Analysis of Single-Station Sigma Using Single-station GMPE by Huge Ground-Motion Data in Taiwan

■ Abstract ■

Recent studies have found that the aleatory uncertainty and epistemic uncertainty is not easy to distinguish when analyzing the single-station variability because the elements of aleatory variability that are treated as being random, but come from the epistemic uncertainties. In this study, we propose the single-station GMPE to solve this problem. This GMPE is established from observed records by a station, so its site uncertainty can be ignored directly. In here, we use 150 crustal earthquakes with moment magnitudes greater than 4.0 obtained from the Taiwan Strong-Motion Instrumentation Program network to build 305 single-station GMPEs. The nonlinear regression analysis of ground-motion prediction model is the mixed-effect model with maximum likelihood method. Comparing the total sigma (σ_T=0.621), general single-station sigma which is estimated by the variability decomposition method (σ_{ss}=0.576) and the single-station sigma of single-station GMPEs ($\sigma_{ss,station}$=0.420-0.522). The result shows the $\sigma_{ss,station}$ is the smallest variability and always depends on the regional site. Finally, we advance the new approach which is the spatial-correlation mobile widow to analyze the single-path sigma for each station and using this sigma in PSHA, the resultant hazard level would be 20% lower than the traditional one in 2475 return period.

■ Introduction ■

It is well known that the results of PSHA are susceptible to the sigma of GMPEs, and, even small reductions in sigma may have a significant impact on the hazard level in particular for a long return period (Restrepo-Velez and Bommer, 2003; Bommer and Abrahamson, 2006) (**Figure 1**).

The aleatory variability only represents the variability of motions expected at a single site over many earthquakes; it is related to the inevitable unpredictability of ground motion parameters, and it is irreducible. The epistemic uncertainty reflects incomplete knowledge and limitations in the available data for GMPEs. Epistemic uncertainty should be incorporated into PSHA using a logic tree method, instead of a mixing of aleatory variability (Anderson and Brune, 1999a,b; Anderson *et al*., 2000; Bommer *et al.* 2005; Bommer and Abrahamson, 2006) **(Figure 2**).

In this study, we established the single-station GMPE to solve the mixing problem. This GMPE can ignore site uncertainty (the part of epistemic uncertainty) directly.

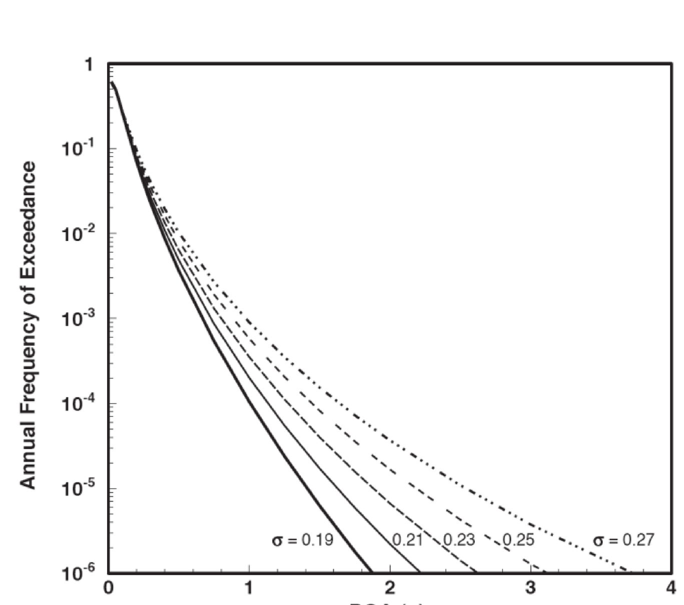


Figure 1. Different sigma results in different hazard level. (Bommer and Abrahamson, 2006)

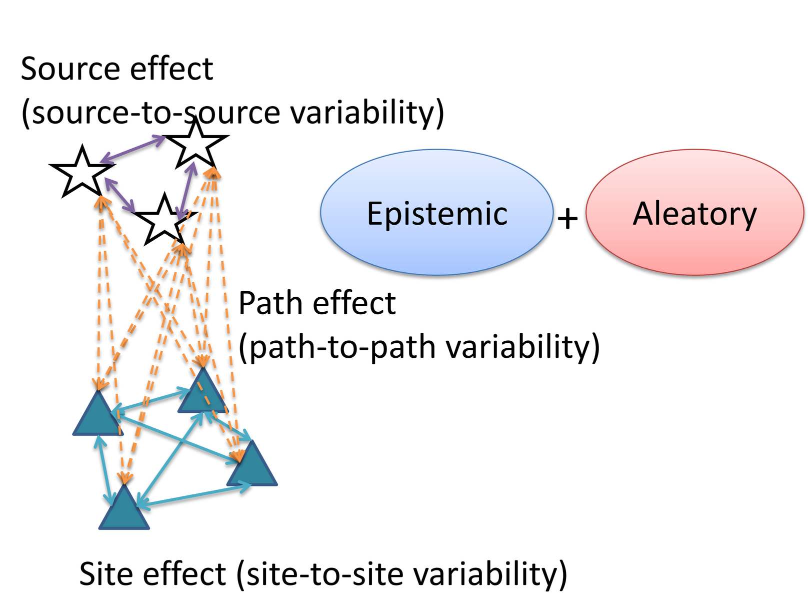
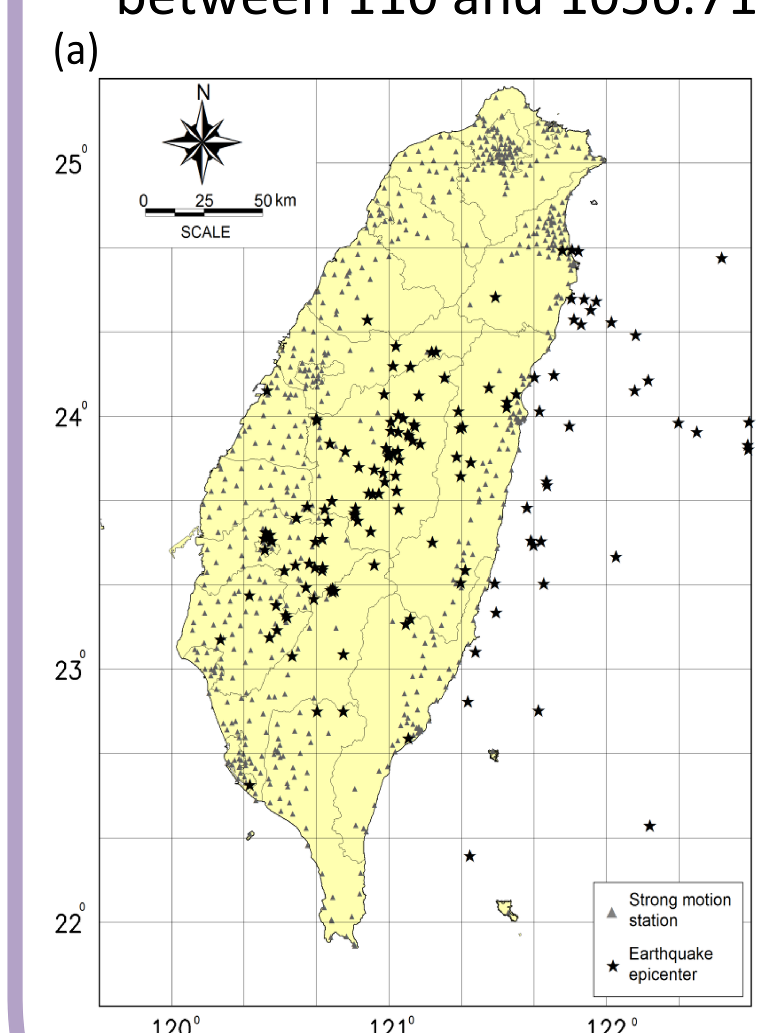


Figure 2. The reason for seismic hazard overestimation.

■ Data ■

The 30,602 records are collected from 150 crustal earthquakes in 1991 to 2014, which are Mw ≥ 4.0 with at least 50 strong-motion records per source. All earthquakes should include two horizontal components, one vertical component and fault type, and all stations must include Vs30 parameter. The final selected earthquakes have moment magnitudes in the range of 4.01 to 7.62, distances in the range of 0.32 to 291.59 km, Vs30 ranging between 110 and 1056.71 m/s. The 1999 Chi-Chi mainshock is included in this database, but its distance is different with the other earthquakes (hypocenter distance), it is the only one using the closest distance to the rupture in this study. The distribution map, magnitude, distance, depth, and Vs30 of selected dataset are shown in **Figure 3**.



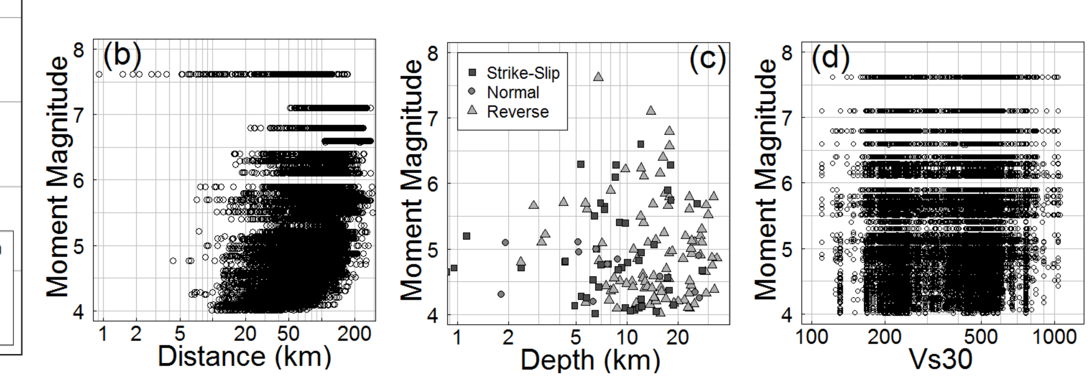


Figure 3. The final selected dataset in this study. (a) Map of strong-motion stations and of earthquakes, (b) distribution of magnitude versus distance, (c) distribution of magnitude versus depth, and (d) distribution of magnitude versus Vs30.

■ Attenuation Model ■

1. Regional GMPE

The maximum likelihood estimation (MLE) and mixed-effects model are adopted in the nonlinear regression in Equation 1 using the whole data (Figure 3). The processing was done using the "nlme" module in the statistical software R (Pinheiro *et al.*, 2015).

$$\ln y = C_1 + C_2M + C_3M^2 + C_4\ln(R + C_5e^{C_6M}) + C_7\ln(\frac{Vs30}{Vref}) + C_8F_n + C_9F_R \quad (1)$$

where y is the ground-motion parameter (g); M is the moment magnitude; R is the distance (km); *VS30* is the average shear-wave velocity in the upper 30 meters of the soil profile (m/s); *Vref* is equal to 1,130 m/s; *FN* and *FR* are indicator variables for the fault types (both being 0 for strike slip faults, 1 and 0 for normal faults, and 0 and 1 for reverse or reverse-oblique faults, respectively).

2. Site-dependence GMPE

The form is same as the regional GMPE (Equation 1), but the regression data is recorded by a site (bring five or four single stations together). In here, we chose five site to do the analysis are shown in **Table 1**.

Table 1. The number of the data for five sites.

Site ID	Number of Station	Number of Record
TAP	4	126
ILA	5	476
HWA	5	704
TTN	5	503
CHY	5	466

3. Single-station GMPE

The function is same as the regional GMPE (Equation 1), but the regression data which is recorded by one single station. The coefficients C_7 of the single-station GMPE will use the value which is obtained by the regression result of site-dependence GMPEs.

Chih-Hsuan Sung, Graduate Institute of Applied Geology, National Central University, Taiwan (R.O.C.), (karen@gis.geo.ncu.edu.tw)
Chyi-Tyi Lee, Graduate Institute of Applied Geology, National Central University, Taiwan (R.O.C.), (ct@gis.geo.ncu.edu.tw)

■ Results & Discussions ■

1. Regional GMPE vs. Site-dependence GMPEs

The total residuals (η_{Ei} + $\xi_{i,k}$) distribution and its log-normal histogram for PGA are shown in **Figure 5**. There may be shifting of the median values from zero for the total residuals; this is common in a mixed-effect model. In Equation 1, $\xi_{i,k}$ are grouped by both the factor of site, η_{Sk}, and the record factor which is not nested within the site factor, $\xi_{Ri,k}$. the intra-event and record-to-record residuals distributions and their log-normal histogram for PGA are also shown in **Figure 5**. In here, we select five sites (TAP, ILA, HWA, TTN and CHY) to do the site-dependence GMPE analysis and compare their results with the regional GMPE as shown in **Figure 6**. Finally, **Table 2** presents the regression coefficient of regional GMPE, site-dependence GMPEs and the components of the standard error estimated from the four residuals: total, inter-event, site-to-site, and record-to-record for PGA. The results show that, for the site-dependence approach, its sigma are about 3-10% smaller than the regional GMPE.

Table 2. Regression coefficients and variability for the regional and site-dependence GMPEs (Equation 1) in this study.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Total Sigma	Inter-event Sigma	Site-to-site Sigma	Record-to-record Sigma	Reduction
Regional	-4.407	1.142	-0.012	-1.450	0.140	0.623	-0.389	-0.057	0.188	**0.621**	0.322	0.230	0.477	
TAP	-4.222	0.563	0.0674	-1.220	0.140	0.623	-0.175	-0.169	-0.046	**0.602**	0.461	0.079	0.277	3%
ILA	-2.106	0.999	0.0097	-1.630	0.150	0.623	0.698	-0.159	-0.303	**0.573**	0.431	0.141	0.256	7%
HWA	-7.029	1.100	0.0029	-1.312	0.072	0.623	-2.493	-0.017	0.239	**0.599**	0.463	0.080	0.276	3%
TTN	-3.020	0.299	0.0965	-1.525	0.140	0.623	-0.922	-0.134	0.064	**0.572**	0.418	0.122	0.399	7%
CHY	-4.742	1.462	0.0008	-1.530	0.150	0.623	0.489	-0.205	0.167	**0.561**	0.408	0.092	0.262	10%

We plot the residuals for CHY and HWA site-dependence GMPEs in **Figure 7a** and compare attenuation curves between regional GMPE and site-dependence GMPEs in **Figure 7b**. When we use the site-dependence GMPEs to do the analysis, the distribution of the "total residual" are more intensive than the regional GMPE, and curves are fitter than the regional.

2. Single-station GMPEs

We select the four stations which are located in CHY site to do the single-station GMPEs and compare their results with the site-dependence GMPE. **Table 3** shows the regression coefficients of four single-station GMPEs and their single-station standard deviation (σ_{SS}). The different GMPE curves are shown in **Figure 8**.

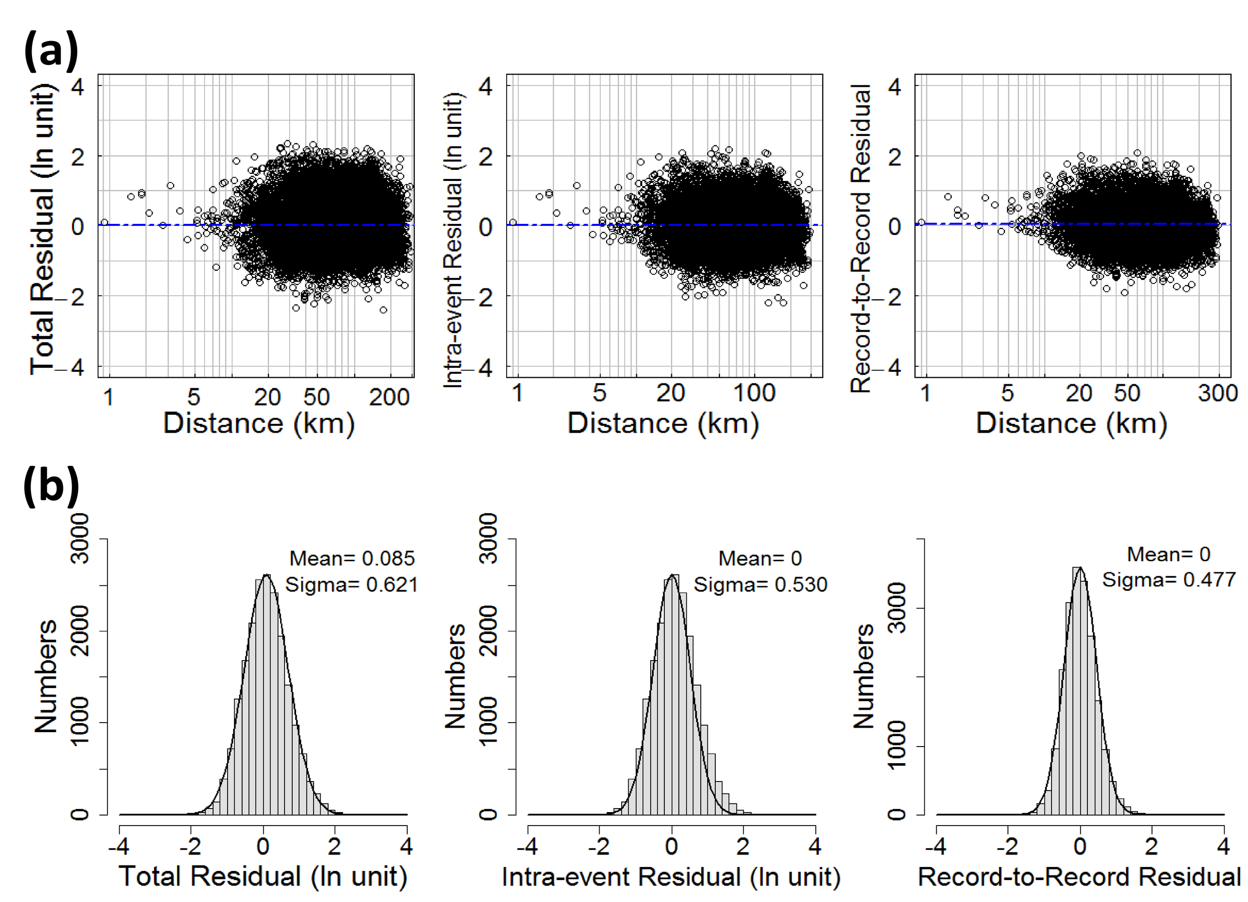


Figure 5. Total, intra-event and record-to-record residuals of PGA are displayed in (a) distribution of residuals versus distances and (b) log-normal histogram.

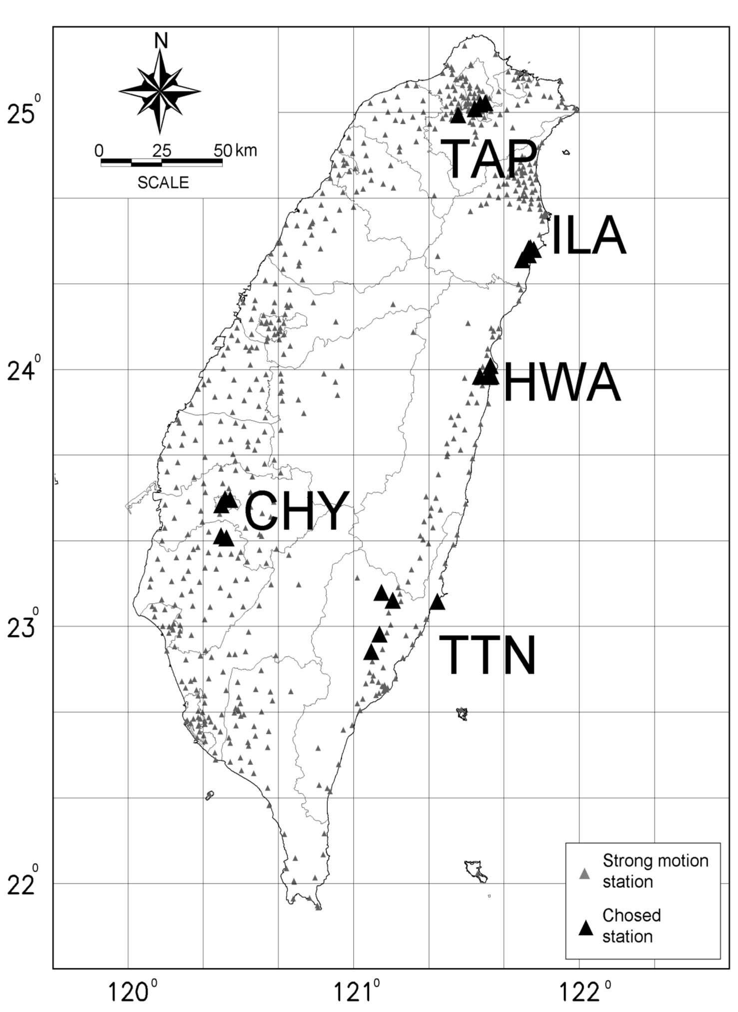


Figure 6. The location for five sites (black triangles).

Table 3. Regression coefficients and variability for the single-station GMPEs in this study.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	Sigma	Reduction
TAP022	-10.310	3.101	-0.184	-1.255	0.140	0.623	-0.175	0.032	0.299	**0.534**	14%
TAP088	-0.584	-1.040	0.198	-0.948	0.142	0.623	-0.175	-0.217	0.139	**0.435**	29 %
TAP115	-9.114	1.952	-0.084	-0.710	0.145	0.623	-0.175	-0.547	-0.706	**0.385**	38%
TAP117	-7.258	1.342	-0.0061	-1.203	0.141	0.623	-0.175	0.014	-0.012	**0.516**	17%
ILA050	-1.993	1.594	-0.039	-2.082	0.152	0.623	0.698	-0.065	-0.372	**0.543**	13%
ILA062	-3.806	1.415	-0.045	-1.377	0.155	0.623	0.698	-0.135	-0.138	**0.515**	17%
ILA064	-3.136	1.096	0.0079	-1.487	0.143	0.623	0.698	-0.254	-0.295	**0.543**	13%
ILA066	-3.346	1.473	-0.019	-1.667	0.128	0.623	0.698	-0.320	-0.295	**0.531**	14%
HAW013	-5.969	0.612	0.028	-1.044	0.073	0.623	-2.493	-0.043	0.129	**0.583**	6%
HWA014	-9.637	1.851	-0.062	-1.121	0.060	0.623	-2.493	-0.385	0.109	**0.491**	21%
HWA028	-8.117	1.541	-0.039	-1.306	0.124	0.623	-2.493	0.013	0.255	**0.540**	13%
TTN021	-3.022	0.574	0.054	-1.605	0.133	0.623	-0.922	-0.101	0.129	**0.567**	9%
TTN024	-3.563	0.284	0.089	-1.314	0.141	0.623	-0.922	-0.085	0.069	**0.494**	20%
TTN025	-2.920	0.285	0.111	-1.603	0.144	0.623	-0.922	-0.432	-0.088	**0.476**	23%
TTN041	-3.518	0.434	0.086	-1.457	0.140	0.623	-0.922	-0.098	0.113	**0.502**	19%
CHY009	-2.928	0.733	0.069	-1.485	0.120	0.623	0.489	-0.287	-0.040	**0.557**	10%
CHY015	-3.956	1.371	0.016	-1.677	0.215	0.623	0.489	-0.169	0.294	**0.495**	20%
CHY073	-6.321	1.885	-0.042	-1.384	0.092	0.623	0.489	-0.295	-0.029	**0.506**	18%
CHY088	-5.054	1.362	0.022	-1.503	0.160	0.623	0.489	-0.349	0.377	**0.530**	15%

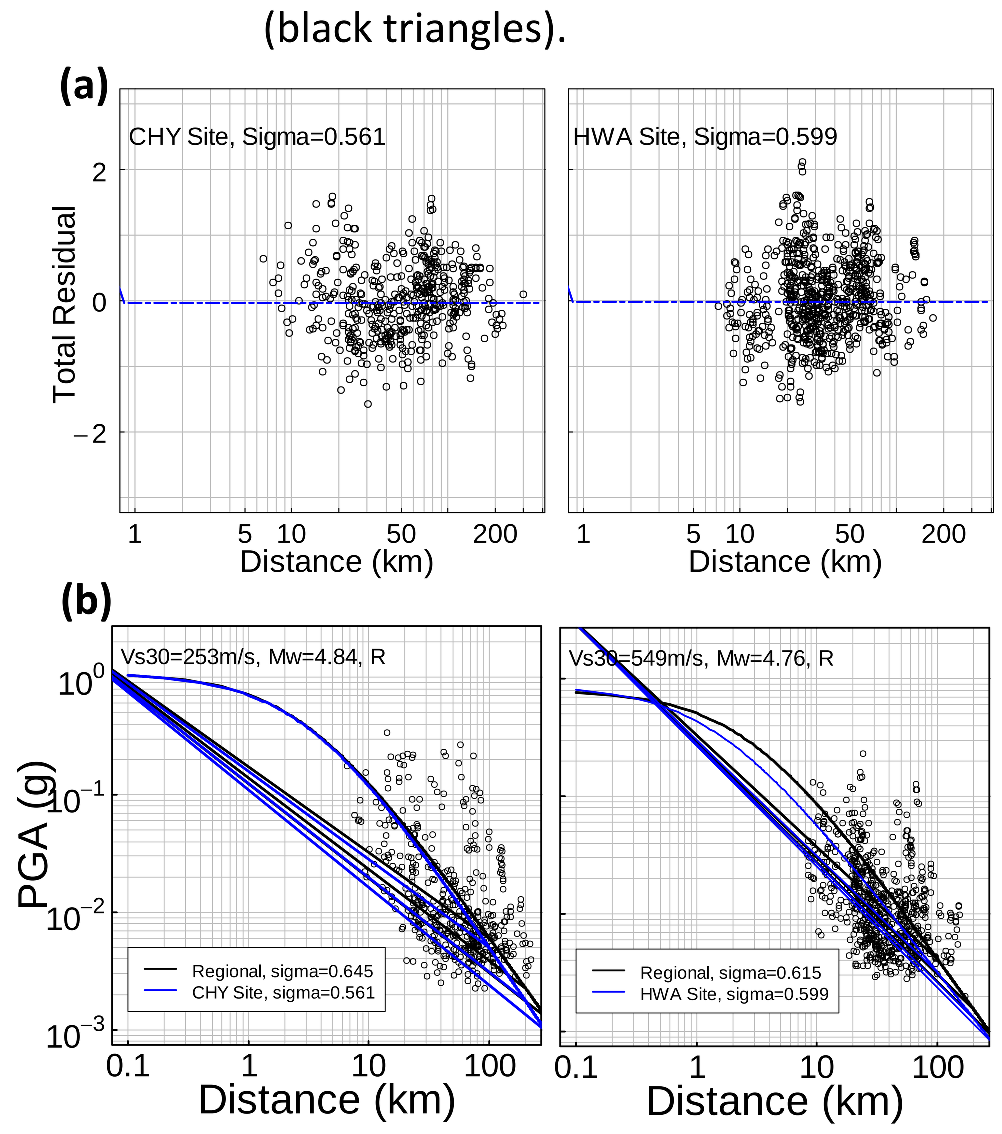


Figure 7. (a) The distribution of site-dependence residuals versus distance for CHY and HWA GMPEs, (b) the comparison of attenuation curves, regional GMPE vs. CHY and HWA site-dependence GMPEs .

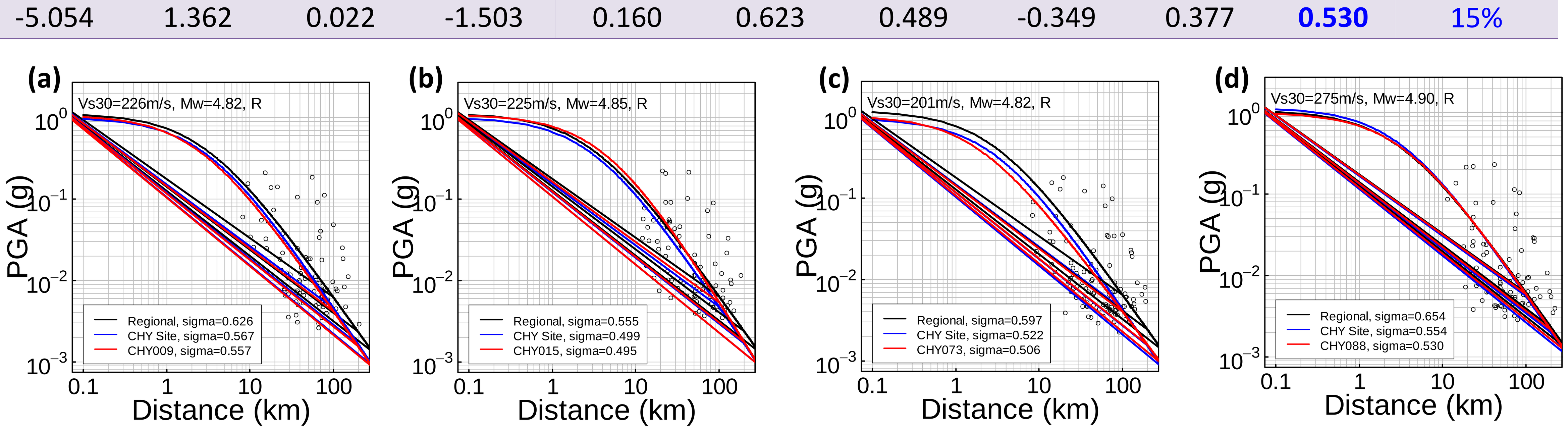


Figure 8. the comparison of attenuation curves, regional GMPE, site-dependence GMPEs and single-station GMPEs for (a) CHY009, (b) CHY015, (c) CHY073, and (d) CHY088.