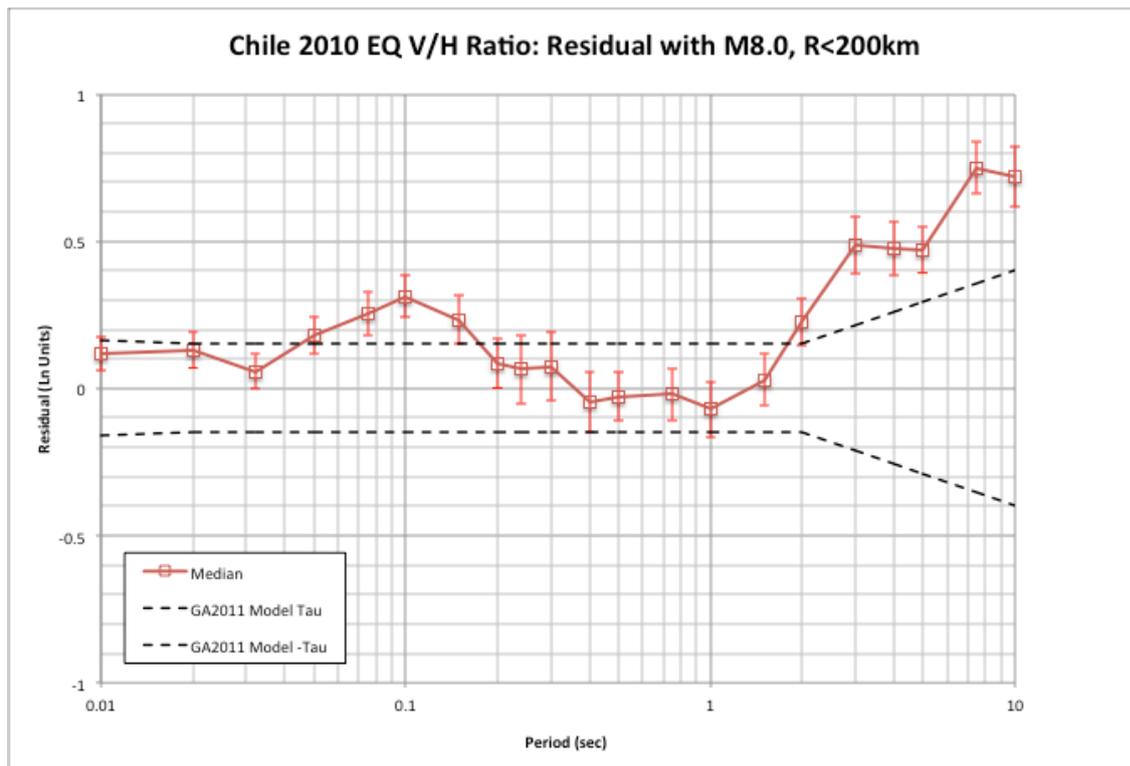


Figure 5a. Mean residual and standard errors with GA2011 model using M_w 8.0 for the 2010 Chile earthquake.

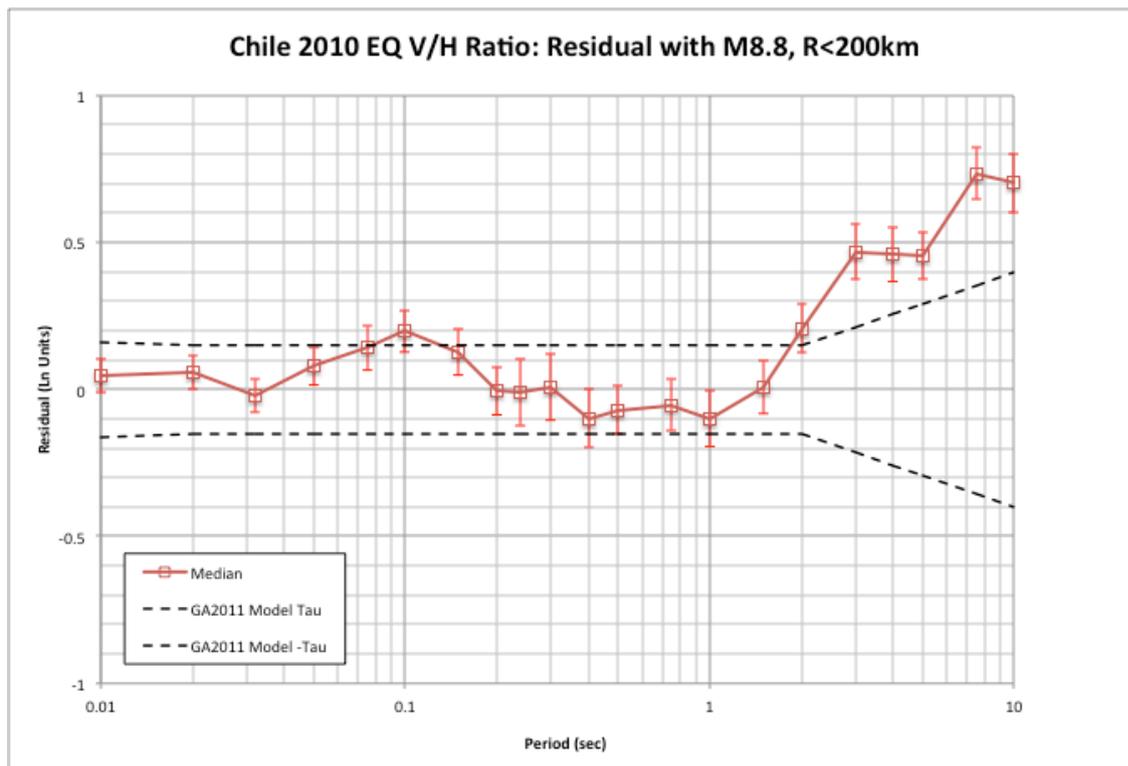


Figure 5b. Mean residual and standard errors with GA2011 model using M_w 8.8 for the 2010 Chile earthquake.

For the 2011 Tohoku earthquake, the residual calculations were binned based on the closest distance with distance bins of: 0 – 100 km, 100 – 200 km, and 200 – 300 km. These bins were based on the observed difference in attenuation rates of the empirical data as a function of distance as noted in Abrahamson et al. (2012). The median and standard error results are shown in Figure 6a for the upper magnitude value of 8 and Figure 6b for the event specific magnitude value of 9.0. Similar overall comparisons to those made in the previous section are observed with the data from the 2011 Tohoku earthquake, specifically, that the residuals fall within an acceptable range of the uncertainty when compared to the GA2011 model. It is also observed for the 2011 Tohoku event that the use of either the upper magnitude value of 8 or the event specific magnitude value of 9 does not significantly bias the results of the residual analysis. Unlike the results from the 2010 Chile earthquake, the empirical data from the 2011 Tohoku earthquake does not show a large positive residual (i.e., over-prediction by the GA2011 model) for longer spectral periods.

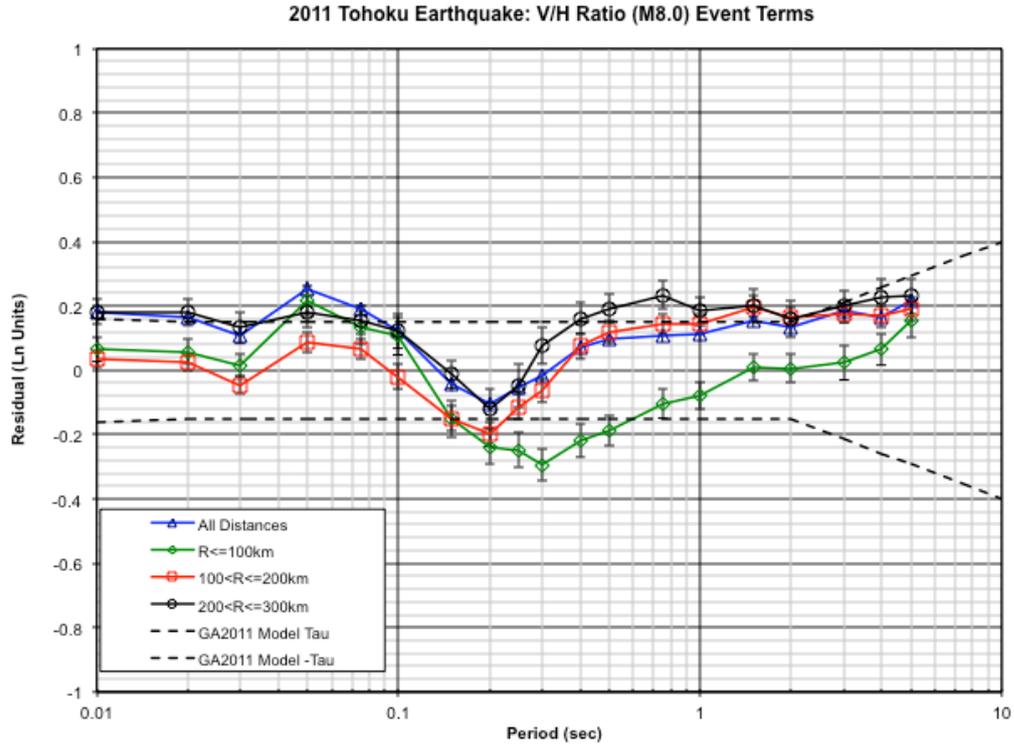


Figure 6a. Mean residual and standard errors with GA2011 model using M_w 8.0 for the 2011 Tohoku earthquake.

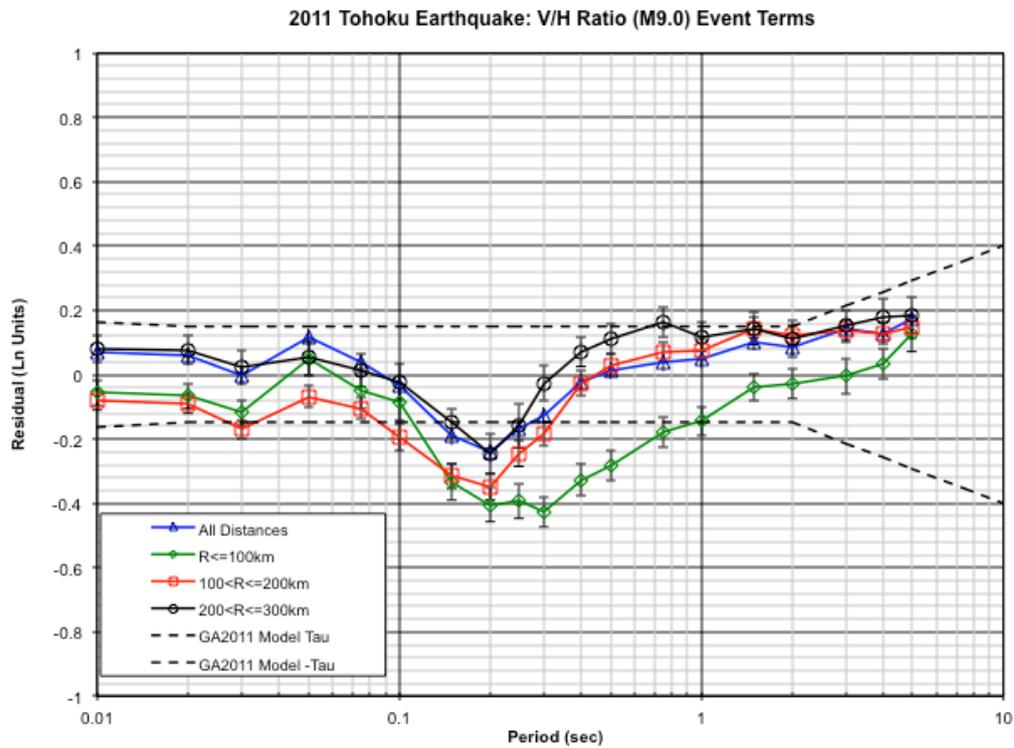


Figure 6b. Mean residual and standard errors with GA2011 model using M_w 9.0 for the 2011 Tohoku earthquake.

5. CONCLUSION AND RECOMMENDATIONS

Based on the comparison of the empirical strong ground motion recordings from two recent large megathrust subduction zone earthquakes, pending the development of V/H ratio models for subduction earthquakes, the GA2011 V/H model is suitable for estimating V/H spectral ratios from large megathrust earthquakes. This acceptance is based on the favorable comparison of the residuals from the empirical data and the GA2011 and the inter-event (i.e., tau) terms developed as part of the GA2011 model over a broad spectral period range from PGA to about 2.0 sec; however, for longer spectral periods (>2.0sec), the comparison is less favorable with the GA2011 V/H model under-predicting spectral ratios relative to the empirical data. It can also be inferred from this comparison that the use of an event-specific magnitude that is greater than the limit of $M_w 8$ (imposed by the GA2011 model) does not appear to bias the residuals and is thus permissible for use in estimating V/H values from the GA2011 model for large megathrust subduction earthquakes.

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