ABSTRACT

Given the different geology and earthquake activity, establishing a regional attenuation relationship is deemed important for the seismic design of structures. This study presents a ground motion prediction equation (GMPE) model for estimating horizontal ground motion amplitudes caused by shallow crustal earthquakes in the active tectonic region of Taiwan. This model is developed based on an integrated dataset that includes mainly the local Taiwan events with moment magnitude (Mw) greater than 3.5 and partially the global events with only Mw greater than 6.5 from the NGA-West2 database. The function form provided by Chiou and Youngs (2014) (CY14) was considered and adjusted to be appropriate for capturing both large magnitude scaling and regional differences in large distance attenuation for Taiwan region, and was adopted to regress against the selected data using a standard mixed-effect regression approach. In this study, we discuss the regional difference of ground motion in term of the spectral shape, magnitude scaling, depth scaling, style of faulting factors, site effects between Taiwan and California.

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Ground Motion Prediction Equation for Shallow Crustal Earthquakes in Active Tectonic Region of Taiwan

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\textbf{ABSTRACT}

Given the different geology and earthquake activity, establishing a regional attenuation relationship is deemed important for seismic design of structures. This study presents a ground motion prediction equation (GMPE) model for estimating ground motion amplitudes caused by shallow crustal earthquakes in the active tectonic region of Taiwan. This model is developed based on an integrated dataset that includes mainly the local Taiwan events with moment magnitude ($M_W$) greater than 3.5 and partially the global events with only $M_W$ greater than 6.5 from the NGA-West2 database. The function form provided by Chiu and Youngs (2014) (CY14) was considered and adjusted to be appropriate for capturing both large magnitude scaling and regional differences in large distance attenuation for Taiwan region, and was adopted to regress against the selected data using a standard mixed-effect regression approach. In this study, we discuss the regional difference of ground motion in term of the spectral shape, magnitude scaling, depth scaling, style of faulting factors, site effects between Taiwan and California.

\textbf{Introduction}

A key component in seismic hazard calculation is the expected ground motion prediction equation (GMPE) that expresses the predicted intensities measure (such as spectral acceleration or duration) as a function of magnitude ($M$), distance ($R$), and some other predictor variables. The previous researches on the GMPE had been developed for Taiwan area [1–4]; however, these GMPEs were simply formed with just magnitude and distance. In the recent years, a number of GMPEs have been redefining the state of practice for probabilistic seismic hazard analysis (PSHA) in many earthquake prone regions which are summarized in a series of public reports by the second author [5]. The Next Generation Attenuation (NGA) project developed a set of GMPEs for application to multiple regions. The NGA-West1 GMPEs are superseded by the NGA-West2 GMPEs because the NGA-West2 project database greatly expanded the previous PEER (2008) NGA ground motion database to include worldwide ground motion data recorded from shallow crustal earthquakes in active tectonic regimes. The NGA-West2 GMPE models are presented in a series study [6]–[10]. With the advance of knowledge and with the greatly expanded database, the

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NGA-West2 GMPE have been developed involving many more ground motion predictor variables (e.g., $Z_{TOR}$, $V_{S30}$, and $Z_{1.0}$) to describe the ground motion. Examples evolve the effect of depth to top surface rupture, the style of fault, average shear wave velocity in the top 30m ($V_{S30}$), and basin depth ($Z_{1.0}$). As a result, the NGA-West2 models have been widely used as the first priority for many applications.

As one of the five NGA-West2 models, the CY14 function form has been reviewed with respect to the Taiwan empirical dataset to find the key modelling parameters needed to adjust (e.g., near source distance scaling, attenuation rate, site effects, and $Z_{TOR}$—effects). In this study, we first develop a GMPE model for Taiwan and then compare the resulted model with the CY14 model. We finally discuss the regional difference of ground motion in term of the spectral shape, magnitude scaling, distance scaling, depth scaling, site effect between Taiwan and California.

Ground Motion Dataset

The empirical dataset used for the development of GMPE model was selected from the SSHAC_GM_v5_20170331 Taiwan ground motion database (March 31, 2017, version) and the NGA-West2 database (January 17, 2015 version). We supplemented the NGA-West2 flat file with the Fukushima Japan’s earthquake (March 10, 2014 version). Our approach for selecting the subset of data for use in the regression analysis is to include all crustal events, including shallow and deep crustal earthquakes, and aftershocks from Taiwan database. Since there is a lack of ground motion data for large magnitude earthquakes and distance in the near field in Taiwan, foreign ground motion data for earthquakes magnitude greater than 6.50 from the NGA-West2 database have been added. Figure 1 shows scatter plots of $M - R_{RUP}$ (left) and $M - Z_{TOR}$ (right) distribution of the selected recordings for the final dataset. Crustal events in Taiwan can have depth to top of rupture ($Z_{TOR}$) ranging up to 50 km or more while all crustal events in the NGA-West2 database having $Z_{TOR}$ are less than 20 km.

![Figure 1. Plots showing earthquake $M - R_{RUP}$ distribution (left) and $M - Z_{TOR}$ distribution (right) of the selected records.](image)

Each strong station has been assigned a value of $V_{S30}$. Shear wave velocities have been measured or inferred and provided in the database. Figure 2 shows the data distribution of $V_{S30}$ for the selected recordings; no data from hard rock sites (NHERP class A ~ $V_{S30}$ ≥ 1500) and very few data from rock sites (NHERP class B ~ 760 ≤ $V_{S30}$ < 1500). The bulk of the data are from NHERP class C to NHERP class D which ranges from hard soil to medium soil.
Figure 2. Bar chart showing Vs30 bin for records in the selected dataset: (a) Taiwan dataset and (b) NGA-West2 dataset.

**Base-case Model Function Form**

The model formulation for median ground motions is given by Eq. (1) for ground motion on the reference site condition \((V_{S30} = 1130 \text{m/s})\), and by Eq. (2) for ground motion on the surface of soil condition.

\[
\ln(y_{refij}) = c_1 + c_2(M_i - 6) + \frac{c_2 - c_3}{c_n} \ln\left(1 + e^{c_n(c_M-M_i)}\right) + c_4 \ln\left(\frac{R_{RUPij} + C_{NS}}{C_{NS}} + (c_{4a} - c_4) \ln\left(\sqrt{\frac{R_{RUPij}^2 + c_{RB}^2}{R_{UPij}}} + y(M)R_{RUPij}\right) \right)
\]

\[
\ln(y_{ij}) = \ln(y_{refij}) + \phi_1 \cdot \min\left(\ln\left(\frac{V_{S30}}{1130}\right), 0\right) + \phi_2 \left(e^{\phi_3 \min(V_{S30}, 1130) - 360} - e^{\phi_3 (1130 - 360)}\right) \ln\left(\frac{y_{refij} e^{\frac{\phi_1 + \phi_4}{\phi_4}}}{\phi_4}\right) + \eta_i + \epsilon_{ij}
\]

Where \(y_{refij}\) is the pseudo-spectral acceleration (e.g., PGA) at reference site condition. The predictor variables are: \(M = \) Moment magnitude; \(R_{RUP} = \) Closest distance (km) to the rupture plane; \(V_{S30} = \) time-weighted average shear wave velocity (m/sec) of the top 30 m of soil. The random error \(\eta\) and \(\epsilon\) are denoted as the inter-event residuals and the intra-residuals, respectively, and assumed to be normally distributed with zero mean and standard deviation \(\tau\) and \(\phi\). The total standard deviation can be computed as \(\sigma_{tot} = \sqrt{\tau^2 + \phi^2}\).

**Model Setup and Model Development**

The base-case Eq. (1) and (2) can be setup as shown in Figure 3: \(f_{mag}(M, \theta), f_{ant}(M, R, \theta), f_{path}(M, R, Z_{TOR}, \theta)\) and \(f_{Site}(V_{S30}, y_{ref}, \theta)\) represents source dependent function, path function, anelastic function, and site amplification function. The coefficients in red are fixed at those given in CY14, and the coefficients in black are determined from regression.

The magnitude scaling term is semi-linear model incorporating linear term and a complex logarithm of natural exponential function of magnitude. Coefficients \(c_2\) represents the scaling rate at large magnitudes, and coefficient \(c_3\) represents the scaling rate at small magnitudes. Coefficient \(c_M\) is the magnitude at which ground motions turn the scaling rate from large magnitude scaling \((c_2)\) to smaller magnitude scaling \((c_3)\). Coefficient \(c_n\) defines the magnitude range for which the turning takes place. Determination of coefficient \(c_2\) was guided by the analyses of stochastic ground motion model and the empirical source spectra model for California earthquakes [9] need
to be used; thus coefficient $c_2$ was constrained to the value of 1.06 in this study. The coefficients $c_3$, $c_n$, and $c_M$ in Eq. (1) were determined from regression for each period.

Chiou and Youngs (2014) determined the coefficients for $C_{NS}$ by fitting the general distance scaling function form to ground motion data for individual earthquakes with $Z_{TOR}$ less than 20 km. The determination of $C_{NS}$ term requires a full range of near source recordings from small to large events so as to adequate capture the near source scaling. However, there exist numerous offshore earthquakes, and numerous inland earthquakes with hypocenter occurred at a depth up to 50 km or more in Taiwan, leading to a lack of near source recordings. Therefore, the $C_{NS}$ term is not derived through regression in this study, yet we take the advantage of its published value estimated by CY14 to model the near source scaling of Taiwan’s shallow crustal earthquakes. On the contrary, there are 42 events with 3636 recordings with $Z_{TOR}$ greater than 20 km which is equivalent to 25% of total records in the final dataset. Since the coefficient $c_5$ controls the near source scaling of small to moderate earthquakes, so an additional term needs to be added to $c_5$ to capture the extended rupture of Taiwan’s deep crustal events. $C_{NS}$ with its component modifying is then defined by Eq. (3). Figure 4 compares the CY14 relationships for $C_{NS}$ with its values modified by the additional term. The effect of adding the additional term to $C_{NS}$ is presented in the following section.

$$C_{NS} = \left( c_5 + d_p \max \left( \frac{Z_{TOR} - 20}{30} , 0 \right) \right) \cosh \left( c_6 \cdot \max \left( M_i - c_{HM} , 0 \right) \right)$$

The final dataset includes recordings mainly from Taiwan region and partially from worldwide; thus, the regional differences are addressed in term of attenuation rate at large distance (e.g., $Q$ term) and in term of local site effects. A set of coefficients specified to capture the large distance attenuation for the Taiwan dataset is $\{c_{y1}^1, c_{y2}^1, c_{y3}^1, c_{gas}^1\}$ and for the NGA-West2 and Taiwan dataset is $\{c_{y1}^0, c_{y2}^0, c_{y3}^0, c_{gas}^0\}$. The coefficient $c_{gas}^1$ is used to fit the aftershock events since the event number of aftershock in the dataset is significant with 39 events contributing up to 24% of the total recordings used in the model development. Analysis of ground motion characteristic

Figure 3. Model setup showing for $lnSa_{ij}$ as a combination of a series of function components. The constrained and regressed coefficients are marked in red and blue, respectively.
in Taiwan induced by aftershock events indicated the faster decay with distance than that induced by main shock events [11]. The inclusion of $c_{gas}$ makes the magnitude dependent anelastic attenuation to be expressed by Eq. (4).

$$\gamma(M) = \left\{ c_{\gamma 1} + c_{gas} A_S + \frac{c_{\gamma 2}}{\cosh\left(\max\left(M - c_{\gamma 3}, 0\right)\right)} \right\}$$ (4)

The $Q$ term, $\gamma(M)R_{RUP}$, was assessed in CY14 by fitting data for individual earthquakes to account for data truncation at low amplitudes and large distance (e.g., [12]-[13]). In contrast, in this study we develop $\gamma(M)$ by using Eq. (1) and (2) for regression against using whole dataset because each individual event does not provide sufficient data for a reasonable constraint on the value of $\gamma$. Figure 5 shows the comparison of $\gamma(M)$ together with $\gamma$ derived from 0.5 overlapping magnitude bin for period of 0.01s and 2s. The results show that the attenuation rate in term of $\gamma(M)$ from this study is faster decay than from CY14. This behavior is likely due to the regional difference in $Q$ between Taiwan and California.

Figure 4. Comparison of $C_{NS}$ modified (red curve) by fitting to the Taiwan’s deep crustal events ($Z_{TOR} \geq 20$ km) to $C_{NS}$ relationships developed by Chiou and Youngs (2014) (blue curve).
The median response spectra for the resulted model are compared with the CY14 model in Figure 7 for a vertical strike slip scenarios at an $E_{ZTOR} = f(M)$ km, $R_{RUP} = 30$ km, and $V_{S30} = 760$ m/s and 270 m/s, respectively. It shows that the median spectra from the resulted model are higher than those from CY14 for $M = 5$, but similar to those from CY14 for $M = 5, 6, 7, \text{and } 8$. The difference between the two models for soil site ($V_{S30} = 270$ m/s) is about period range from 0.2s to 0.75s.

Figure 7. Comparison of the median spectral acceleration from the resulted model with the median from the CY14 model.
The distance scaling and the magnitude scaling are shown in Figure 8 and Figure 9 in comparison with the CY14 model for period of 0.01s and 2s. In these figures, the median ground motion from vertical strike slip on reference rock site condition ($V_{S30} = 760$ m/s) is computed for $M = 4, 5, 6, 7, \text{ and } 8$ and for $R_{JB} = 1, 10, 30, 100, \text{ and } 200$ km.

![Vertical Strike Slip](image1.png)

Figure 8. Comparison of the scaling with distance for the resulted model with the CY14.

![Vertical Strike Slip](image2.png)

Figure 9. Comparison of the scaling with magnitude for the resulted model with the CY14.

**Deep Crustal Events**

We examine the effectiveness of adding the additional term to $C_{NS}$ by observing the variability of inter-event residuals. The resulted model can have either a reduction in standard deviation of inter-event residuals or a reduction in the slope of inter-event residuals with respect to $Z_{TOR}$. An example in Figure 10 shows our achievement. Figure 11 shows the goodness of fit of the resulted models to observation data: the 2003 June 10, $M = 5.98$, $Z_{TOR} = 31.36$ km earthquake and the 2009 December 19, $M = 6.47$, $Z_{TOR} = 35.1$ km earthquake. Visually, additional term has impact on near source distance scaling providing our GMPE with a better fit to observation data.

![Inter-Event residuals](image3.png)

Figure 10. Inter-Event residuals resulted from the regression model with and without additional
term plotted against $Z_{TOR}$.

Figure 11. The goodness of fit of the current models to observation data of the deep crustal events ($Z_{TOR} \geq 20$ km) for two cases: the predicted models are estimated without additional term (ypred-1: green-star symbols) and with additional term (ypred-2: red-cross symbols). The corresponding solid colored curves indicate the predicted models for the average $V_{S30}$ of the data (mean-1 and mean-2).

**Aftershocks Events**

Similarly, we examine the effectiveness of adding the additional term to $\gamma(M)$ by observing the variability of inter-event residuals. The resulted model with and without additional term have undistinguishable standard deviation of inter-event residuals, but can remove mean offset of inter-event residuals for the case with additional term as shown in Figure 12. Figure 13 shows the goodness of fit of the resulted models to observation data of two Taiwan aftershock events: the 1999 September 25, $M=6.49$, $Z_{TOR}=10$ km earthquake and the 2005 March 05, $M=6.47$, $Z_{TOR}=6.48$ km earthquake. Visual inspection indicates that $c_{gas}$ has impact on far source scaling providing our GMPE with a better fit to observation data.

Figure 12. Inter-Event residuals resulted from the regression model with and without additional term plotted against $M$. The effectiveness of additional term can reduce mean offset of inter-event residuals.

**Style of faulting effects**

Depth to top of rupture, $Z_{TOR}$ is used to model the source depth scaling in our GMPE. Taiwan source lacks the large magnitude above 6.5; thus, $Z_{TOR}$ in the NGA-West2 database are
used combination with $Z_{TOR}$ from Taiwan allowing us to adjust the $Z_{TOR} - M$ relationship of Chiou and Youngs (2014). The adjusted $Z_{TOR} - M$ relationship for the reverse faulting and for

Figure 13. The goodness of fit of the current models to observation data of the aftershock events for two cases: the predicted models are estimated without considering $c_{yas}$ (ypred-1: green-star symbols) and with considering $c_{yas}$ (ypred-2: red-cross symbols). The corresponding solid colored curves indicate the predicted models for the average $V_{s30}$ of the data (mean-1 and mean-2).

the combined strike-slip and normal faulting are developed. Figure 14 shows inter-events residuals computed for an interim GMPE without style of faulting effects. As shown in Figure 14, the formulation given in CY14 tracked the binning over magnitude of inter-event residual quite well; As a result, it can be used to satisfactorily fit the magnitude dependent effects of faults type.

Figure 14. Magnitude-dependent of the inter-event residuals after removing the $Z_{TOR}$ magnitude dependent.

Discussions and Conclusions

The study addresses the findings which can be considered as three aspects of regional difference between Taiwan and CY14 (one of the representative model for California) as followings: (1) the results presented in this study indicate that potential regional differences in which anelastic attenuation and Vs30 scaling exhibit on the results between Taiwan data and data from different regions in the NGA-West2 database. Ignoring these differences may lead to overestimation in residuals standard deviations in a combined regression analysis of the data. (2) the inclusion of an additional term modifying the near source additive distance tem to capture the extended source of deep crustal earthquakes in Taiwan, specifically to those with $Z_{TOR}$ greater than 20 km. This finding is deemed important for design of structures since the tectonic seismology
of Taiwan often causes many deep crustal events. Having concern about these depth events can be considered as a regional aspect of $Z_{TOR}$ scaling because most worldwide crustal earthquakes presented in the NGA-West2 database are shallow depth with $Z_{TOR}$ less than 20 km. While the NGA-West2 models applicable to predicting Taiwan depth crustal events consider extrapolating ground motion beyond 20 km depth, the depth crustal data available to help us accommodating the near source additive term developed in CY14 and thus verify the NGA-West2 models predicting the near surface ground motion. (3) Introduction $c_{gas}$ to the original $\gamma(M)$ is used to separate the faster attenuation rate of aftershocks from main-shocks. The number of aftershock events are significant contributing useful recordings not only to have a good constrain on site parameter ($\phi_1$) and intra-variability but also to be useful for predicting ground motion induced by aftershocks. This study indicates a reduction of approximately 20 % changes in attenuation rate resulted from aftershocks as compared to that from main-shocks.

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