Comparison of the NGA-W1 Vertical-to-Horizontal Spectral Acceleration Ratio Prediction Equations with Turkish Strong Ground Motion Database

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SUMMARY:
Ground motion prediction models for the vertical-to-horizontal spectral acceleration (V/H) ratio were developed recently by Gulerce and Abrahamson (2011) using NGA-W1 database. Turkish strong ground motions may show a divergence from the V/H ratio model predictions, since only six earthquakes occurred in Turkey were included in the database. A strong motion dataset consistent with the V/H ratio model parameters is developed by including strong motion data from earthquakes occurred in Turkey with at least three recordings per earthquake. The objective of this study was to evaluate the compatibility of V/H ratio prediction model with magnitude, distance, and site amplification scaling of the Turkish ground motion dataset. No significant trend is observed in the model residual with respect to magnitude, rupture distance, and V_{s30} plots within the applicability range of the prediction model. Analysis results indicate that Gulerce and Abrahamson (2011) model is a suitable candidate model for probabilistic seismic hazard assessment studies in Turkey.

Keywords: NGA, GMPE, V/H ratio, Turkish ground motion database, probabilistic seismic hazard assessment

1. INTRODUCTION

Vertical ground motions are considered in the seismic design of critical structures such as nuclear power plants and dams. Results of recent studies revealed that the effect of vertical component ground motion is also significant on the seismic response of ordinary highway bridges located in the near-fault zones (Gulerce and Abrahamson, 2010). In a probabilistic seismic hazard assessment (PSHA), vertical design spectra may be developed by computing the hazard using vertical ground motion prediction equations (GMPEs). This approach requires accurate vertical ground motion predictions nevertheless; new and updated vertical GMPEs are not available for many active tectonic regions. Also, conducting separate vertical and horizontal component PSHAs may lead to inconsistent horizontal and vertical spectra due to the different distance and magnitude scaling and different standard deviation values of vertical GMPEs compared to horizontal GMPEs (Gulerce and Abrahamson, 2011). The alternative is to use empirical vertical-to-horizontal spectral acceleration ratio (V/H ratio) prediction models to scale the horizontal spectrum that was developed using the results of horizontal component PSHA.

Empirical V/H ratio predictive models may be built by developing separate vertical and horizontal GMPEs and then computing the ratio for a given magnitude and distance. In their studies, both Campbell and Bozorgnia (2003) and Bindi et al. (2009) used this approach on different sets of ground motion data. Database of Campbell and Bozorgnia (2003) model includes 1380 recordings from 80 earthquakes that were mainly occurred in California with a moment magnitude range of 4.7 to 7.7. Bindi et al. (2009) used the Italian Acceleometric Archive (ITACA) database, which is composed of 107 earthquakes occurred in Italy from year 1972 to 2007 with magnitudes 4.0 to 6.9. Both site conditions and style of faulting effects are represented by dummy variables in Campbell and Bozorgnia (2003) and Bindi et al. (2009) models. Magnitude and distance scaling of the models are also quite similar ensuing consistent results in the range of applicability of the models.

In their recent studies, Bommer et al. (2011), Edwards et al. (2011), and Gulerce and Abrahamson (2011) used datasets consist of the directly calculated V/H ratios of ground motions to develop the prediction equations. The datasets used by the authors, functional forms and range of applicability of each model is considerably different. Database of Bommer et al. (2011) model includes 1267 ground motions from 392 earthquakes occurred in Europe and surrounding regions with the magnitude range of 4.5 to 7.6 and Joyner-Boore distances up to 100 km. Edwards et al. (2011) combined two datasets; small magnitude data from Switzerland was enriched with moderate-to-large magnitude data from Japan, therefore the model covers a large magnitude range from magnitude 2 to 7.3. Gulerce and Abrahamson (2011) used the horizontal-component PEER-NGA-W1 dataset of Abrahamson and Silva (2008) horizontal model with small changes due to exclusion of recordings with missing vertical components. The dataset consists of 2,636 recordings from 126 shallow crustal earthquakes from active tectonic regions around the world. The magnitude range of the events is $4.3 \leq Mw \leq 7.9$ with rupture distances up to 200 km. Edwards et al. (2011) modeled the V/H ratio at rock with a single site parameter sites independent of the earthquake magnitude, the average quarter-wavelength velocity, but the residuals of the model were corrected by a distance term for short distances. Bommer et al. (2011) and Gulerce and Abrahamson (2011) models define the V/H ratios as function of magnitude, distance and dummy style-of-faulting variables (reverse, normal, strike-slip) with different functional forms. However, the main divergence of the models lays in the definition of the site response effects. While Bommer et al. (2011) model used dummy variables for site class (rock, stiff soil, soft soil); Gulerce and Abrahamson (2011) classified the sites as a continuous function of V_{S30} and included the soil non-linearity, which leads to higher V/H ratios then the other two models at soft soil sites.

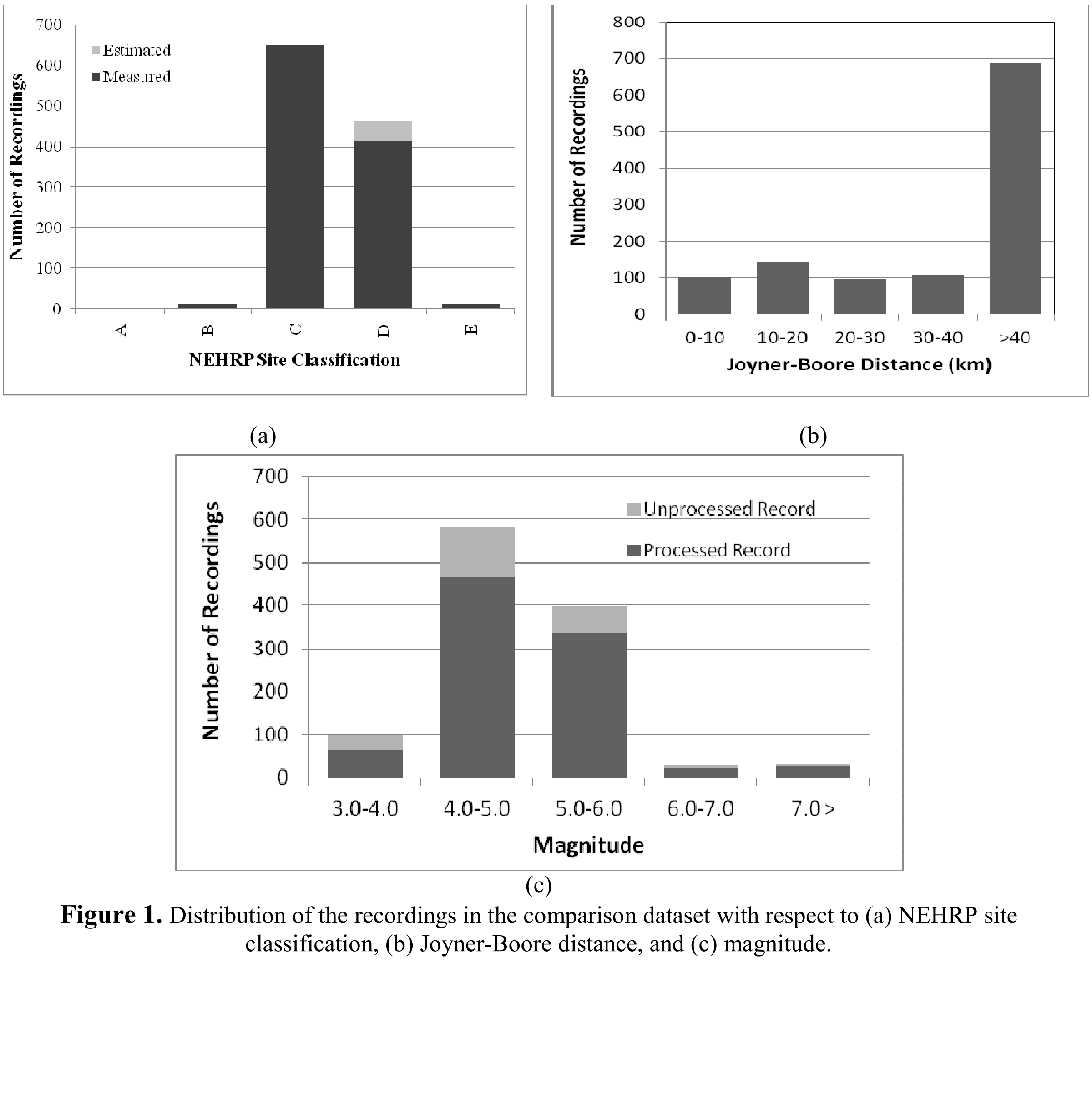
The applicability of the global ground motion models, especially the NGA-W1 models developed mainly for California, in the other shallow crustal and active tectonic regions is a topic of ongoing discussion. Applicability of the horizontal component NGA models in Europe and Italy has been investigated by Stafford et al. (2008) and Scasserra et al. (2009), showing that NGA-W1 models may be used in the PSHA studies in these regions with small adjustments. Gulerce and Abrahamson (2011) model is based on the NGA-W1 project database, in which the strong ground motions from the earthquakes occurred in Turkey are poorly represented. Table 1 shows that only 6 events occurred in Turkey and 35 recordings from these events were included in the Gulerce and Abrahamson (2011) dataset. A recently completed study by the authors aimed to develop an up-to-date dataset that includes all possible source information for the events occurred in Turkey (moment magnitude, style of faulting, depth to the top of the rupture, rake and dip angles, etc.), site information (especially the average shear wave velocity at the top 30 meters) for the recording stations, orientation independent horizontal spectral accelerations (Boore et al., 2006), vertical spectral accelerations and V/H ratios up to 10 seconds spectral periods. Using the developed V/H ratio dataset, compatibility of Gulerce and Abrahamson (2011) model predictions and magnitude, distance and site effects scaling of Turkish strong ground motions is evaluated. A similar study comparing the horizontal component NGA-W1 models to the Turkish strong ground motion data is conducted by Gulerce et al. (2012). These studies together will provide insight on application of NGA models in the probabilistic seismic hazard assessments in Turkey.

Table 1. Earthquakes and the number of ground motions from these events in the Gulerce and Abrahamson (2011) model dataset that occurred in Turkey.

Event Name	Event ID in NGA-W1 Database	Year	Mw	Number of Recordings
Dursunbey	47	1979	5.34	1
Erzincan	121	1992	6.69	1
Dinar	134	1995	6.4	2
Kocaeli	136	1999	7.51	17
Duzce	138	1999	7.14	13
Caldiran	141	1976	7.21	1
Total				**35**

2. COMPILATION OF TURKISH STRONG GROUND MOTION DATABASE

Strong motion data recorded by the Turkish national strong motion network had been compiled and processed together with detailed geophysical and geotechnical site measurements for all of its stations by Akkar et al. (2010). The Turkish strong motion database (TSDM) is disseminated through the Web at http://daphne.deprem.gov.tr. For this study, the TSMD including 4067 sets of recordings from 2996 events is used a starting point. Only 173 of these events are magnitude 5 or bigger and during these 173 events 685 recordings were taken. To preserve all valuable data, all of these recordings are added to the comparison dataset. 2823 of these events are smaller than magnitude 5 and during these 2823 events 3922 recordings were taken. The recording from these events were included in the comparison dataset only if 3 or more recordings were available in the database. The moment magnitude values for 109 of events were not available, so they are estimated from M_L using available local magnitude conversion relationship (Akkar et al., 2010). Unfortunately, no site information (V_{s30} or site classification) could be found for 431 of these recordings. The V_{S30} values of 67 recordings were estimated from the NGA-W1 dataset and the remaining recordings were removed. Figure 1(a) shows the number of measured and estimated recordings in each NEHRP site class. 3 of the remaining events were missing focal depth information and depths of these earthquakes were taken from ERD-GDDA database. The style of faulting for 68 recordings was estimated using the mechanisms of other earthquakes in the sequence or the dominant mechanism of the region. Distance measures of 96 recordings were missing. These values were either determined from the fault plane solutions or the rupture distances and Joyner-Boore (R_{JB}) distances were estimated from hypocentral and epicentral distances, respectively. Distribution of recordings with respect to R_{JB} is shown in Figure 1(b).



(c)

Figure 1. Distribution of the recordings in the comparison dataset with respect to (a) NEHRP site classification, (b) Joyner-Boore distance, and (c) magnitude.

Majority of the recordings in the remaining dataset were processed by Akkar et al., 2010. We aimed to preserve as much data as possible to obtain a representative dataset; therefore 284 unfiltered recordings were included to the database along with processed data. The number of filtered and unfiltered recordings in each magnitude range is presented in Figure 1(c). The waveform data of all remaining ground motions were checked for data quality and 68 unfiltered recordings were eliminated from the dataset due to spike, insufficient digitizer resolution, multi-event or S-wave trigger problems. A sample waveform from the discarded recordings with North - South, East –West and Vertical ground motion components is shown in Figure 2.

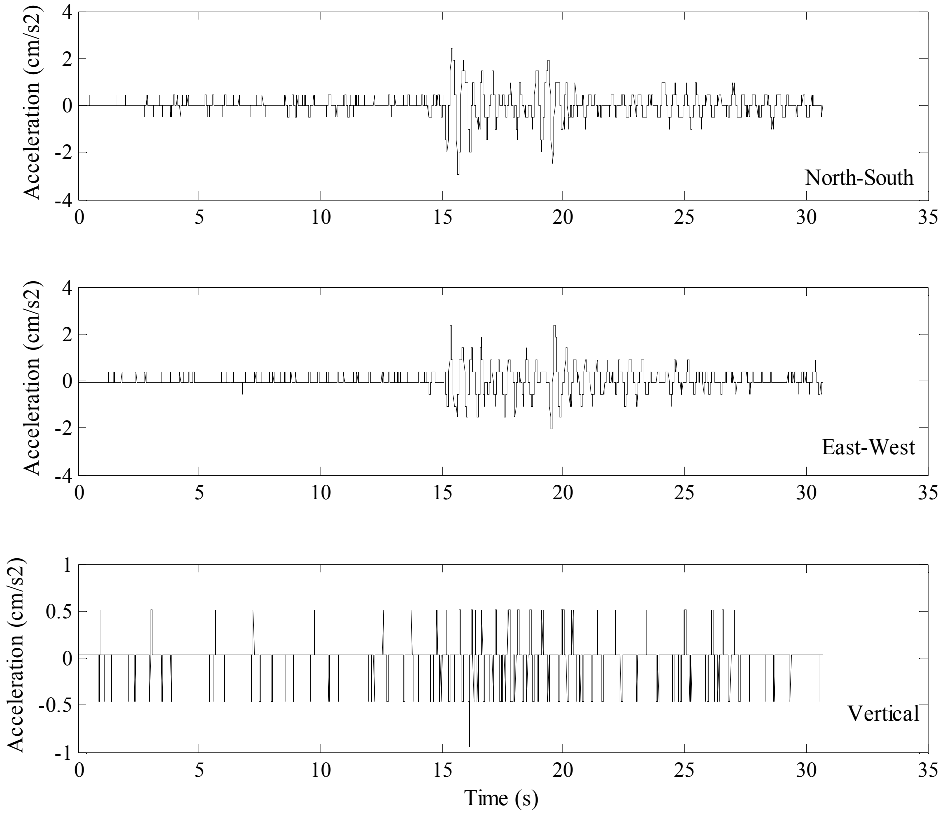
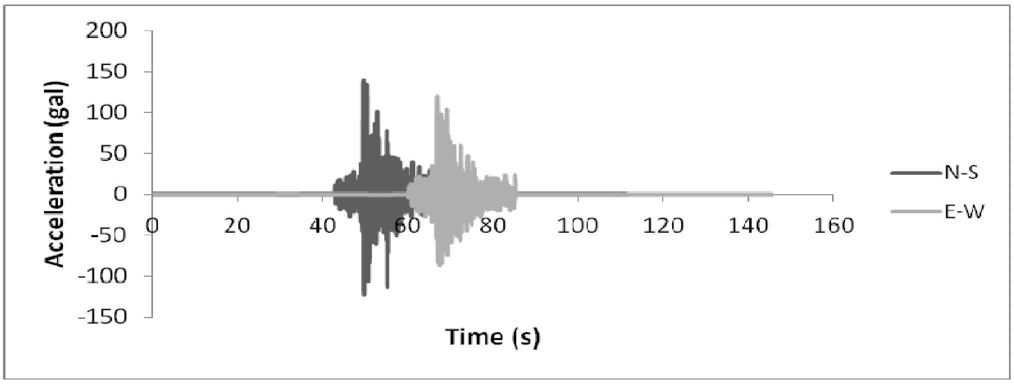


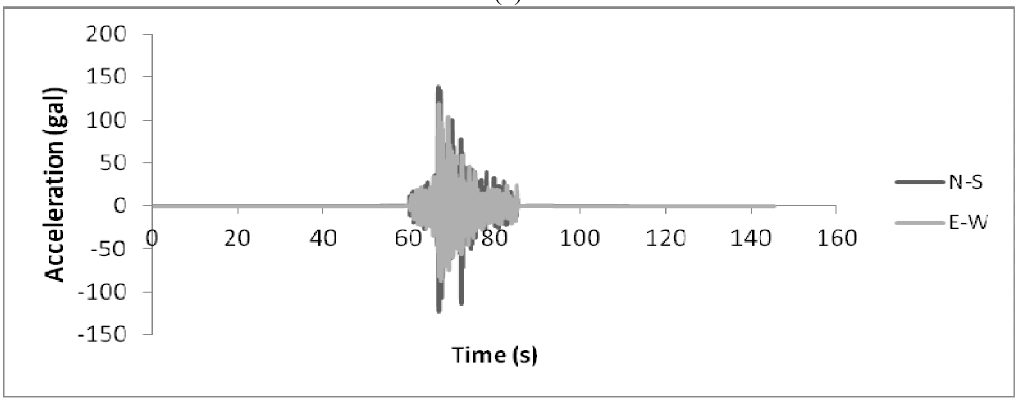
Figure 2. A sample record with (NS, EW and Vertical components) that was discarded due to low digitizer resolution (record name: 19981008204912_2401).

During the data quality check for the waveforms, we observed that the initial excitation time of the three orthogonal components is not consistent for a large number of processed records. This time lag results from the separate a-causal low-cut filtering applied to the components of the record by adding zero pads in different lengths. Figure 3(a) shows a sample record with two orthogonal horizontal components shifted with added zero pads during processing. To calculate the orientation independent ground motion intensity measures, two horizontal components of the records should have the same excitation time. Boore et al. (2012) discussed that removal of the zero pads may lead to incompatibilities in the ground motion intensity measures, especially in the spectral accelerations at long periods (periods longer than 10 seconds). We performed a little exercise to see the effect of zero pad cut-off on the orientation-independent horizontal spectral accelerations (GMRotI50 as used in the NGA-W1 models) by adding zeros to the shorter horizontal component (denoted by zero added in Figure 4) and cutting the zero-pad in the longer horizontal component (denoted by pad-stripped in Figure 4) to align two components and calculating the horizontal spectra for each case. The difference in the horizontal spectra calculated by these two procedures is negligible as shown in Figure 4 for the scope of this project.

We performed a systematic screening procedure on the waveforms in the comparison dataset and shifted the short horizontal component by adding zero pads to align with the longer horizontal component in each recording with a time lag. The shifted waveform for the time-lagged recording in Figure 3(a) is presented in Figure 3(b). We note that adding zero pads to the time histories to align the horizontal components creates very long recordings which would increase the computational time significantly for engineering applications.



(a)



(b)

Figure 3. (a) Waveform of the processed recording showing the time lag due to separate zero pads in horizontal components and (b) Waveform of the same recording after shifting to align the start times (Record name: 19990817000139_1404)

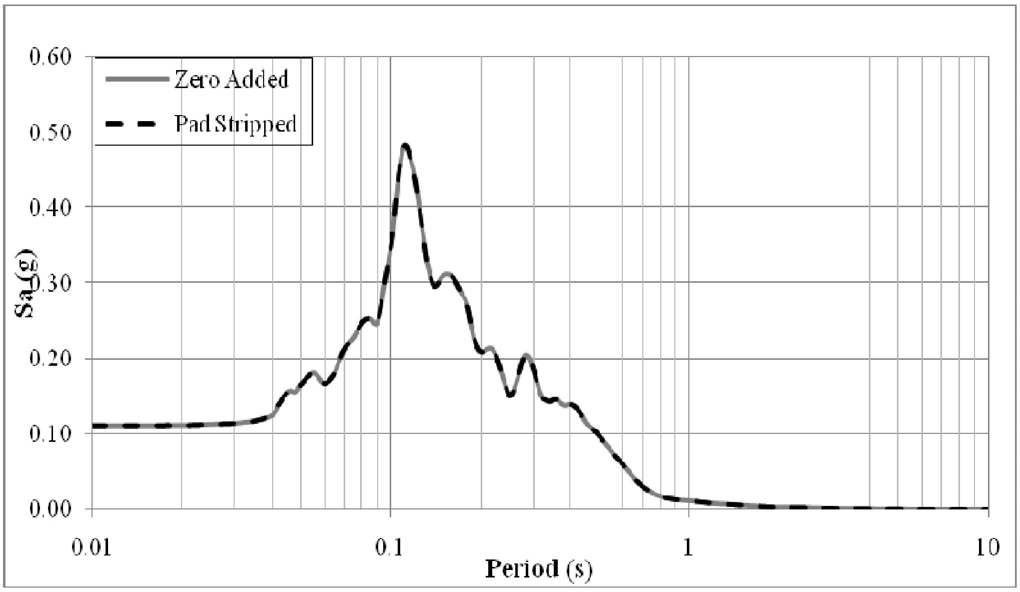


Figure 4. GMRotI50 horizontal spectra for the same recording with zero pads cut-off (denoted by pad-stripped) from the long component and zero added to the short component for alignment (denoted by zero-added) (Record name: 19991107165434_9906)

Final flat-file used in the comparison includes 1142 recordings from 288 events with the earthquake metadata (moment magnitude, style of faulting, rake and dip angles, etc.), distance metrics for the recordings (rupture distance and R_{JB}), V_{s30} values for the recording stations, horizontal component spectral values in terms on GMRotI50, vertical spectral accelerations and V/H ratios for 22 spectral periods (0.01, 0.02, 0.03, 0.04, 0.05, 0.075, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 7.5, 10.0 seconds).

3. MODEL RESIDUALS

Gulerce and Abrahamson (2011) V/H ratio model prediction for each recording in the comparison dataset is determined and the total model residual is calculated using Equation 1 as given below:

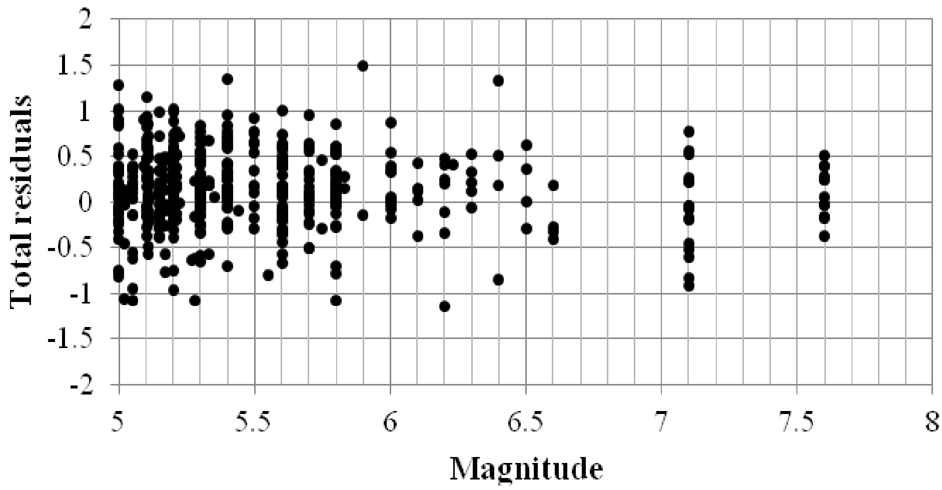
$$Residual_{total} = \ln(V/H)_{actual} - \ln(V/H)_{predicted} \tag{1}$$

where $\ln(V/H)_{actual}$ is the V/H ratio of the recording and $\ln(V/H)_{predicted}$ is the model prediction in natural log terms. Plots of the total residuals with respect to moment magnitude, rupture distance, and V_{s30} are prepared to evaluate the differences in the magnitude, distance, site amplification scaling between the Turkish V/H ratio comparison dataset and the prediction model. Figure 4(a), Figure 5(a), and Figure 6(a) show the distribution of residuals with respect to moment magnitude of the corresponding recordings within the applicability range of the model for peak ground acceleration (PGA), 0.2 second and 1 second spectral periods, respectively. The residuals are equally distributed along the zero-line indicating no bias in the magnitude scaling of the prediction model. Similarly, Figure 4(b), Figure 5(b), and Figure 6(b) present the distribution of residuals with respect to rupture distance for PGA, 0.2 second and 1 second spectral periods, respectively. No significant trend is observed on the short distance range (up to 40 kilometers) where the vertical ground motions are critical for engineering design. Actual V/H ratios are slightly larger than the model predictions in the longer distances according to Figures 4(b) and 5(b) for short periods, but the trend is insignificant in Figure 6(b) for longer periods. The magnitude-distance scaling of the Gulerce and Abrahamson (2011) model is shown in Equation 2 where a_1-a_8 are the model coefficients. The underestimation of the V/H ratios in longer distances can be adjusted by modifying the coefficients a_2 and a_3 in Equation 2 by repeating the regression analysis for the comparison dataset.

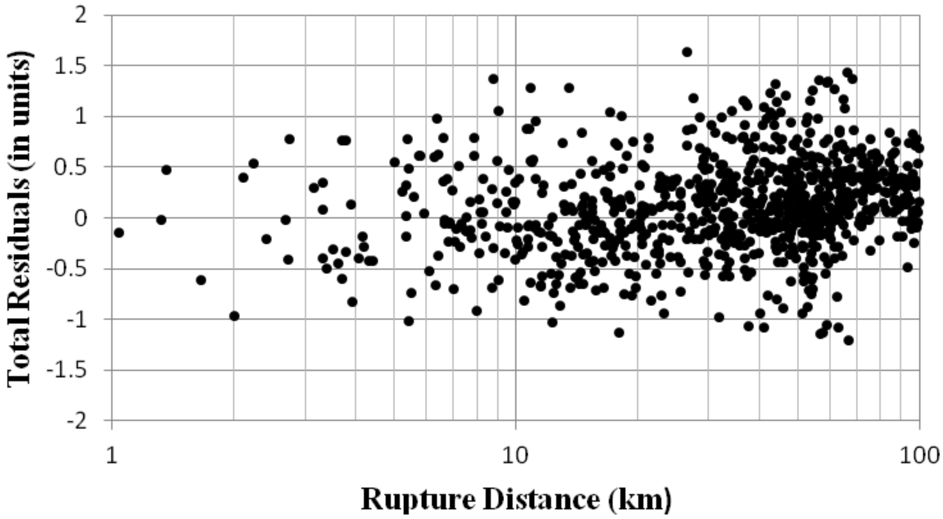
$$f_1(M, R_{rup}) = \begin{cases} a_1 + a_4(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) \rightarrow for(M \le c_1) \\ a_1 + a_5(M - c_1) + a_8(8.5 - M)^2 + [a_2 + a_3(M - c_1)]\ln(R) \rightarrow for(M > c_1) \end{cases} \tag{2}$$

Distribution of residuals with respect to V_{s30} for PGA, 0.2 second and 1 second spectral periods are given in Figure 4(c), Figure 5(c), and Figure 6(c), respectively. Again, actual V/H ratios are slightly larger than the model predictions in Figures 4(c) and 5(c) in a consistent manner indicating a mean offset from the model predictions. The mean offset from the model predictions requires the modification of coefficient a_1 of Equation 2 in the new regression analysis for the comparison dataset. A trend in the residuals is visible in Figure 6(c), especially for stiff soils where model predictions are higher than the actual values. The site amplification dependence of V/H ratio model is given in Equation 3. All coefficients in the non-linear site amplification scaling in Equation 3 was constrained outside the regression analysis, therefore the linear site amplification term, a_{10} in Equation 3, should be adjusted for the Turkish dataset.

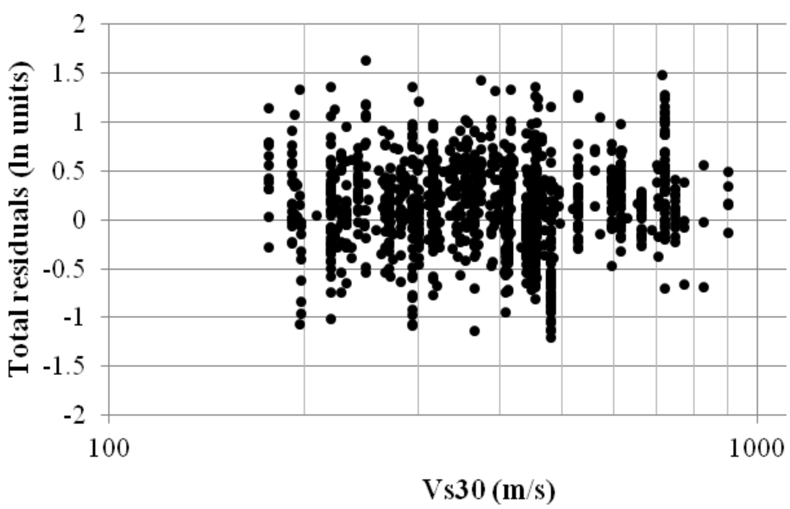
$$f_5(P\hat{G}A_{1100}, V^*_{S30}) = a_{10}\ln\left(\frac{V^*_{S30}}{V_{LIN}}\right) - \begin{cases} -b\ln\left(P\hat{G}A_{1100} + c\right) + b\ln\left(P\hat{G}A_{1100} + c\left(\frac{V^*_{S30}}{V_{LIN}}\right)^n\right) for V^*_{S30} < V_{LIN} \\ (bn)\ln\left(\frac{V^*_{S30}}{V_{LIN}}\right) \quad for V^*_{S30} \ge V_{LIN} \end{cases} \tag{3}$$



(a)

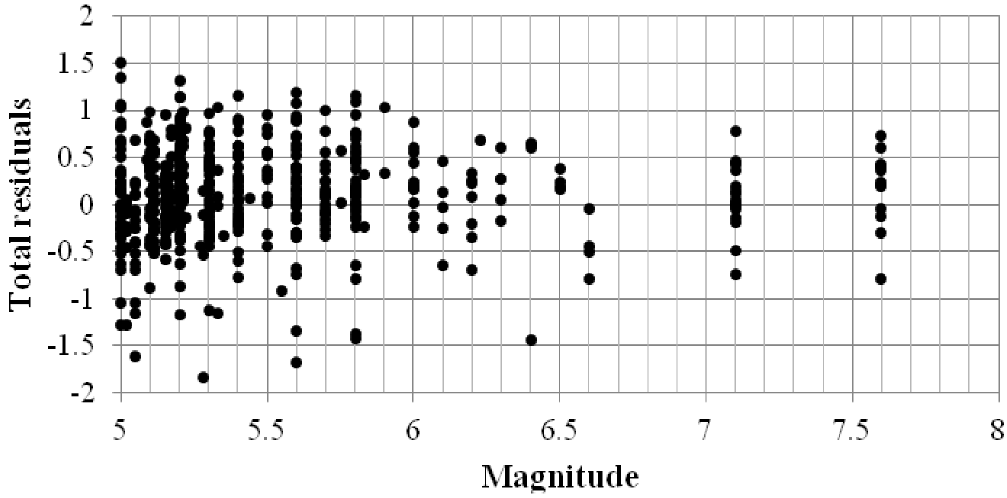


(b)

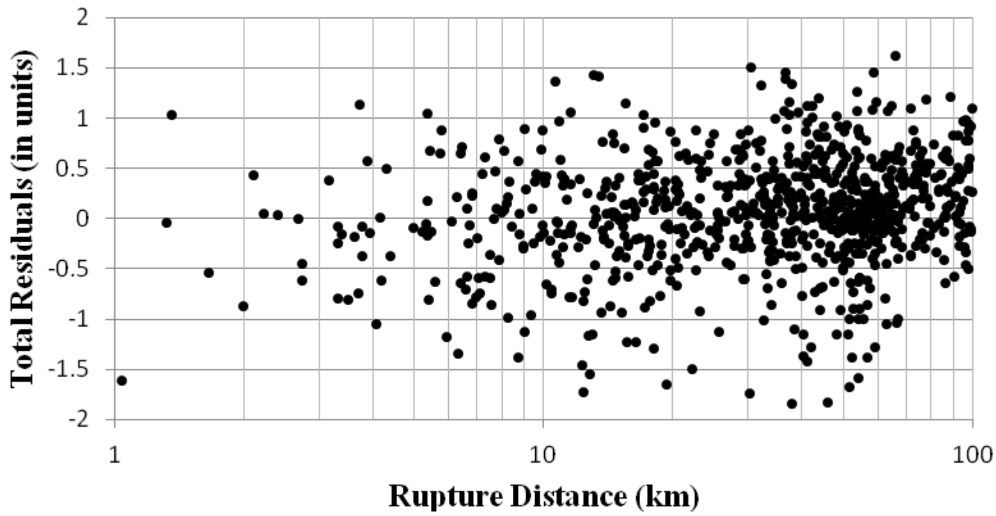


(c)

Figure 4. The model residuals in natural log units for PGA with respect to (a) magnitude (M_w), (b) rupture distance, and (c) average shear wave velocity at the top 30 meters.



(a)



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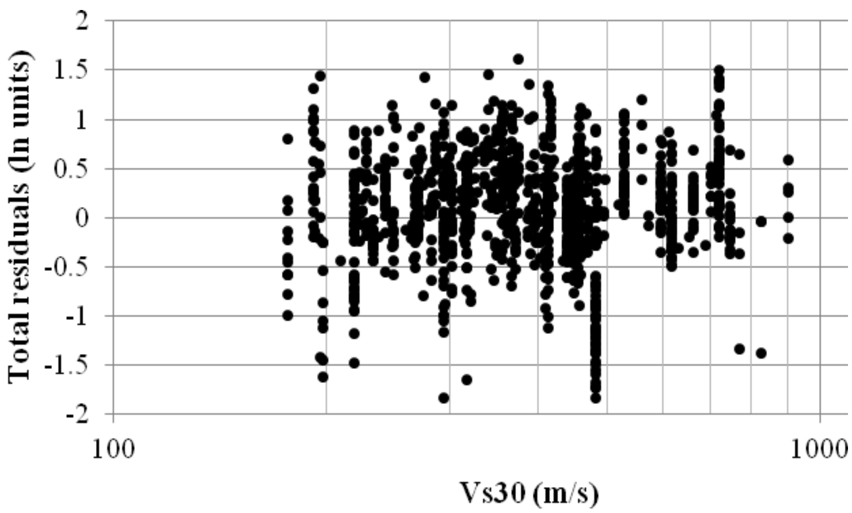
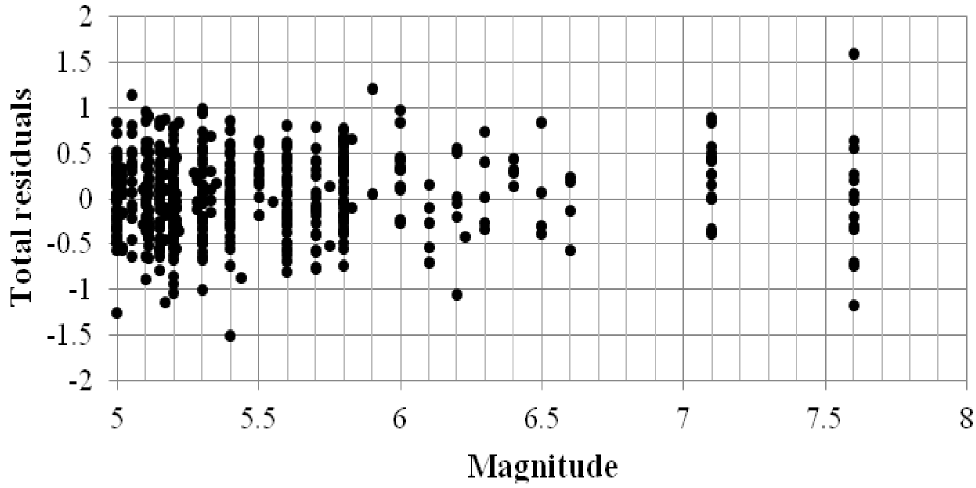
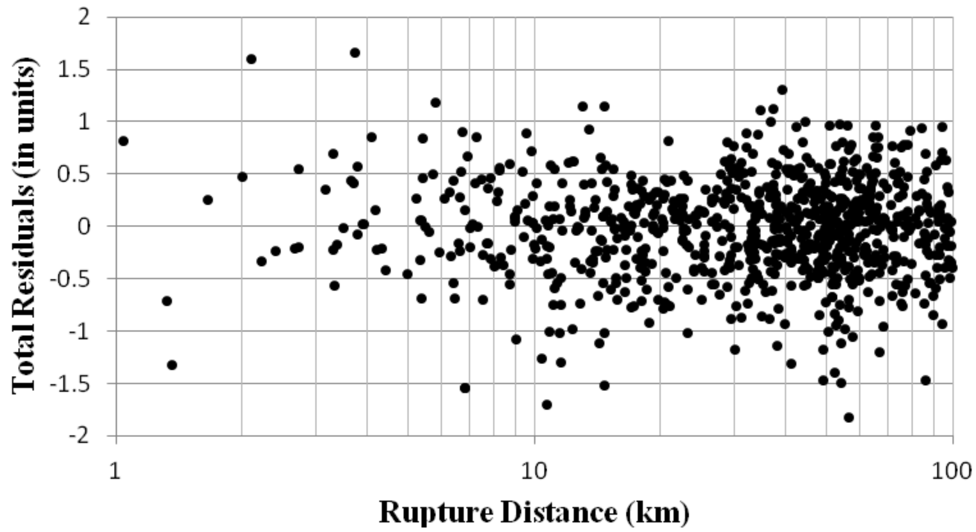


(c)

Figure 5. The model residuals in natural log units for 0.2 second spectral period with respect to (a) magnitude (M_w), (b) rupture distance, and (c) average shear wave velocity at the top 30 meters.



(a)



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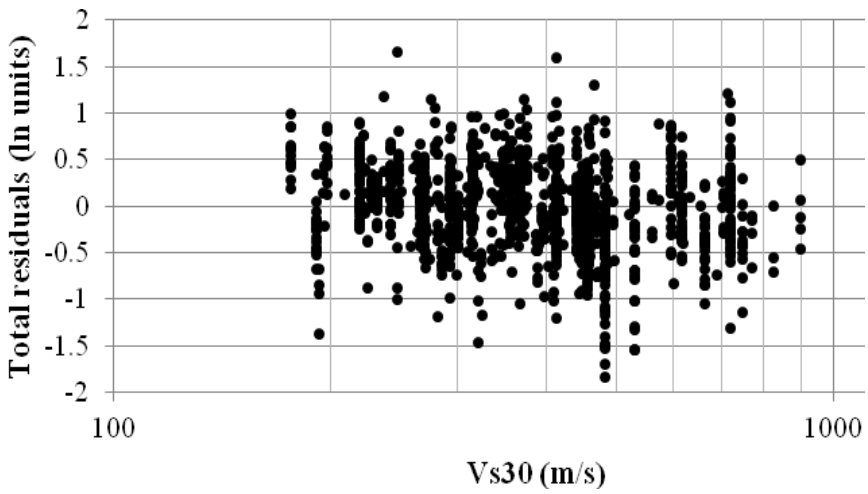

(c)

Figure 6. The model residuals in natural log units for 1 second spectral period with respect to (a) magnitude (M_w), (b) rupture distance, and (c) average shear wave velocity at the top 30 meters.

4. CONCLUSIONS

Ground motion prediction models for the vertical-to-horizontal spectral acceleration ratio were developed recently by Gulerce and Abrahamson (2011) using NGA-W1 database. Turkish strong ground motions may show a divergence from the V/H ratio model predictions, since only six earthquakes occurred in Turkey and 35 ground motions from these earthquakes were included in the database. A strong motion dataset consistent with the model parameters is developed by including strong motion data from earthquakes occurred in Turkey with at least three recordings per earthquake. Final comparison dataset includes 1142 recordings from 288 events with the earthquake metadata, distance metrics for the recordings, V_{s30} values for the recording stations, and spectral accelerations of the horizontal and vertical component. Trends of the total residuals with respect to moment magnitude, rupture distance, and V_{s30} are checked to evaluate the differences in the magnitude, distance, site amplification scaling between the Turkish V/H ratio comparison dataset and the prediction model. Observations on the total residuals point out that: (i) the magnitude scaling of the model is compatible, (ii) distance scaling of the model is suitable for short distances where the vertical ground motions are critical in engineering design, however the model predictions are smaller than the actual V/H ratios at larger distances, (iii) an average misfit from the actual data is present in the site amplification at short periods, and (iv) V/H ratios for stiff soil/rock sites are slightly over predicted at longer periods. The prediction model coefficients in the distance term and linear site amplification term along with the constant term might be modified by regressing the Turkish ground motion dataset using the same functional form and keeping other coefficients unchanged. We believe that the deviations from the original values in these coefficients will be insignificant since the total residuals are tolerable. Analysis results indicate that Gulerce and Abrahamson (2011) model is a suitable candidate model for probabilistic seismic hazard assessment studies in Turkey.

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