A Comparison of NGA Ground-Motion Prediction Models with Taiwan Models and Data

YU-WEN CHANG
Department of Civil Engineering, National Taiwan University, Taipei, Taiwan

WEN-YU JEAN
National Center for Research on Earthquake Engineering, Taipei, Taiwan

CHIN-HAIUNG LOH
Department of Civil Engineering, National Taiwan University, Taipei, Taiwan

SUMMARY:
The tectonic environment causes of the high seismicity in and around the Taiwan Island. The earthquake hazard mitigation consequently is an important issue. A key parameter in the estimation of seismic hazard is the consideration of ground motion intensity. Recently, the attenuation relation has been redefining the effect s of these parameters for describe the ground motion evaluation, such as the Next Generation Attenuation (NGA) project. About six Taiwan earthquakes with magnitude greater than 5.9 were collected in the NGA dataset. It provides an opportunity for inspecting the attenuation relation in Taiwan. This paper aims at comparing the model parameters and results between the NGA models and the Taiwan models. Based on the attenuation models, the simply response spectrum in Taiwan for most engineering applications can be compared with the uniform response spectrum of NGA models.

Keywords: Attenuation relation, NGA models, Ground motion prediction, simplified response spectrum

1. INTRODUCTION

Taiwan is located at the convergent plate boundary where the Eurasian plate has been eastward underthrusting and colliding with the Philippine Sea plate at a rate of about 70 to 80 *mm/yr*. This tectonic environment results in high seismicity in and around the Taiwan. The statistics shows that more than 7,780 people were died due to the damaging earthquakes in the last century (Cheng *et al.*, 1999). In addition, the majority of the catastrophic earthquake events such as the 1999 Chi-Chi earthquake occurred at the western area of Taiwan which possesses the higher population. Undoubtedly, earthquake hazard mitigation is an important issue in Taiwan.

A key parameter in the estimation of seismic hazard is the consideration of ground motion intensity. The attenuation relation is probabilistic descriptions of the level of ground motion as a function of the earthquake. The trustworthy calculation of the probabilistic seismic hazard analysis (PSHA) depends on the attenuation relation. This relation describe the variation of the median and lognormal standard deviation of ground motion measures (such as peak ground acceleration, spectral acceleration) with magnitude, distance, site condition, and other parameters. The previous researches on the ground-motion attenuation relation have been developed (e.g., Campbell, 1981; Joyner and Boore, 1981; Abrahamson and Silva, 1997; Campbell, 1997) as well as in Taiwan (e.g., Tsai et al., 1987; Shin, 1998; Wu et al., 2002; Jean et al., 2006; Lin and Lee, 2008). With the advance of knowledge regarding ground-motion attenuation characteristic, the relevant parameterizations or functional forms have been applied to describe the ground-motion attenuation characteristic in attenuation relations. Examples include the effect of depth to top of surface rupture, average shear-wave velocity in the top 30m (V_{s30}) for site categories, the style of fault, and nonlinear site response. Recently, the attenuation relation has been redefining the effects of these parameters for describe the ground motion evaluation, such as the Next Generation Attenuation of Ground Motions (NGA) project of PGA and response spectral for shallow crustal earthquakes in active tectonic regions.

For the development of ground-motion model, a high-quality ground motion database is an important key to the successes. Taiwan government supported an extensive seismic instrumentation program, which operated by the Central Weather Bureau (CWB) for the populated areas with dense digital strong-motion networks. This instrumentation program consists of two networks around Taiwan: (1) The Taiwan Rapid Earthquake Information Release System (TREIRS, also known as the Real-Time Digital stream output system, RTD); and (2) The Taiwan Strong Motion Instrumentation Program (TSMIP). The RTD system using a real-time strong-motion accelerograph network consisting more than 80 stations is currently capable of routine broadcasting of the earthquake location and its magnitude about one minute after the occurrence of an earthquake (Wu et al., 2002). The TSMIP system, composed of more than 700 stations that are spaced approximately 5 km apart in populated areas, is widely deployed in Taiwan area. Figure 1 shows the locations of TSMIP and RTD networks in the Taiwan. Since 2000, CWB and National Center for Research on Earthquake Engineering (NCREE) have been establishing a free-field strong-motion station drilling project to construct the Engineering Geologic Database for TSMIP (EGDT) (Kuo et al., 2011). Till 2010, the site investigation at 469 TSMIP stations was completed which all the results of investigation are systematically organized in the EGDT project. With detailed subsurface soil profile and quantitative soil properties (SPT-N values and wave velocities) on a station site, the site effect of ground motions could be thoughtfully analyzed for a certain class of site conditions. Accordingly, a large amount of the high quality earthquake records were collected by the network of TSMIP can be used in this study for ground-motion attenuation relation development as well as for engineering practice. It also supplies the NGA database with the records of 1999 Chi-Chi, Taiwan, earthquake and its 5 aftershocks (Chiou et al., 2008).

It is of interest to evaluate whether the NGA models can be applied in Taiwan. There is an opportunity for inspecting the attenuation relation in Taiwan. This objective is to examine this issue by testing the ability of Taiwan models to capture the NGA models. Because of the past limited geologic datasets cannot resolve many significant fault parameters and site effects. The Taiwan models, such as Jean et al. (2006), use the simple parameters of magnitude and distance to evaluate the ground-motion value. This paper aims at comparing and discussing the model parameters, and results from the NGA models and the Taiwan models. In addition to the determination of the peak ground acceleration (PGA) attenuation equation, we also determine the spectral acceleration (SA) attenuation relations for engineering application purposes. Besides the attenuation models, the simplified response spectrum in Taiwan, which was built with respect to PGA, spectral acceleration response at period of 0.3 seconds and spectral acceleration response at period of 1.0 second, for most engineering applications can be compared with the response spectra by NGA models. On the basis of these comparisons, it is believe that attenuation relations in Taiwan will more appropriately describe the ground motion estimation including the fault effect or site effect.

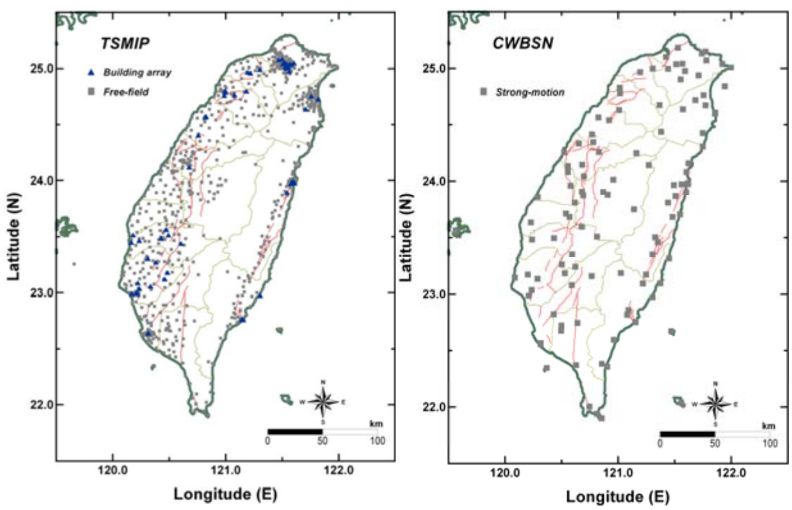


Figure 1. The station locations of TSMIP (left) and TREIRS (right) networks.

2. GROUND-MOTION DATABASE

Among the earthquake events occurred from 1991 to 2008, fifty-eight earthquake events with the magnitude of greater than M_L5.5 and depth of smaller than 35 km were selected. The locations of the epicenters of those 58 selected earthquake events are depicted in Figure 2, from which the main shock and five large aftershocks of the 1999 Chi-Chi earthquake are also observed. Considering the lack of near source earthquake data for the RTD network and the distribution of hypo-central distance, a hybrid database was collected from both the RTD and TSMIP networks for developing the rock-site attenuation relationships: (1) all the RTD earthquake data, and (2) the TSMIP data those with hypo-central distance less than 50.0 km. Based on the database of Engineering Geologic Database for TSMIP (EGDT), the site classifications of Taiwan free-field strong-motion stations were determined. From those fifty-eight selected earthquake events, 302 earthquake histories recorded by the TSMIP and RTD network were adopted in the desired analysis database. This is a small number of records because it only includes rock sites that the Vs30 of site is greater than 760 m/sec. Distributions of the magnitude and hypo-central distances in this data set are shown in Figure 3. The magnitudes of the selected earthquakes are between M_L 5.5 and 7.3, with distances of 0 to 200 km. However, the all of earthquake data collected from the 1999 Chi-Chi earthquake the closest distances to the surface fault rupture were used to improve lack of the near fault data. Obviously, using the extensive analysis database instead of the previous one is capable of determining the more adequate distribution of ground-motion data. The site effect of ground motions could be thoughtfully analyzed for a certain class of site conditions.

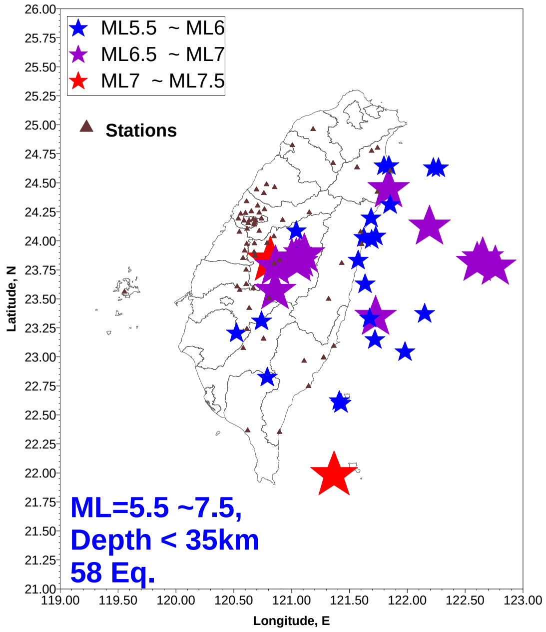


Figure 2. The locations of stations which the greater than 760 m/sec and the epicenter of 58 selected earthquake events in the Taiwan.

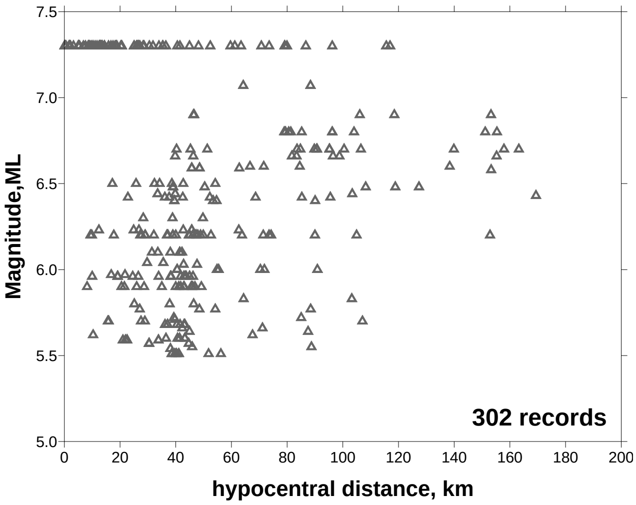


Figure 3. The magnitude and distance distribution of the ground-motion data set used in this study.

3. ATTENUATION RELATIONSHIP DEVELOPMENT

The attenuation relations are probabilistic descriptions of the level of ground motion as a function of the earthquake magnitude, distance and site parameters. The Campbell's attenuation form (Campbell, 1981) can reasonably predict the characterization of ground motion attenuation for TSMIP array data, and is applied in this study. The Campbell's form is expressed as

$$Y_r(g) = f(M,R) = C_1 e^{C_2 M} \left[R + C_4 \exp(C_5 M)\right]^{-C_3} \qquad (1)$$

where Y_r is peak ground acceleration (or the spectral acceleration), M is local magnitude, and R is source-site distance, the coefficients C_1, C_2, C_3, C_4 and C_5, were obtained by regression analysis of earthquake data. The significant feature of the Campbell form is the term, $C_4\ e^{C_5 M}$, which describes a magnitude dependence of the transition from near-field to far-field attenuation and it reflects a distance saturation that depends on the extent of fault rupture. The source-site distance R for the present study is taken as the hypo-central distance; however, for the earthquake data collected from the 1999 Chi-Chi earthquake the closest distances to the surface fault rupture were used. In the regression analysis the geo-mean va1ue of two horizontal peak ground acceleration values for sites have been used to establish the attenuation relations.

Regression analysis was preformed to fit the attenuation relations. Coefficients of PGA, PGV, and SA at spectral periods between 0.01 s and 10 s for the median ground motion were determined through regression analysis and the standard deviations were obtained. Since each regression analysis was performed on the natural logarithm of peak acceleration, it implies that the PGA is lognormal distributed. The coefficients for all parameters of PGA, two periods of the SA attenuation relationships are tabulated in Table 1. Figure 4 shows a comparison of the earthquake data with these different intensity attenuation relationships which including the kinds of PGA, S_{as}(T=0.3s), S_{a1}(T=1.0s). The standard deviation of the natural logarithm of the peak ground accelerations, σ_{lnErr}=0.66-0.85, representing the dispersion about their respective median value was calculated.

The reactivation of the Chelungpu fault triggered the 1999 Chi-Chi Taiwan earthquake (M_L7.3, M_w7.6) which caused a 92 km long surface rupture that trends north to south. The surface ruptures trend from N30°W to N20°E and dip about 20°–30°E (Chen et al., 2004). It is a typical reverse fault of a shallow dip angle. Estimates of PGA, S_{as}(T=0.3s), and S_{a1}(T=1.0s) from Taiwan models are compared with those from the NGA models of BA08(Boore and Atkinson,2008),CB08(Campbell and Bozorgnia,2008) and CY08(Chiou and Youngs,2008) that the assumptions are use the parameters of Chelungpu fault, as shown in Figure 5. Moreover, there are about 190 observed data from rock site(Vs_{30}≥360 m/sec) which are collected from Taiwan strong motion network also were showed in Figure 5. As shown by Taiwan models, the Chi-Chi earthquake records and NGA predicted medians generally compare well over the range of distances well constrained by the data. The slopes of the median curves for a given magnitude are generally steeper for the Taiwan models than NGA models, suggesting faster distance attenuation especially the pseudo-spectral acceleration at 1.0 s.

Based on the work of the dispersion analysis of attenuation form, the residual, $\ln Err$, is defined as the difference between the observed value and that predicted by the median attenuation form of the natural logarithm of PGA or Sa-value. It is expressed as

$$\ln Err_i = \ln PGA_i - \ln \overline{PGA_i} \qquad (2)$$

where PGA_i is the PGA value (or S_a-value) of the observed earthquake record of station i and $\overline{PGA_i}$ is that predicted by the median attenuation form. Based on these 190 records of 1999 Taiwan Chi-Chi earthquake and the geologic parameters of Chelungpu fault, the variation of standard deviation in each attenuation relation is listed in Table 2. The distribution of the residual for each attenuation relation is shown in Figure 6. Comparison on the PGA and Sa-value between observed data and those calculated from the attenuation relations is constructed. For the case that the data points fall onto the dashed line means that the attenuation relation can predict well for this site. The results show that the epistemic uncertainty of different attenuation relation with using Taiwan observed data represents the approximately standard deviation. It indicates that the attenuation relation including simple parameters with magnitude and distance of site to source for describing the ground motion estimation in Taiwan is adapted.

4. RESPONSE SPECTRUA

4.1. Simplified response spectrum

For the particular site, especially near the fault, a deterministic approach to seismic hazard assessment (DSHA) will be used to decide the seismic demand. DSHA defines a maximum credible earthquake (MCE) in terms of magnitude and location and then calculates the ground-motion value by attenuation models. A common approach for estimating the MCE is from the largest historical earthquake. For a given pair of MCE and distance, the simplified design response spectrum is defined for seismic design.

The seismic design code for buildings in Taiwan, the elastic seismic demand is represented by the design spectral response acceleration S_{aD} corresponding to a uniform seismic hazard level of 10% probability of exceedance within 50 years. In addition, utilizing the uniform hazard analysis, the mapped design 5%-damped spectral response acceleration at short periods (S_{DS}) and at 1 second (S_{D1}) have been tabulated for each municipal unit of village, town or city level. For the sake of simplicity, the design spectral response acceleration S_{aD} for a given site can be developed directly from the design spectral response acceleration S_{DS} and S_{D1} as well as the corner period T_0. It can be expressed as:

$$S_{aD} = \begin{cases} S_{DS}\left(0.4 + 3T/T_0\right) & ; \quad T \le 0.2T_0 \quad (very \quad short \quad period) \\ S_{DS} & ; \quad 0.2T_0 < T \le T_0 \quad (short \quad period) \\ S_{D1}/T & ; \quad T_0 < T \le 2.5T_0 \; (medium \quad long\ period) \end{cases} \quad \text{with} \quad T_0 = \frac{S_{D1}}{S_{DS}} \tag{3}$$

where T is the structure's fundamental period. The shape of the simplified design response spectrum is illustrated in Figure 7.

Based on the source characteristic of 1999 Chi-Chi earthquake, the simplified response spectrum that was described by the spectral response acceleration relations at short periods, S_{as}(T=0.3s), and at 1 second, S_{a1}(T=1.0s), in Taiwan code and the median response spectra by NGA models are compared in Figure 8. It indicates that the median spectral for NGA models and value of the simplified response spectrum at short periods are similar. At long period after the corner period T_0, the simplified response spectrum show the strongest result than the other models. It shows that the simplified response spectrum in MCE or a scenario earthquake at a particular site can proper to use in seismic design.

Table 1. The coefficients of attenuations forms in this study

Period	C_1	C_2	C_3	C_4	C_5	σ_{lnErr}
PGA	0.00466	1.72882	2.06573	0.11318	0.80312	0.6619
S_{as}(T=0.3s)	0.00858	1.73017	2.06507	0.11954	0.79494	0.7231
S_{a1}(T=1.0s)	0.00337	1.72920	2.06569	0.12046	0.79585	0.8457

Table 2. The epistemic uncertainty of different attenuation relation with using Taiwan observed data

	Taiwan			CB08			CY08			BA08		
	PGA	$Sa_{0.3s}$	$Sa_{1.0s}$	PGA	$Sa_{0.3s}$	$Sa_{1.0s}$	PGA	$Sa_{0.3s}$	$Sa_{1.0s}$	PGA	$Sa_{0.3s}$	$Sa_{1.0s}$
$\sigma_{921data}$	0.552	0.626	0.685	0.543	0.647	0.617	0.527	0.624	0.631	0.500	0.599	0.617
σ_{form}	0.633	0.660	0.830	0.478	0.544	0.568	0.563	0.591	0.581	0.566	0.608	0.654

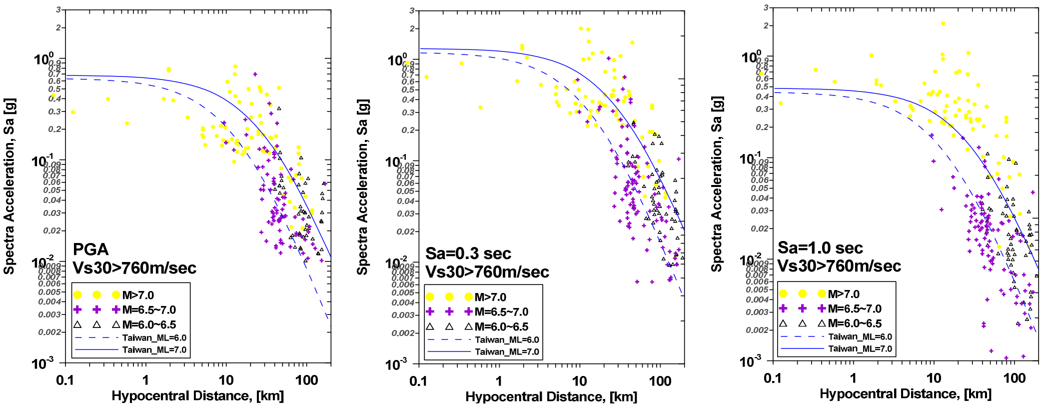


Figure 4. Comparison of the earthquake data with the attenuation forms.

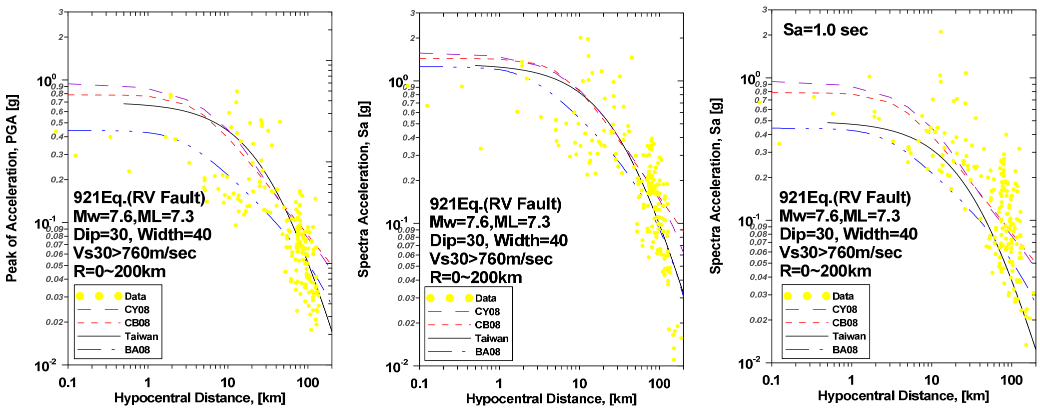


Figure 5. Comparison of median predictions of peak ground acceleration (PGA) and pseudo-spectral acceleration of period at 0.3s, 1.0s for reverse fault and rock site conditions from NGA, Taiwan models and the Chi-Chi earthquake records(distance range is 0-200km). Assumed condition is dipping fault with zero depth to top of rupture, for which $R=R_{rup}$.

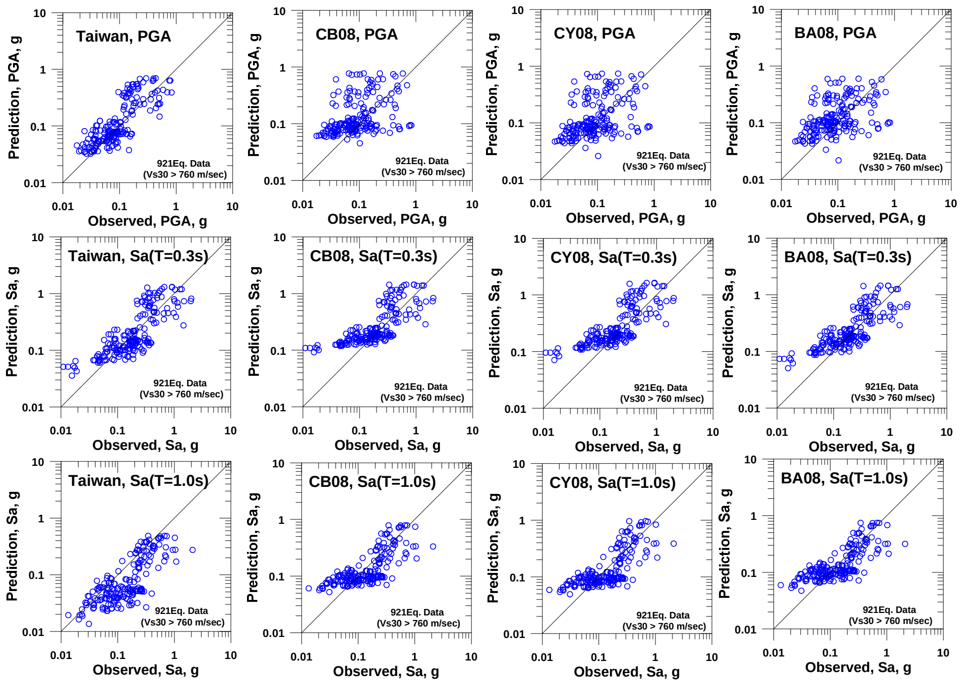


Figure 6. The distributions of the residual for attenuation relations

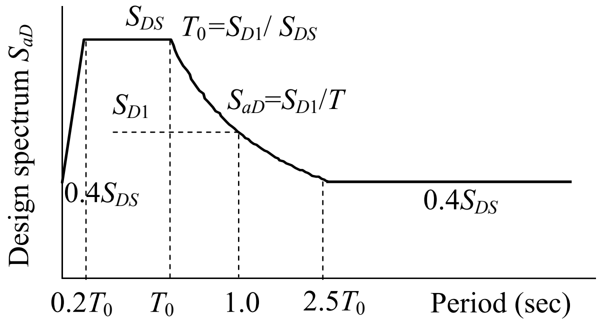


Figure 7. Simplified design response spectrum developed by site-adjusted parameters S_{DS} and S_{D1}

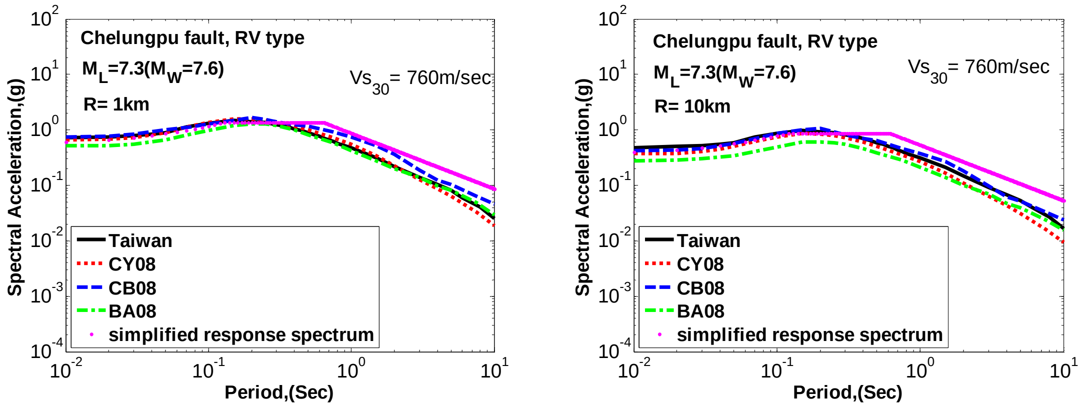


Figure 8. Comparison of the median spectra for NGA models and simplified response spectrum that is developed by Taiwan models of S_{as}(T=0.3s) and at 1 second, S_{a1}(T=1.0s).

4.2. **Median response spectra**

The median response spectra for M=5.0, 6.0, and 7.0 for earthquake for rock site condition at different distances are compared in Figure 9. For M7.0, the predictions of Sa-value for each attenuation relation are similar. At the smaller magnitude, the NGA models have a large reduction in the long-period ground motion, but the Taiwan models do not have an effect on long-period ground motion for the rock site. This is due to the functional form and small database.

A bin-array inside particular magnitude and distance of the seismic records is established. Seismic array apertures of the range of distance and magnitude are 0 km to 200 km and M_L5.5 to M_L7.5, respectively. In each M-R bin, it consists about 10-100 observed records and sorts the site conditions by Vs_{30}≥760 m/sec and Vs_{30}=360-760 m/sec. For a given M-R bin and its representative of magnitude and distance, the observed response spectra and median response spectra of NGA and Taiwan models are compared. Figure 10 shows the comparison of the response spectra between observed and median prediction of attenuation relations. For the part (a), the spectral for different magnitude are compared. It shows that the observed spectra on long period for smaller magnitude for soft site are decreased. In the part (b), the median spectra are similar with observed spectra at smaller magnitude. There shows that the estimation by Taiwan model almost is overestimated at long-period ground motion. For the larger magnitude and closest distance, the predictions by each model and observed data are similar. It indicates that the site condition cannot affect the ground-motion attenuation characteristic on the larger magnitude and closest distance.

5. CONCLUSIONS

Because the attenuation models are an important parameter for PSHA and DSHA, the more precise estimation for the ground-motion value by attenuation models is needed. The NGA models are formulated with varying degrees of complexity in the functional form as a result of author preference. This study has investigated the compatibility of the attenuation relation in Taiwan with the models established by the Next Generation Attenuation (NGA) project for shallow crustal earthquakes in active regions. In this study, the rock site (Vs_{30}≥760 m/sec) data from Taiwan TSMIP array were used to develop the attenuation relations of PGA, and SA at spectral periods between 0.01 s and 10 s. However, for the earthquake data collected from the 1999 Chi-Chi earthquake the closest distances to the surface fault rupture were used. It improves the lack of the information of site condition in the past study and provides an exactly attenuation relation for rock site in Taiwan. The seismic demands for a particular site can be obtained by predicting ground-motion value that is generated by hazard analysis for structural seismic design and earthquake loss estimation. The results indicates that the ground motion prediction model in Taiwan shows the approximately evaluation as compared with the NGA models. It means that the attenuation relation including simple parameters for describing the ground motion estimation in Taiwan is adapted. Obviously, using Taiwan models to estimate the spectra acceleration at long period is largest than real data and NGA models. It should be more discuss with the functional form of magnitude scaling and distance scaling in the future.

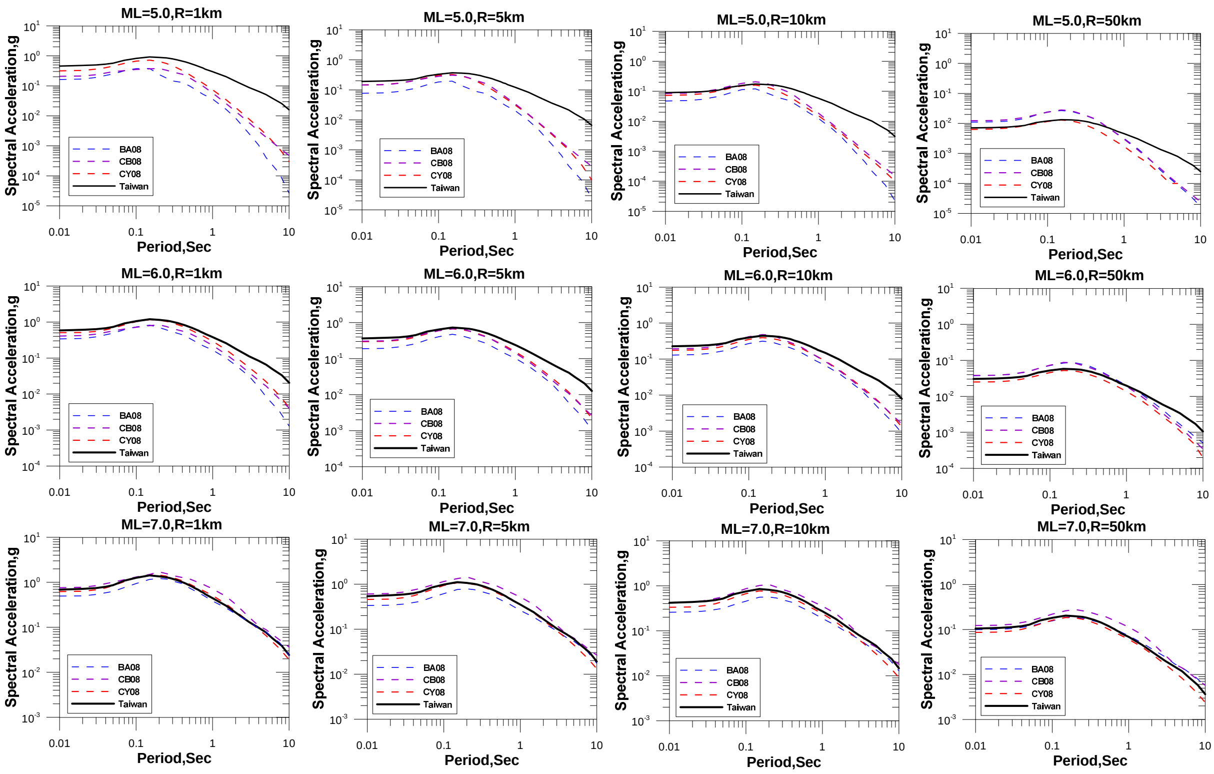
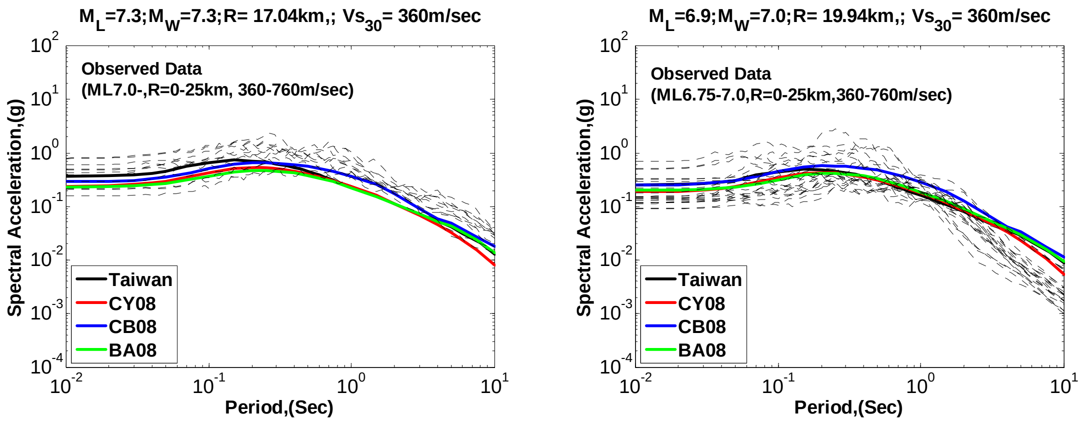
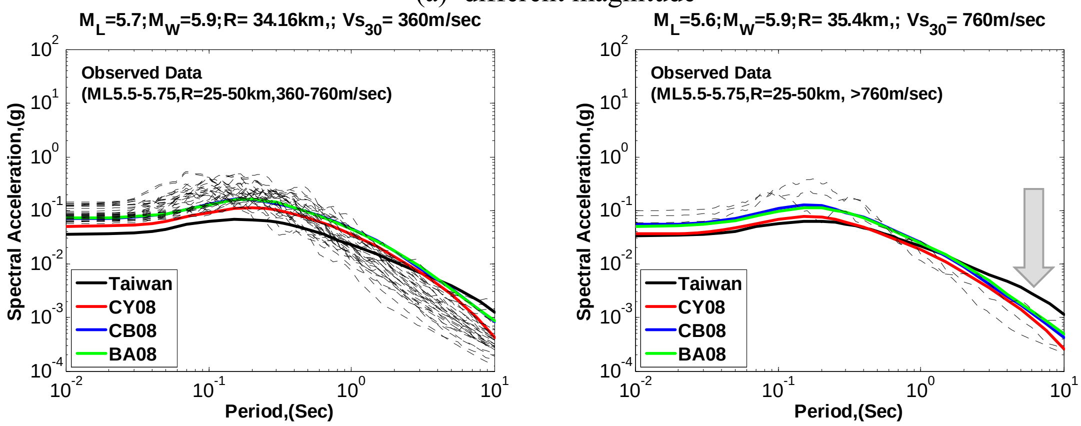


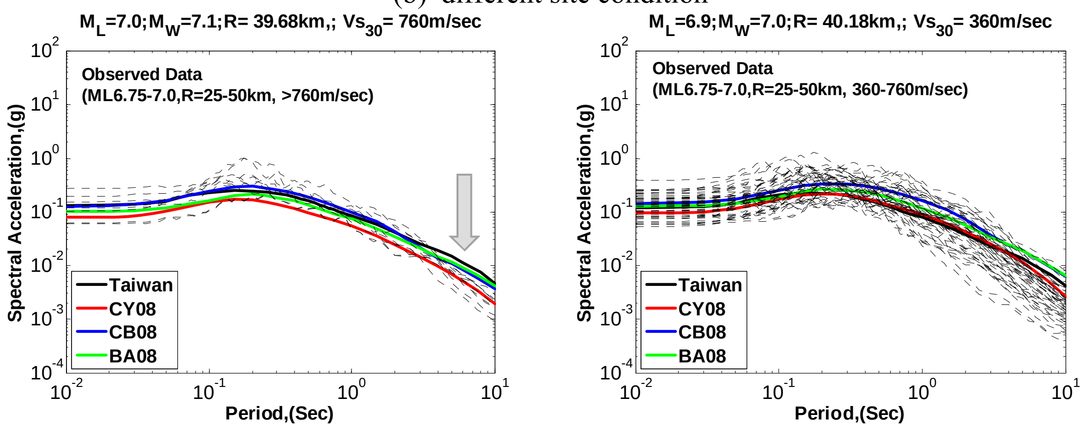
Figure 9. Predicted dependence of 5% damped acceleration response spectra on magnitude and distance. The ground motion model is evaluated for M_L=5.0, 6.0, 7.0 and R=1, 5, 10, 50 km. Assumed condition is F_{RV}=F_{NM}=0, R=R_{rup}. (The local magnitude ML was converted to the moment magnitude Mw by Wu et al.(2001))



(a) different magnitude



(b) different site condition



(c) different distance and site condition

Figure 10. Comparison of median spectra for different M-R bins with rock and soft site conditions.

AKCNOWLEDGEMENT

The study was supported by the National Center for Research on Earthquake Engineering (NCREE) of Taiwan. The support is acknowledged. Immense gratitude is conveyed to Central Weather Bureau (CWB) in Taiwan for the great support of rich earthquake data in TSMIP network to this study.

REFERENCES

Abrahamson, N.A. and Silva, W.J. (1997) .Empirical response spectral attenuation relations forshallow crustal earthquakes, *Seismological Research Letters* **68:1**, 94-127

Joyner, W. B., and D. M. Boore (1981). Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake, *Bull. Seismol. Soc. Am.* **71**,

2011–2038.
Boore D. M. and Atkinson,G. M. (2008). Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s, *Earthquake Spectra* **24**, 99-138.
Campbell, K.W. (1981). Near-Source Attenuation of Peak Horizontal Acceleration, *Bull. Seism. Soc. Am.***71:6**, 2039-2070.
Campbell, K. W. (1997). Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra, *Seismological Research Letters* **68:1**, 154 -179.
Campbell K. W. and Bozorgnia, Y. (2008). NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10s, *Earthquake Spectra* **24**, 139-171.
Chen, W.S., K.J., Lee, L.S., Lee, Daniel. J. Ponti, C., Prentice, Y.G., Chen, H.C., Chang, Y.H. Lee (2004) Paleoseismology of the Chelungpu fault during the past 1900 years, *Quaternary International* **115:116**, 167-176.
Cheng, S.N., Y.T. Yeh, M.T. Hsu, and T.C. Shin, (1999), Photo Album of Ten Disastrous Earthquakes in Taiwan, *Report CWB-9-1999-002-9,* Central Weather Bureau.
Chiou B. S. J. and Youngs, R. R. (2008). An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra, *Earthquake Spectra* **24**, 173-215.
Jean, W.Y., Chang Y.W., Wen K.L. and Loh C.H. (2006), Early Estimation of Seismic Hazard for Strong Earthquakes in Taiwan, *Natural Hazard* **37**, 39-53.
Kuo, C. H., K. L. Wen, H. H. Hsieh, and K. W. Kuo (2011). Introduction of the Geological Database for TSMIP, *8CUEE Conference Proceedings, Tokyo, Japan*, 157-163.
Lin, P.S., Lee, C.T. (2008). Ground-motion attenuation relationships for subduction-zone earthquakes in Northeastern Taiwan. *Bull. Seismol. Soc. Am.* **98**, 220–240.
Shin, T. C. (1998). A preliminary study of earthquake early warning system in the Taiwan area, *Meteorol. Bull.* **42:2**, 118–134 (in Chinese).
Tsai, C. C., C. H. Loh, and Y. T. Yeh (1987). Analysis of earthquake risk in Taiwan based on seismotectonic zones, *Mem. Geol. Soc. China* **9**,413–446.
Wu, Y. M., T. C. Shin, and C. H. Chang (2001). Near real-time mapping of peak ground acceleration and peak ground velocity following a strong earthquake, *Bull. Seismol. Soc. Am.* **91**, 1218–1228.
Wu, Y.M., Hsiao N.C., Teng T.L. and Shin T.C. (2002). Near Real-Time Seismic Damage assessment of the Rapid Reporting System, *TAO* **13:3**, 313-324.