Updating the Chiou and Youngs NGA Model: Regionalization of Anelastic Attenuation

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SUMMARY: (10 pt)
Ground motion data for individual earthquakes from California, Japan, New Zealand, Taiwan, and Turkey were analyzed to determine the anelastic attenuation and ln(V_{S30}) scaling coefficients of the Chiou and Youngs (2008) ground motion prediction equation. These values were obtained for PGA and PSA at 0.3 and 1.0 second periods. The results indicate differences in these parameters between the various regions. Differences were also found within regions with diverse conditions, such as between the fore arc and back arc regions of Japan, and between Northern and Southern California. These regional differences should be accounted for when developing ground motion prediction equations from large multi-region data sets.

Keywords: NGA Update, GMPE Regionalization

1. INTRODUCTION

The Chiou and Youngs (2008) Next Generation Attenuation (NGA) ground motion prediction equation (GMPE) is being updated as part of the Pacific Earthquake Engineering Research Center's NGA-West2 Project. Previous evaluations have shown the general applicability of the NGA GMPEs for prediction of strong ground motion from shallow crustal earthquakes in active tectonic regions (e.g. Stafford et al., 2008; Scasserra, et al., 2009; Shoja-Taheri et al., 2009; Bommer et al, 2010). However, some of these evaluations have indicated differences in the rate of attenuation with distance (e.g. Scasserra, et al., 2009). In addition, the study by Chiou et al. (2010) suggested region differences in attenuation within California. The greatly expanded strong motion database developed for the NGA-West2 project provides the opportunity to evaluate the applicability of the Chiou and Youngs GMPE to various active tectonic regions. To these data we add supplemental ground motion recordings from small-to-moderate earthquakes from California, Japan, Taiwan, Turkey, and New Zealand. We use this combined dataset to assess need to incorporate variation in attenuation rate among the various regions into the updated GMPE.

2. ANALYSIS APPROACH

The attenuation of ground motion amplitude with distance is a combination of the effects of geometric spreading and energy absorption due to wave scattering and material damping. As noted by many researchers (e.g. Atkinson, 1989; Frankel et al., 1990) these effects are not readily separated due to the high degree of correlation in estimates of their parameters. Chiou and Youngs (2008) adopted the approach of fixing the geometric spreading term at large distances (R > ~100 km) to the theoretical value for Lg waves of $1/R^{1/2}$ and then estimated an anelastic attenuation term proportional to R that accounted for departure of the observations from theoretical geometric spreading. The resulting form for distance attenuation of the natural log of peak ground motion, ln(y), with distance from the earthquake rupture, R_{RUP}, is given by:

$$\ln(y) \propto -2.1 \times \ln\left[R_{RUP} + C_{NS}\right] + (-0.5 + 2.1)\ln\sqrt{R_{RUP}^2 + 50^2} + \gamma(\mathbf{M}) \times R_{RUP} \tag{2.1}$$

In Equation (2.1) the first term defines the near source geometric spreading. Parameter C_{NS} defines the degree of near-source saturation as a function of moment magnitude **M**, and is given by the expression:

$$C_{NS} = c_5 \cosh\{c_6 \max(\mathbf{M} - 3,0)\} \tag{2.2}$$

The second term of Equation (2.1) defines a smooth transition from body wave geometric spreading at distances less than 50 km to Lg wave geometric spreading at larger distances. The third term defines a magnitude-dependent anelastic attenuation term given by the expression:

$$\gamma(\mathbf{M}) = c_{\gamma 1} + \frac{c_{\gamma 2}}{\cosh\{\max(\mathbf{M} - 4,0)\}} \tag{2.3}$$

The coefficients c_5, c_6, $c_{\gamma 1}$, and $c_{\gamma 2}$ in Equations (2.2) and (2.3) were determined from fitting strong motion data and are dependent on the spectral period of the ground motion parameter.

Chiou and Youngs (2008) determined the coefficients for $\gamma(\mathbf{M})$ by analyzing the data for individual earthquakes. They demonstrated the need to include additional data from other sources where possible and to use a truncated regression model (Toro, 1981; Bragato, 2004) to account for truncation in reported motions at low ground motion levels. Figure 1 illustrates the effect for the data from four earthquakes

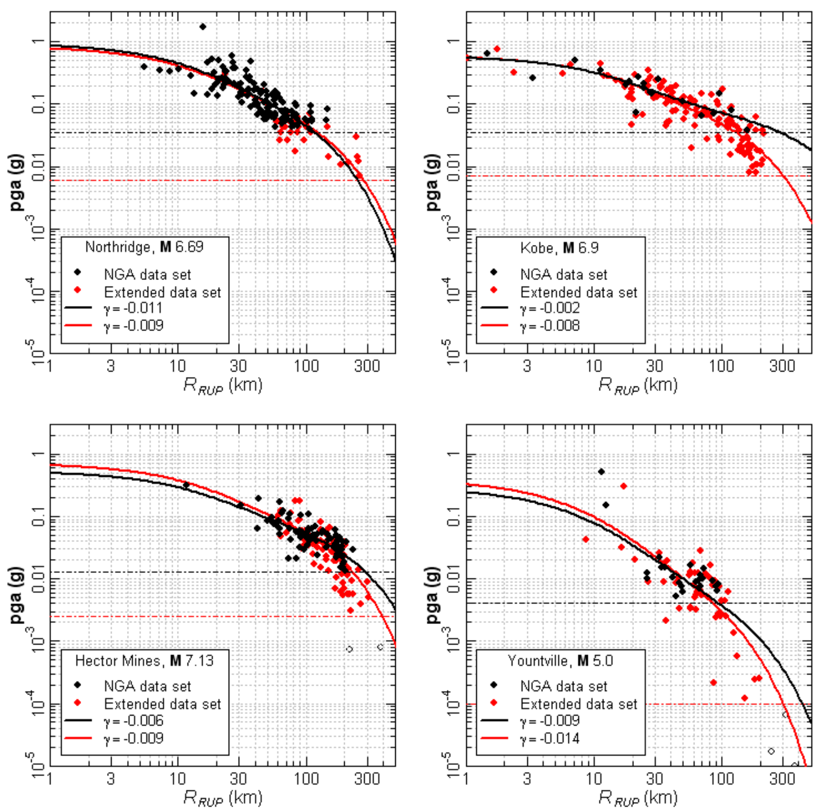

Figure 1. Example truncated regression fits to data for individual earthquakes (from Chiou and Youngs, 2008). Black and red horizontal dashed lines indicate the level of data truncation used in the truncated regression fitting.

The approach used by Chiou and Youngs (2008) was followed in this study. Data sets were developed for individual earthquakes in the regions studied. Individual earthquakes were identified for which there were sufficient data to provide an estimate of parameter γ. Based on past experience, a minimum of five data points for distances less than 100 km and a minimum of five data points for distances greater than 100 km are needed in order to provide a reasonable constraint on the value of γ. The data for each individual earthquake was fit by the model

$$\ln(y_{ref}) = c_1 - 2.1 \times \ln\left[R_{RUP} + C_{NS}\right] + (-0.5 + 2.1) \times \ln\sqrt{R_{RUP}^2 + 50^2} + \gamma \times R_{RUP}$$

$$\ln(y) = \ln(y_{ref}) + \phi_1 \times \ln(V_{S30}) + f_{NL}(V_{S30}, y_{ref}) \tag{2.4}$$

The first line of Equation (2.4) provided the estimate of peak ground motion on the reference site condition used by Chiou and Youngs (2008), which is a site with an average shear wave velocity in the top 30 m (V_{S30}) of 1,130 m/s. A constant c_1 is used to represent the average level of ground motion. The second line of Equation (2.4) represents the site term of the Chiou and Youngs (2008) model. The term $f_{NL}(V_{S30}, y_{ref})$ represents the nonlinear soil response term for which the coefficients were fixed at the values given in Chiou and Youngs (2008). The linear $\ln(V_{S30})$ scaling parameter ϕ_1 was computed from the earthquake data as part of the fitting process. Because V_{S30} is used as a proxy variable for the general effects of the shallow crust on ground motions, there is the potential that the linear scaling may vary from region to region. The parameters obtained for each earthquake consist of c_1, γ, and ϕ_1. The variability in γ and ϕ_1 from region to region was then used to assess the need for regionalization of these parameters in developing the update to the Chiou and Youngs GMPE.

3. GROUND MOTION DATA

The primary dataset used for the assessment is the PEER NGA-West2 ground motion database. These data were supplemented by data from the ShakeMap archives for California, data from Kik-net for Japan, data from the Central Weather Bureau for Taiwan, data from the Strong Motion Database of Turkey, and data from GeoNet for New Zealand. Table 1 summarizes the size of the datasets analyzed for each region. These represent the earthquakes for which the parameters γ and ϕ_1 are reasonably well constrained.

Table 1. Summary of Data Used to Assess Regional Variation in γ and ϕ_1

Region	Number of Earthquakes	Magnitude Range
California	184	3.1 – 7.3
Japan	19	5.0 – 7.3
New Zealand	7	4.1 – 7.0
Taiwan	26	4.7 – 7.6
Turkey	7	5.1 – 7.5

4. ANALYSIS RESULTS

Parameters γ and ϕ_1 were estimated from the data for individual earthquakes in each of the regions studied. The earthquakes analyzed were limited to those for which the parameters are reasonably well constrained as indicated by the ratio of 2.0 or greater for the parameter estimate divided by its standard error of estimation.

2.1. Results for γ

Figures 2, 3, and 4 compare the estimated values of γ for individual earthquakes for PGA, 0.3 sec PSA, and 1.0 sec PSA, respectively. The data are color-coded by region. The data for southern and northern California are shown separately. In addition, the data from Japan are separated into fore arc and back arc groups depending on the earthquake location relative to the volcanic front.

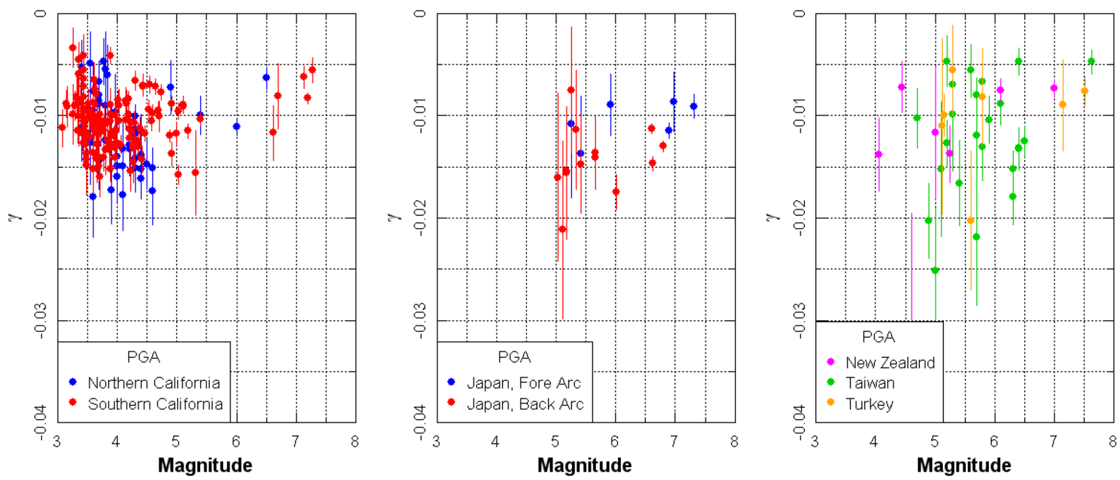

Figure 2. Comparison of γ estimates for individual earthquakes for peak ground acceleration (PGA). Vertical bars denote 90 percent confidence interval.

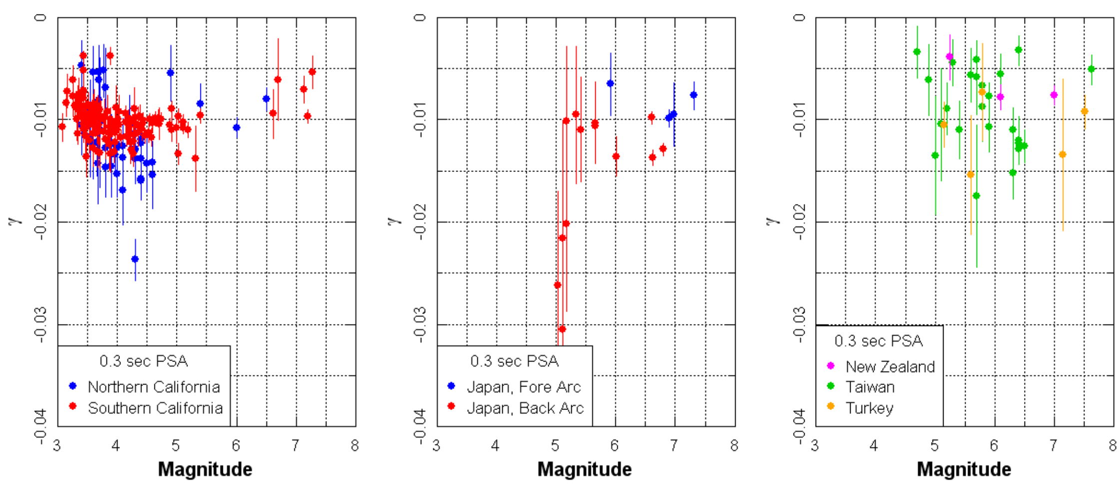

Figure 3. Comparison of γ estimates for individual earthquakes for 0.3 second pseudo spectra acceleration (PSA). Vertical bars denote 90 percent confidence interval.

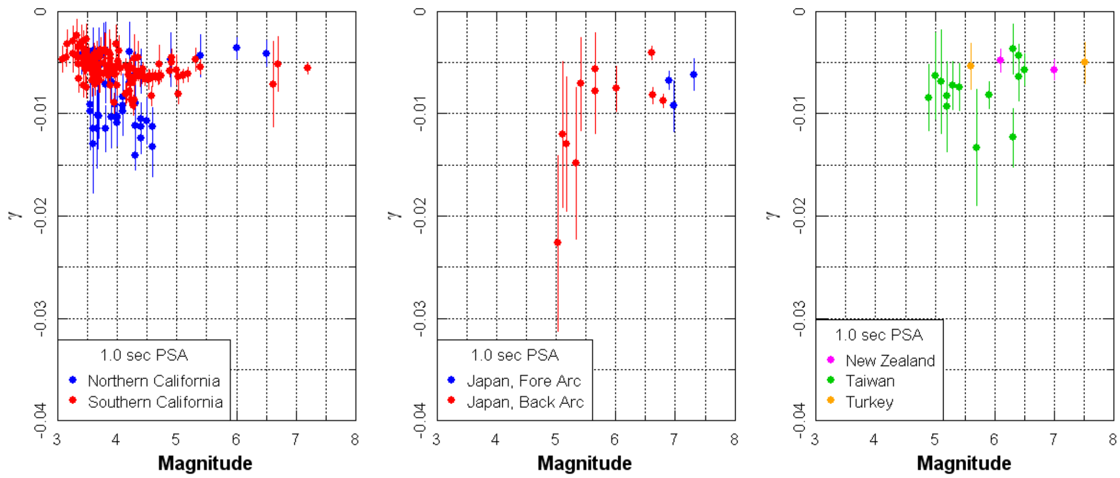

Figure 4. Comparison of γ estimates for individual earthquakes for 1.0 second pseudo spectra acceleration (PSA). Vertical bars denote 90 percent confidence interval.

Potential differences in the average value of γ for various subsets were analyzed using the Welsh two sample *t*-test implemented in the statistical language **R**. Table 2 summarizes the results of these comparisons in terms of those differences that appear to be statistically significant (*p*-value < 0.05). The results indicate differences in γ for smaller earthquakes within California that are not observed at larger magnitudes. There are also clear differences between the values of γ in the fore arc and back arc regions of Japan, at least for shorter spectral periods. The estimated values of γ for New Zealand earthquakes appear to differ from those for Northern California at some spectral periods, as do the values for Taiwan. The values for the Turkey earthquakes appear to be consistent with those for California.

Table 2. Summary of Tests for Statistically Significant Differences in Sample Means for parameter γ

Sample 1	Sample 2	*P*-value for Difference in Means ≤ 0.05 (Yes/No)		
		PGA	0.3 sec PSA	1.0 sec PSA
N. California, **M** ≤ 5.5	S. California, **M** ≤ 5.5	Y	Y	Y
N. California, **M** > 5.5	S. California, **M** > 5.5	N	N	N
Japan, Fore Arc	Japan, Back Arc	Y	Y	N
Japan, Fore Arc	California	N	N	N
Japan, Back Arc	California	Y	Y	N
New Zealand	N. California	N	Y	Y
New Zealand	S. California	N	N	N
Taiwan	N. California	N	Y	Y
Taiwan	S. California	N	Y	N
Turkey	N. California	N	N	N
Turkey	S. California	N	N	N

2.1. Results for ϕ_1

Figures 5, 6, and 7 compare the estimated values of ϕ_1 for individual earthquakes for PGA, 0.3 sec PSA, and 1.0 sec PSA, respectively. Potential differences in the average value of ϕ_1 for various subsets were again analyzed using the Welsh two sample *t*-test. Table 3 summarizes the results of these comparisons in terms of those differences that appear to be statistically significant (*p*-value < 0.05).

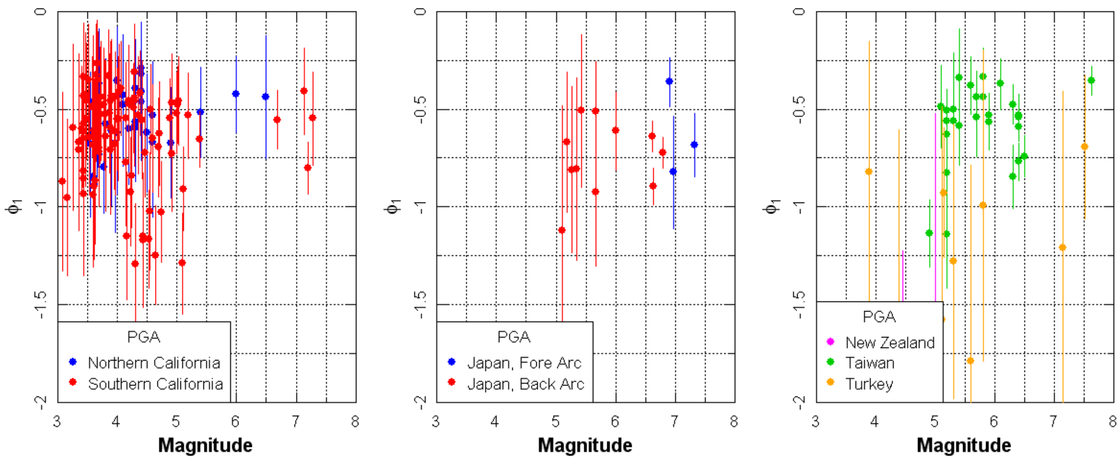

Figure 5. Comparison of φ_1 estimates for individual earthquakes for peak ground acceleration (PGA). Vertical bars denote 90 percent confidence interval.

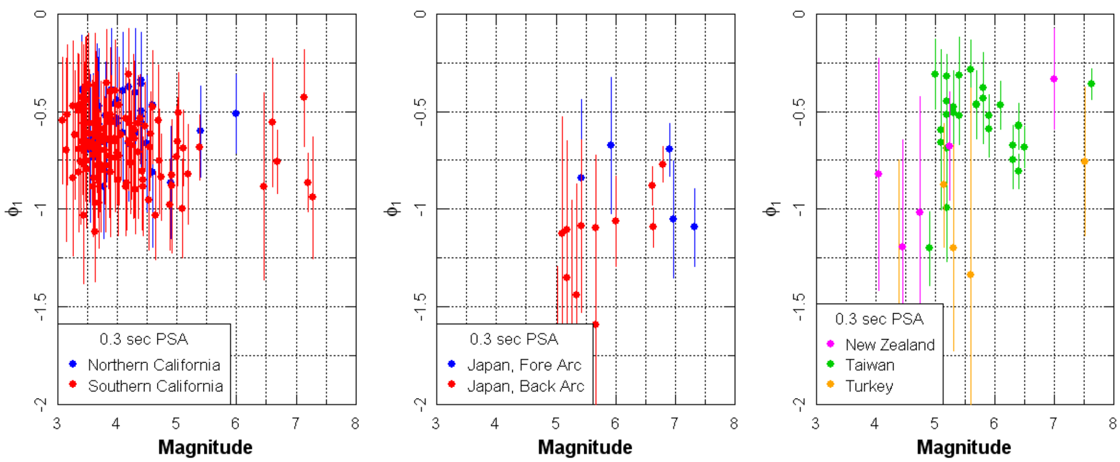

Figure 6. Comparison of φ_1 estimates for individual earthquakes for 0.3 second pseudo spectra acceleration (PSA). Vertical bars denote 90 percent confidence interval.

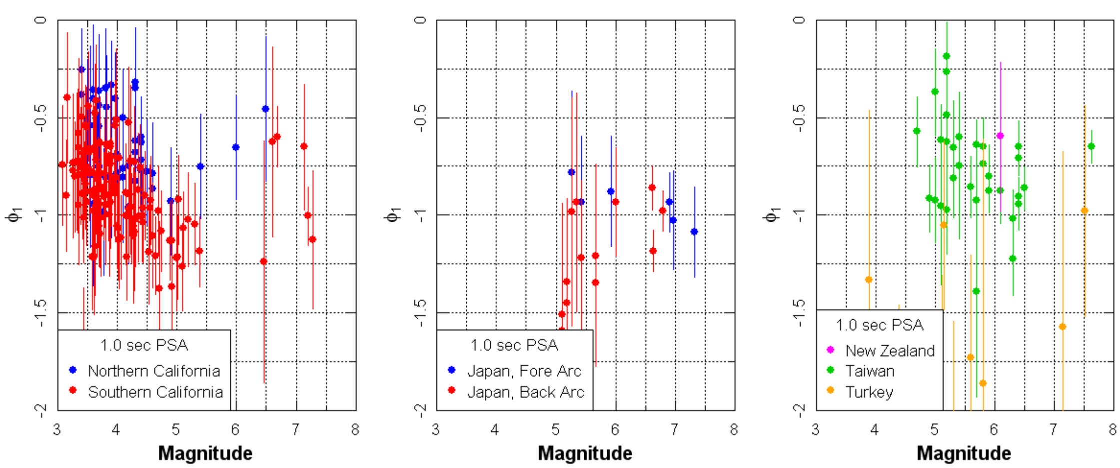

Figure 7. Comparison of φ_1 estimates for individual earthquakes for 1.0 second pseudo spectra acceleration (PSA). Vertical bars denote 90 percent confidence interval.

The results indicate differences in φ_1 for earthquakes within California and for earthquakes within Japan. There are also clear differences between the values of φ_1 for California and Japan, for California and Turkey, and potentially for California and New Zealand.

Table 3. Summary of Tests for Statistically Significant Differences in Sample Means for parameter ϕ_1

Sample 1	Sample 2	*P*-value for Difference in Means ≤ 0.05 (Yes/No)		
		PGA	0.3 sec PSA	1.0 sec PSA
N. California	S. California	Y	Y	Y
Japan, Fore Arc	Japan, Back Arc	N	Y	Y
Japan	California	Y	Y	Y
New Zealand	California	Y	N	--
Taiwan	California	N	N	Y
Turkey	California	Y	Y	Y

The differences in the V_{S30} scaling parameter ϕ_1 among the various regions may be affected by the presence of basin effects within the data sets that are not accounted for in this initial evaluation. This may account for the differences between the values for Northern and Southern California earthquakes, as the Southern California earthquake data set contains a large amount of data recorded in deep basins.

5. DISCUSSION AND CONCLUSION

The results presented in this study indicate that potential differences in anelastic attenuation and V_{S30} scaling exist between earthquake data from different regions in the NGA-West2 ground motion database. Ignoring these differences may lead to overestimation of residual standard deviations in a combined regression analysis of the data. Differences in anelastic attenuation may inflate the estimate of earthquake to earthquake variability and differences in V_{S30} scaling may affect estimates of both earthquake to earthquake variability and within earthquake variability. Evaluation of differences in V_{S30} scaling is further complicated by the presence of basin effects in some of the data sets.

The conclusion from this study is that the update to the Chiou and Youngs (2008) GMPE will need to incorporate regional differences in the parameters γ and ϕ_1. The potential for such regional differences will also need to be accounted for when assessing the applicability of the updated GMPE to other active tectonic regions.

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