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A Comparison of Recorded Response Spectra from the 2008 Wenchuan, China, Earthquake with Modern Ground-Motion Prediction Models

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Abstract We compared response spectra from the M_w 7.9 2008 Wenchuan earthquake with five modern ground-motion prediction equations (GMPEs). Ninety-three strong-motion records within 300 km of the fault plane were selected for comparison with the GMPE models of Zhao, Zhang *et al.* (2006), Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008) and Chiou and Youngs (2008) for spectral periods up to 5.0 s. The site class of the recording stations used for the Zhao, Zhang *et al.* (2006) model was inferred from response spectral ratios of the horizontal and vertical components (H/V) computed from the strong-motion records in moving and overlapping time windows. The average shear-wave velocity of the top 30 m (V_{S30}) was only available for two stations. V_{S30} was extrapolated from the average of the top 20 m (V_{S20}) when possible and inferred from the H/V response spectral ratios when necessary. The average predictions of all models were acceptable. The Zhao, Zhang *et al.* (2006) model gave the best predictions for peak ground acceleration and short spectral periods, especially up to 100 km of the source distance. All Next Generation Attenuation (NGA) models predicted the recorded spectra very well for periods of 0.5–1.0 s and at 5.0 s. The Chiou and Youngs (2008) model gave the best overall predictions. The standard deviations of all attenuation models were similar at a 5% significance level. However, differences between spectra estimated by various NGA models were statistically and practically significant, with the largest difference between the average predictions being nearly a factor of 1.4 at the 0.1-s period and 2.3 at the 5.0-s period for data within a source distance of 100 km. Although one earthquake did not produce median ground motions that the GMPEs are designed to predict, such a large difference represents a challenge for empirical models when estimating spectra from very large crustal earthquakes.

Introduction

The Wenchuan earthquake (M_w 7.9) struck the western part of Sichuan Province, China, on 12 May 2008, resulting in unprecedented human casualties and infrastructural damage. Large ground-surface ruptures along the Longmen Shan fault have been reported by Xu *et al.* (2008). The largest horizontal permanent ground displacement was 5.3 m and the largest vertical displacement 6.2 m. Both the Longmen Shan fault (main fault) and the Hanwang–Bailu fault (secondary fault) had a relatively shallow dipping angle toward the northwest. The fault-surface displacements reported by Xu *et al.* (2008) suggest that a reverse mechanism dominated at least 2/3 of the main fault from the southern end. At the northern part of the main fault, the dominant displacement occurred along the strike of the fault.

Fault-rupture models have been derived from inversion analyses using teleseismic records by the Institute for Research on Earth Evolution (2008), Ji and Hayes (2008), Wang *et al.* (2008), Zhang *et al.* (2008), and Koketsu *et al.* (2009). The total length of the fault-rupture plane calculated by Wang *et al.* (2008) was just over 300 km, and the slip distribution suggested that both the main and the secondary faults had extensive surface ruptures in many parts of the fault. Koketsu *et al.* (2009) used three near-source strong-motion records and teleseismic records to derive a large permanent vertical slip along the Hanwang-Bailu surface rupture, which is more consistent with the fault displacement reported by Xu *et al.* (2008) for this part of the fault than the estimates derived using the Wang *et al.* (2008) model. Our distances were calculated from the Wang *et al.* (2008) model with minor modifications to incorporate the features of the Koketsu *et al.* (2009) model. The fault model derived by Wang *et al.* (2008) had a complicated geometry with a dip angle of 65° at the surface and 20° at the bottom of the fault, and it had the same dip angles along the whole length of the fault. We used an approximate dip angle of 55° for computing the distances required for modeling the hanging wall effect by the Next Generation Attenuation (NGA) models. Because of the steep topography on the eastern side of the fault, the approximate nature of the estimated site conditions, and an approximate fault model that was not good enough to estimate the relative location of the near-source stations to the fault for possible hanging wall effect, we did not check the variation in the hanging wall effect caused by the choice of dip angle. Only a small number of records may contain a significant hanging wall effect.

We used a moment magnitude of 7.9 and assumed a reverse faulting mechanism for all parts of the fault. The average static stress drop for the Wenchuan earthquake was estimated to be about 18 MPa (Zhang *et al.* 2008), which is similar to that of the 1994 Northridge earthquake (17 MPa, Fletcher and McGarr, 2006) but considerably larger than those of the 1992 Landers event (11 MPa, Fletcher and McGarr, 2006), the 1995 Kobe event (4 MPa, Fletcher and McGarr, 2006) and the 1999 Chi-Chi, Taiwan, earthquake (10 MPa, Hwang *et al.* 2001). The relatively large stress drop may lead to relatively strong short-period ground motions (K. W. Campbell, personal comm., 2009). None of the models we used for comparison has a term for stress drop.

In the present study, we compared the response spectra from the Wenchuan earthquake to the values predicted by the Zhao, Zhang *et al.* (2006) model and four NGA models: Abrahamson and Silva (2008), Boore and Atkinson (2008), Campbell and Bozorgnia (2008) and Chiou and and Youngs (2008), referred to as, respectively, Z2006, AS2008, BA2008, CB2008, and CY2008. Total residuals of the Wenchuan earthquake records were computed from these attenuation models. The distributions of the total residuals with respect to the shortest distance from a site to the rupture plane derived by Wang *et al.* (2008) are presented. The distribution of total residuals with respect to the inferred and measured average shear-wave velocity of the top 30 m is presented to illustrate the modeling of the site effect by the attenuation models. A residual factor, the exponent of the average residuals, and the standard deviation will also be presented to illustrate the overall fit of the models. The data were separated into two distance ranges (0–100 km and 0–200 km) in calculating residual factors and standard deviation of total residuals to test the effect of extrapolation in distance range for the four NGA models, because the NGA models may be better constrained in the distance range of 0–100 m (K. W. Campbell, personal comm., 2009). Residuals for data in a distance range of 200–300 km are presented but were not used in the calculation of residual factor. The applicable ranges for magnitude, distance, and site conditions are given in the figure captions for the first residual plots for each model.

Because we did not have either a well-defined fault model or measured site parameters (V_{S30}), our comparison can reveal the overall fit to the attenuation models but might not be good enough for a detailed comparison of each record.

The Wenchuan earthquake resulted in large fault slips at the ground surface (Xu *et al.* 2008) for most segments of the fault, apart from the fault segment at the northern end that did not have obvious surface fault displacement. The preliminary assessment of the characteristics of three near-source records (Lu *et al.* 2010) showed that the spectra in a period range of 0.3–1.5 s appear to be considerably smaller than those of buried fault earthquakes but similar to those of surface-rupturing earthquakes. In the present study, we assumed that the depth to the top of the rupture was zero for all attenuation models to account for the effect of surface rupture and buried fault earthquakes (Somerville and Pitarka, 2006). However, even though large surface ruptures have been observed along many parts of the main and the secondary faults (Xu *et al.* 2008), one of the largest asperities was at a depth of 10–15 km and another asperity at of 5–10 km (Wang *et al.* 2008). Wang *et al.* (2008) also showed that at least one of the subevents with a deep asperity initiated at depth and propagated toward the ground surface. According to Dalguer *et al.* (2008), this type of rupture location and propagation may actually lead to high short-period spectra. The ground motions recorded at some stations contributed from the deep asperity may not be consistent with other typical surface-rupture earthquakes. We examine this possibility in the comparison with the CB2008 NGA model.

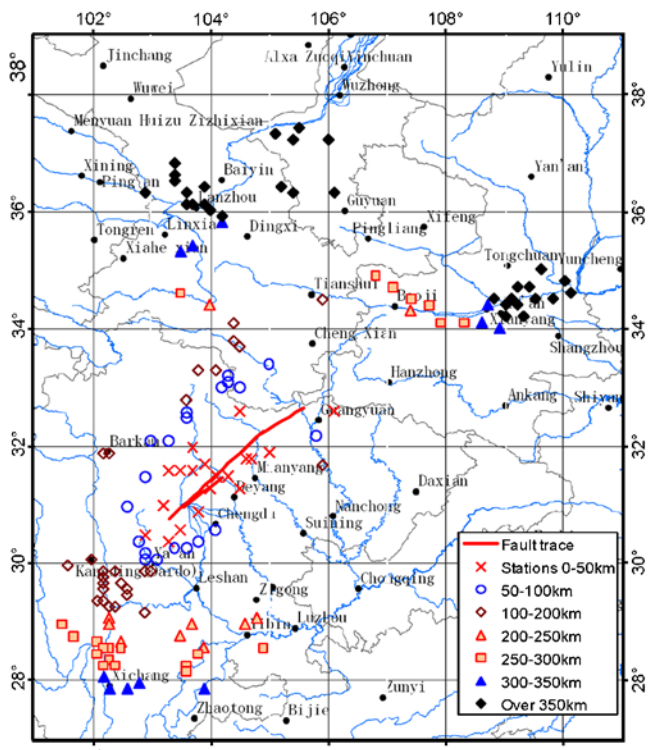

Figure 1. Locations of recording stations and the fault-surface trace of the Wang *et al.* (2008) model. The stations labeled with solid triangles, solid diamonds, and squares in the north and northeast direction from the fault produced abnormally high long-period spectral accelerations as shown in Figure 2. The distance measure is the closest distance from a recording station to the fault plane derived by Wang *et al.* (2008). The color version of this figure is available only in the electronic edition.

It is important to emphasize that the extent of the goodness-of-fit of the Wenchuan earthquake records to a ground-motion prediction equation does not provide a firm conclusion as to whether the prediction equation is appropriate because of the usually large model prediction error. One earthquake may not produce median ground motions that a strong-motion prediction equation is designed to predict. For any model that does not satisfactorily predict the recorded ground-motion spectra from a particular large earthquake, further study is necessary to identify the special earthquake parameter that may lead to the unsatisfactory fit. Because of the large magnitude (at the high end of magnitude range of the dataset used in many models), the Wenchuan earthquake data will provide an important test for all ground-motion prediction models.

Selection of Strong-Motion Records

The strong-motion network maintained by the China Earthquake Administration recorded 100 three-component accelerograms within a distance of 300 km (the closest distance from a site to the fault-rupture plane) during the Wenchuan earthquake, the best ever recorded M_w 7.9+ crustal earthquake (Li *et al.* 2008). There are 3 records within a distance of 10 km, 10 records within 30 km, and 42 records within 100 km. The closest record was from a site within 2 km of the fault-rupture plane and is the closest known record from such a large earthquake (the only other similar record is from the M_w 7.9 2002 Denali earthquake in Alaska, at a source distance of 3 km). This earthquake, therefore, provides a valuable opportunity to test attenuation models that have been developed in the last few years.

Figure 1 shows the location of fault from the Wang *et al.* (2008) model and the stations in different distance ranges. The fault lies close to the western side of the boundary between the hilly region and the Chengdu Basin. Figure 2 shows the variations of recorded response spectra with source distance for spectral periods of 1 s, 2 s, 3 s, and 5 s. The long-period spectra from some stations at source distances greater than 250 km have much larger values than those from other stations at shorter distances. All stations with abnormally large long-period spectra were located at the northern end of the fault (solid diamonds and triangles in Fig. 1). Unpublished research results (X. J. Li, personal

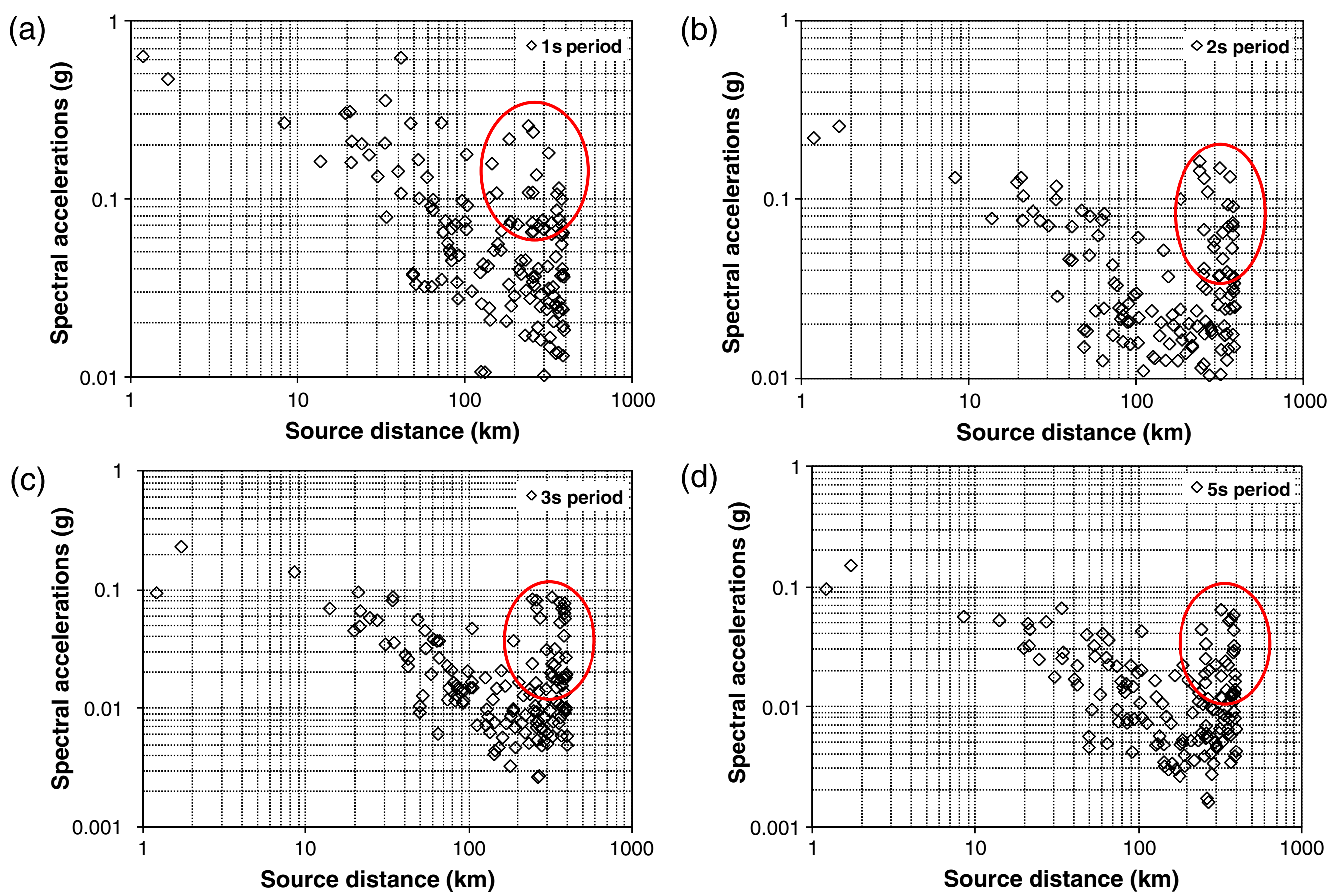

Figure 2. Recorded spectral accelerations at spectral periods of (a) 1 s, (b) 2 s, (c) 3 s, and (d) 5 s for the Wenchuan earthquake records for a source distance up to 400 km. Note that some of the stations at distances over about 250 km (in the ovals) produced abnormally high long-period spectral accelerations, and these stations are concentrated north and northeast from the main fault, as shown in Figure 1. The color version of this figure is available only in the electronic edition.

comm., 2009) suggest that these stations are located in the Weihe basin and that the abnormally high long-period ground motions may have been a basin effect. The stations at the northeast end of the fault labeled by triangles and squares (in the source-distance range of 250–300 km) also are in the Weihe basin and produced abnormally high long-period spectra. These stations were excluded from our comparison.

In some of the NGA models, the geometric means determined from the 50th percentile values of the geometric means computed for all nonredundant rotation angles (Boore *et al.* 2006), instead of the geometric means of the two horizontal components, were used as the measure of the response spectra. In the present study, we used the geometric mean of the two horizontal components for all attenuation models. This should not introduce any significant undesired effects, as the two ground-motion measures differ only slightly (Boore and Atkinson 2008).

The model prediction errors for three of the NGA models are functions of distance, magnitude, and site conditions. This aspect makes it difficult to compare the standard deviation, computed from the strong-motion records with respect to an attenuation model, with the model prediction error. We will calculate the model prediction error using M_w 7.9 and $V_{S30} = 400$ m/s at a source distance of 100 km without any theoretical justification, except that the value of V_{S30} is probably close to the average of all sites.

modeling of Site Effect

We obtained measured average shear-wave velocities for the top 20 m (V_{S20}) for 79 stations and V_{S30} for two stations. However, V_{S20}, the average shear-wave velocity for the top 20 m, is extremely valuable for obtaining site class and approximate V_{S30} for these stations (see discussions in Zhao, Irikura *et al.*, 2006, for K-NET stations). We took V_{S20} as

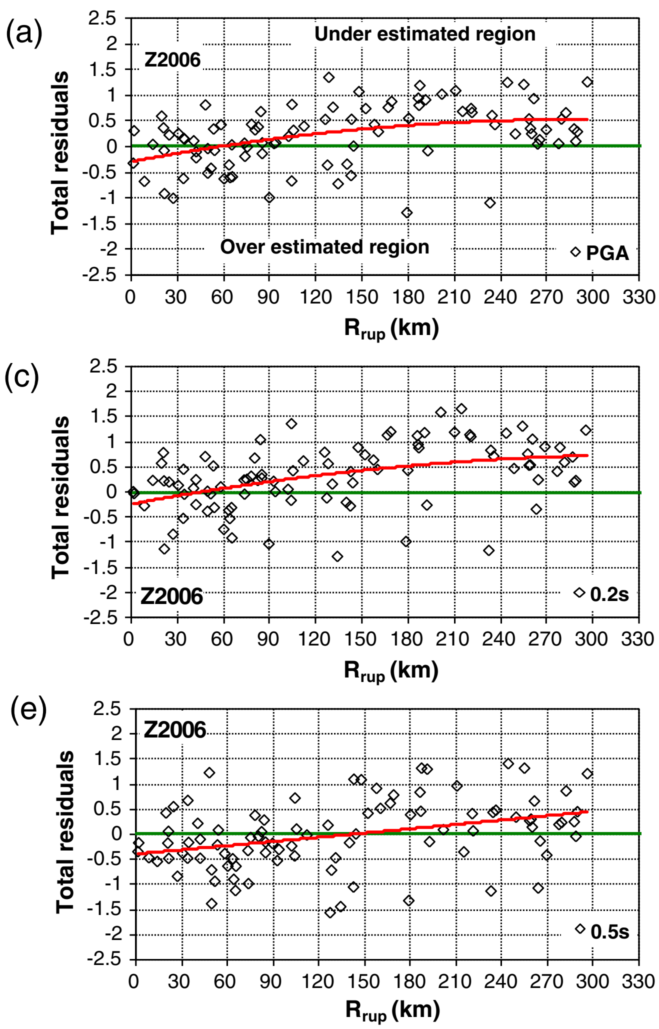

Figure 3. Distribution of residuals with source distance for response spectra with respect to the Zhao, Zhang *et al.* (2006) model (a) for shallow crustal earthquakes for peak ground accelerations (PGA) and for spectral periods of (b) 0.1 s, (c) 0.2 s, (d) 0.4 s, (e) 0.5 s, and (f) 0.7 s. This model is considered to be suitable in an M_W range of 5–7.5 for crustal earthquakes in a distance range of 0–300 km and in a period range of 0–5.0 s. The color version of this figure is available only in the electronic edition.

equivalent to V_{S30} if the soil-layer thickness was greater than 20 m. For stations where the total soil-layer thickness was less than 20 m, we added a 10-m layer of bedrock assumed to have a shear-wave velocity of 650–1000 m/s. We found that the variation of the bedrock shear-wave velocity assumed for the added 10 m had only a very minor effect on the overall fit to the recorded data, so in the present study we used a value of 750 m/s.

For other stations, J. X. Zhao (personal comm., 2009) used the H/V (the horizontal-to-vertical components) response spectral ratios in moving time windows to estimate site class based on the similar method proposed by Zhao, Irikura *et al.* (2006). Each time window had a 50-s duration, and the time of overlap between 2 time windows was 15 s. The record within 10 s at each end of the time window was tapered. Because most records had a duration of over 200 s, and the signal-to-noise ratio was generally high within the duration of most of the records, we were able to use a reasonably large number of time windows for each record. For many records, the averaged H/V response spectral ratios over all time windows usually had a well-defined dominant peak. The time window within the *P*-wave part was discarded because the site effect for the *P*-wave part of a record is small, leading to a flat spectral ratio with an average value of 1.0. If the H/V ratio had a well-defined dominant peak, the period of this dominant peak was used to identify site class and compute V_{S30}, assuming that the bedrock was reached at 30-m depth. If the H/V ratio was flat with a maximum value less than about 2.0, the site was assigned to site class SC I (engineering bedrock, National Earthquake Hazards Reduction Program [NEHRP] class C site system of soil classification) with a V_{S30} of 650 m/s. For those records that did not have well-defined peaks in the H/V ratios, the approach of Zhao, Irikura *et al.* (2006) was used to assign site classes and average V_{S30} values. For three stations for which we had shear-wave velocity profiles, the V_{S30} values derived from the empirical approach are very reasonable. We used the inferred V_{S30} in this method for the comparison of residuals distribution with V_{S30} for the Zhao, Zhang *et al.* (2006) model. The uncertainty associated with SC I (rock/shallow soil) and SC IV (deep soil) should be reasonable but can be fairly large for SC II (hard soil) and SC III (intermediate soil).

The depths to shear-wave velocity 1 km/s or 2.5 km/s horizons were not available for any of the stations.

Terminology Used in the Model Comparison with Ground-Motion Prediction Equations

Following a conventional definition in assessing the goodness-of-fit between strong-motion records and an attenuation model, we present the total residuals in natural logarithm scale (e.g., the natural logarithm of the ratio between the recorded spectra and the predicted spectra for a given record at a given period). For a perfect case, the residuals would be zero. Positive residuals suggest that the recorded spectra are underpredicted, and negative residuals suggest overpredictions. The underestimated and overestimated

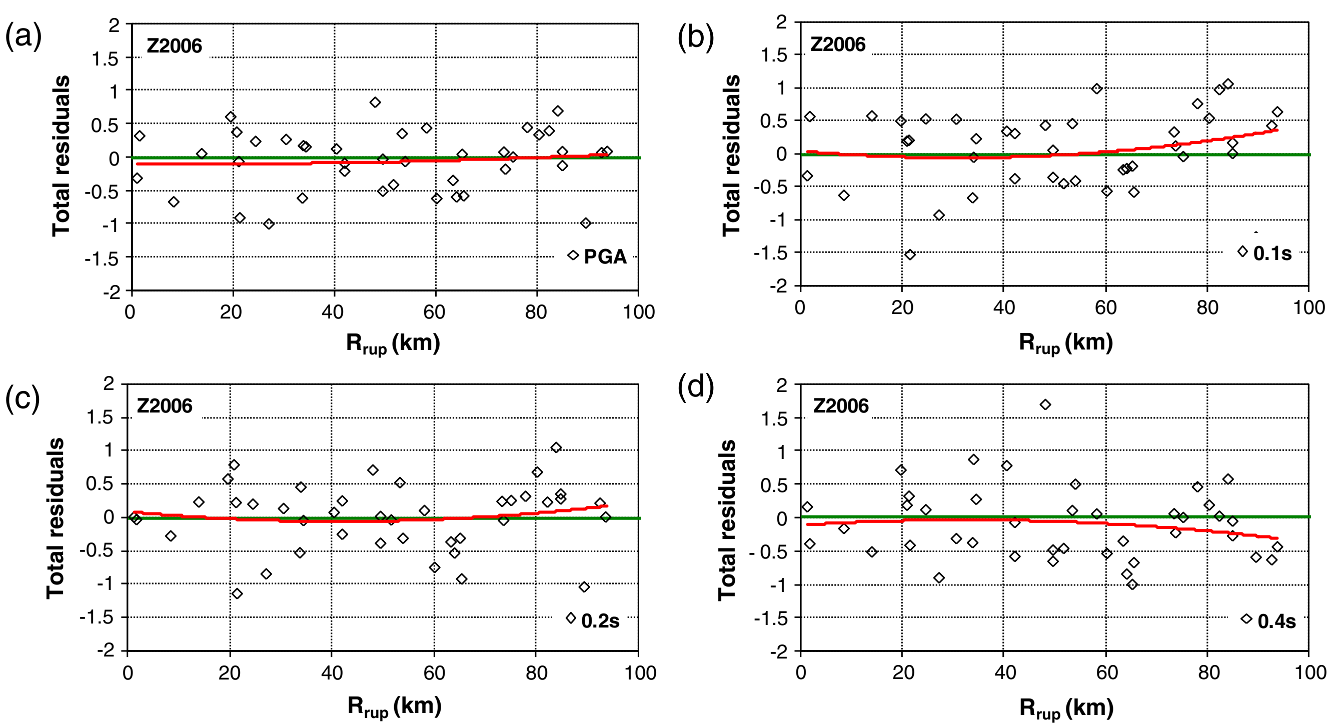

Figure 4. Distribution of residuals with source distance for the response spectra with respect to the Zhao, Zhang *et al.* (2006) model for shallow crustal earthquakes (a) for PGA and for spectral periods of (b) 0.1 s, (c) 0.2 s, and (d) 0.4 s. The color version of this figure is available only in the electronic edition.

regions (i.e., for positive and negative residuals) are labeled in some of the plots.

The distribution of the residuals with respect to model parameters is also very important. For a perfect case, not only are the average residuals of all records zero but also the average value of residuals within a small range of a given model parameter is zero. The best way to demonstrate this aspect of the overall goodness-of-fit is to use a trend line that is fitted to the residuals. For example, Figure 3a shows the trend line as a function of distance (the closest distance from a recording station to the fault plane). For an ideal case, the trend line should be zero at all distance ranges.

The properties of a trend line also provide additional insights to the possible physical reasons for the imprecise prediction. For example, Figure 3a suggests that the geometric attenuation and the anelastic attenuation rates in the Zhao, Zhang *et al.* (2006) model may not be appropriate for the peak ground accelerations (PGAs) of the Wenchuan earthquake records and that a reduced anelastic attenuation rate could perhaps be used to improve the model's predictions. We will not comment on these aspects in this article and instead refer readers to a recent study by Zhao (2010) for more information.

Comparisons with the Zhao, Zhang *et al.* (2006) Model

The Z2006 model was derived mainly from the strong-motion records from Japan with a small supplementary set of near-source records from California and Iran. The model was very simple compared with the NGA models. It had no hanging/foot wall effect, as the number of data with hanging wall/foot wall effect from Japan before 2004 was too small. Site class terms were used to model site effect. The geometric spreading for crustal earthquakes was fixed to −1. An identical anelastic attenuation rate was used for all three types of

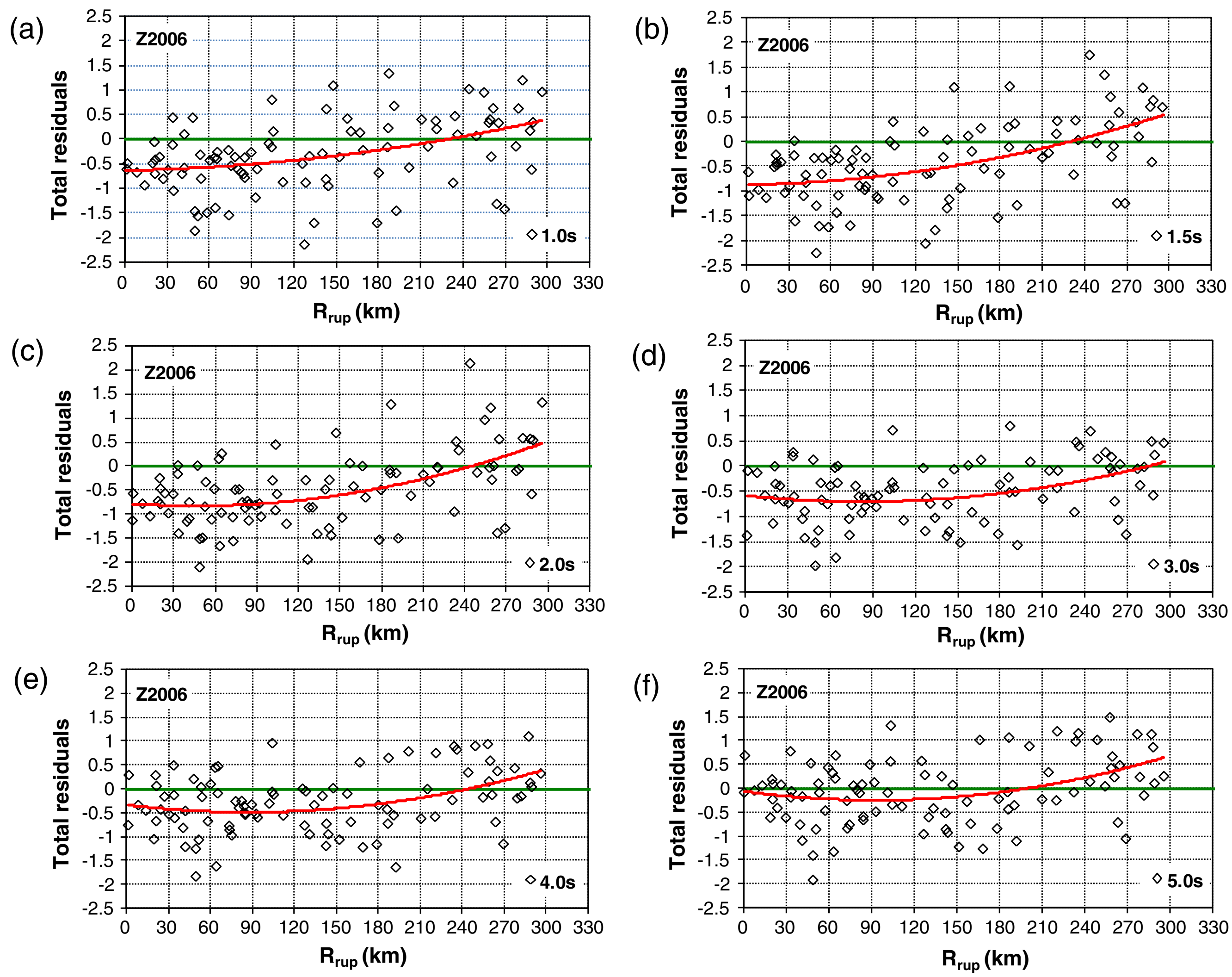

Figure 5. Distribution of residuals with source distance for the response spectra with respect to the Zhao, Zhang *et al.* (2006) model for shallow crustal earthquakes and for spectral periods of (a) 1.0 s, (b) 1.5 s, (c) 2.0 s, (d) 3.0 s, (e) 4.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

earthquakes: shallow crustal, subduction interface, and subduction slab events. These assumptions were imposed on the attenuation models in order to develop a simple form for engineering applications. The data in the Z2006 model contained only two records from a single large crustal earthquake (M_w 7.3), and the largest dataset for crustal events was for the M_w 6.9 1995 Kobe earthquake (the second-largest recorded crustal event). A magnitude of 7.9 represents a large extrapolation from the data magnitude range.

Figure 3 shows the total residuals in natural logarithm scale; that is, $\ln(Y_{\text{recorded}}) - \ln(Y_{\text{predicted}})$, where Y is the response spectrum at a given spectral period. Positive total residuals suggest that the model underpredicts the recorded spectra, and negative total residuals mean an overprediction by the model. For an ideal model, the trend line fitted to the residuals would equal zero at all source distances. A systematic deviation from zero may suggest that the model does not predict the recorded ground motion uniformly well. Clearly, the Z2006 model for crustal earthquakes underpredicts the spectra at distances over 100 km for spectral periods of 0–0.4 s. At 0.5 s and 0.75 s, the model moderately overpredicts the recorded spectra at short distances and moderately underpredicts the recorded spectra at large distances. Figure 4 shows that the prediction within a source distance of 100 km is excellent on average for spectral periods of 0–0.4 s.

Figure 5 shows the distribution of residuals with respect to source distance for long periods. Clearly, the data within a source distance of about 100 km are overpredicted, by a factor of nearly 2 on average. The data over 250 km are generally underpredicted. Within about 220 km of source distance, the fit to the data improves at the 4.0-s and 5.0-s

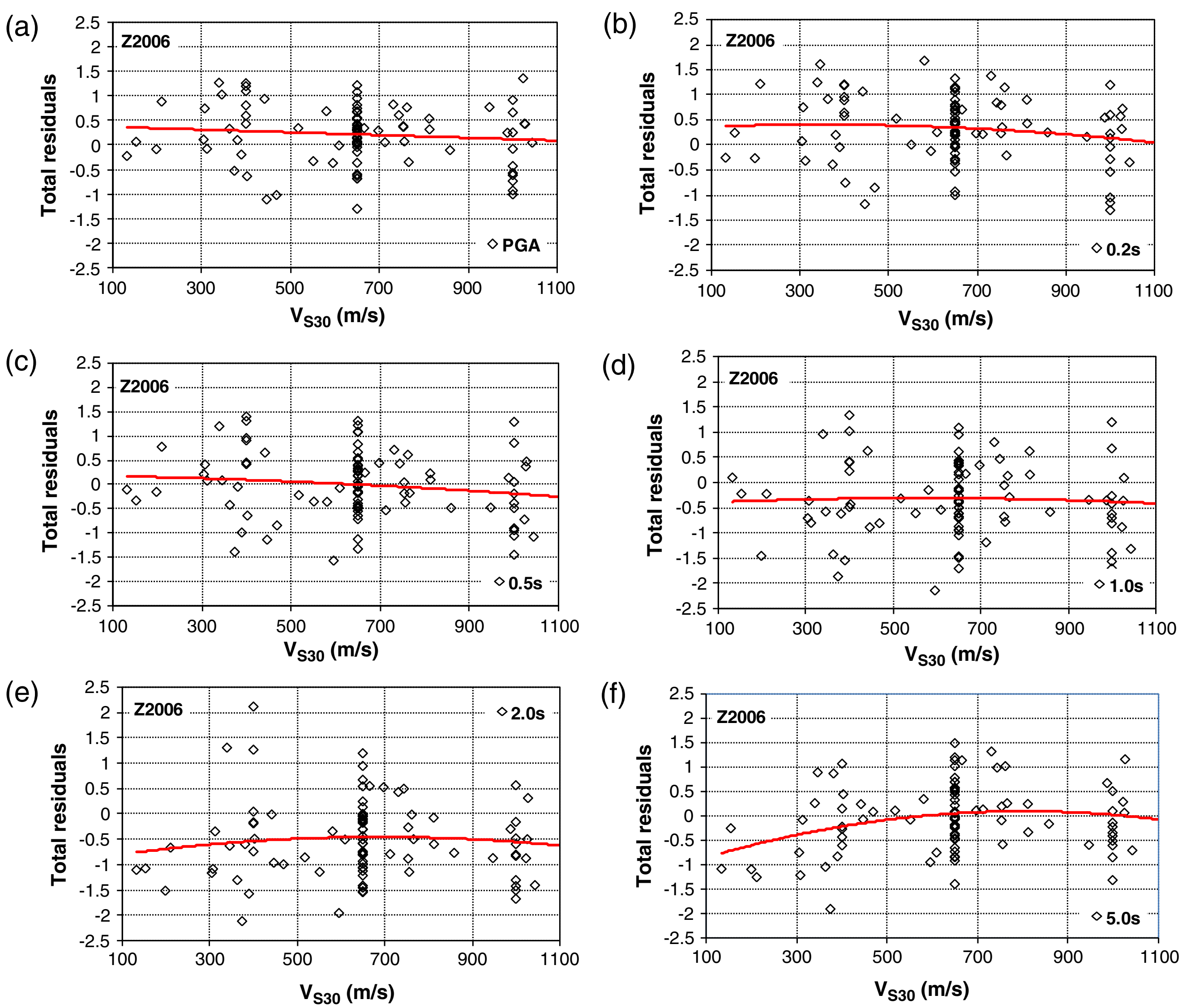

Figure 6. Distribution of residuals with V_{S30} for the response spectra with respect to the Zhao, Zhang *et al.* (2006) model for shallow crustal earthquakes (a) for PGA, and for spectral periods of (b) 0.2 s, (c) 0.5 s, (d) 1 s, (e) 2 s, and (f) 5 s. The color version of this figure is available only in the electronic edition.

spectral periods, and the average residuals are close to zero at 4.0 s.

Figure 6 shows the variation of total residuals with the inferred V_{S30}. The Z2006 model used site class based on site period and the residuals have a reasonably unbiased distribution with respect to the inferred V_{S30} at spectral period less than 5 s. Most of the stations have an inferred site class of SC I, with only three in the inferred site class of SC III (intermediate soil) and three in the inferred site class SC IV (deep or soft soil). Two sites have an inferred V_{S30} less than 180 m/s, the lower limit of the V_{S30} in the NGA models. The unbiased distribution of residuals with respect to V_{S30} perhaps suggests that the estimated V_{S30} does not have a systematic error. However, the unbiased distribution of residuals does not necessarily suggest that the inferred V_{S30} is accurate because a completely random selection of V_{S30} for each station might also lead to an unbiased distribution.

Figure 7 shows the residual factor and the standard deviation for data in distance ranges of 0–100 km, 0–200 km, and 0–300 km. The residual factor is the exponential of the average total residuals over a given distance range. If the residual factor is more than 1, the attenuation model underpredicts the recorded spectra on average. If the residual factor is less than 1, the model overpredicts the recorded spectra. The median $\pm$ standard deviation for the Z2006 model is a factor just over 2.0 (within the range of 0.5–2.0 of the residual factor). The 95% confidence limits for the data within 100 km are presented in Figure 7a, and it can be seen that the residual factor for 0–200-km distances is very close to the upper end of the 95% confidence limits for the data in the distance range of 0–100 km. The average residual factor for the data within a source distance of 100 km is very close to 1.0 and is reasonably small with the largest value about 1.3 at the 0.1-s spectral period for the data within 200 km, suggesting that the model predicts the recorded spectra up to a spectral period of 0.5 s reasonably well. At spectral periods of 0.75–3.0 s, the Z2006 model on average overpredicts the spectra by a factor of 2.0, while the model on average predicts the recorded spectra at the 4-s and 5-s periods quite well. The standard deviations for the data within a distance of 100 km are markedly smaller than the data within a source distance of 200 km and are much less than those of the Z2006 model. The standard deviations for the data within a 300-km distance are generally similar to those of the data within 200 km source distance.

Comparisons with the Chiou and Youngs (2008) Model

Figure 8 shows the residuals with respect to the Chiou and Youngs (2008) model (referred to as CY2008) for PGA and five spectral periods. For PGA and short periods (0.1 s and 0.2 s), the CY2008 model underpredicts the data for distances between 100–200 km by a factor just over 1.5 on average. This model predicts the spectra at 0.4 s, 0.5 s, and 0.75 s very well at all distances, even though the data used by the CY2008 model are within 200 km.

Figure 9 shows the residuals for PGA and the 0.1-s, 0.2-s, and 0.4-s spectral periods within a source distance of 100 km, and the prediction is generally very good.

Figure 10 shows the residuals for spectral periods of 1.0 s, 1.5 s, 2.0 s, 3.0 s, 4.0 s, and 5.0 s. Overall, the CY2008 model predicts the spectra of the Wenchuan records reasonably well at all distances. At periods of 1.0 s, 1.5 s, and 2.0 s, the CY2008 model on average overpredicts the data by a factor of about 1.5. The fit to the data at the 5.0-s period is excellent in the distance range of 100–200 km.

Figure 11 shows the distribution of residuals with respect to the inferred V_{S30} for six spectral periods. At spectral periods 0.5 s or less, the distribution of the residuals is not biased with respect to V_{S30}. At long periods, the stations with a V_{S30} less than about 400 m/s are generally overpredicted, but the predictions for two stations with V_{S30} less than 180 m/s are generally similar to stations with a higher V_{S30}.

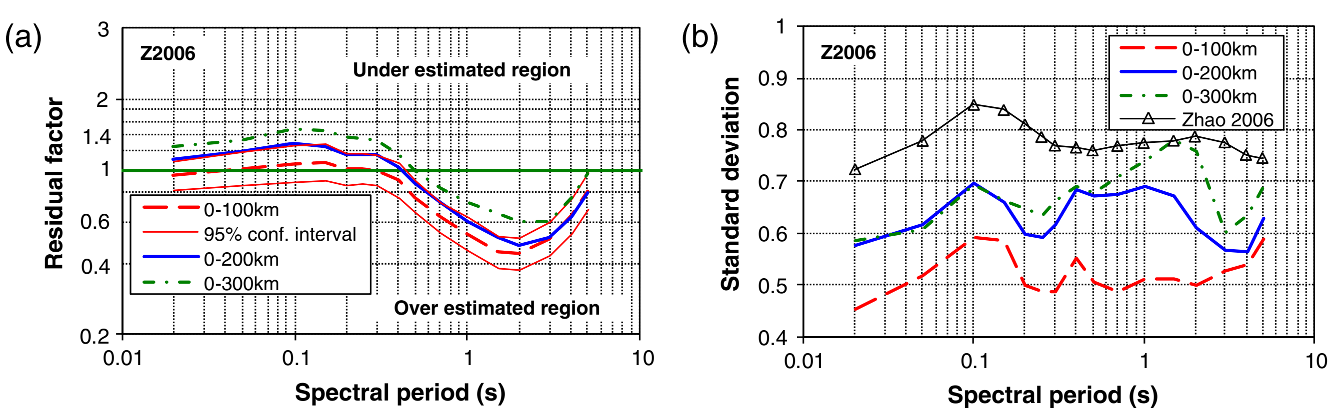

Figure 7. (a) Residuals factor and (b) standard deviation for the Zhao, Zhang *et al.* (2006) model for shallow crustal earthquakes for source-distance ranges of 0–100, 0–200, and 0–300 km. The 95% confidence limits for the data within a distance of 100 km are also presented in (a). We plotted the residual factor in natural logarithm scale, and the distance from the straight line at residual factor = 1 indicates the extent of prediction error in either the overestimated or underestimated region. The color version of this figure is available only in the electronic edition.

At the 1.0-s, and 2.0-s spectral periods, the records from stations with an inferred V_{S30} less than 500 m/s are generally overpredicted. At 5.0 s, the spectra from rock sites (with a V_{S30} over 650 m/s) are generally underpredicted by a significant amount. The data from the Wenchuan earthquake has no correlation between source distance and the inferred V_{S30}.

Figure 12a shows the residual factors together with the 95% confidence limits for the data within a 100-km distance, and Figure 12b shows the standard deviations of the Wenchuan records with respect to the CY2008 model and the total model prediction error. The residual factor for the data within 200 km source distance generally falls in the 95% confidence limits of the data within a 100-km distance. The largest residual factor is at 0.1 s, is about 1.4 for the data within the source distance of 100 km, and is 1.7 for the data within a source distance of 200 km. The residual factor for periods over 0.5 s is small, and the smallest residual factor is 0.67 at the 1.5-s spectral period for the data within a 100-km distance, suggesting a reasonable model prediction at long periods. The generally good fit of the CY2008 model at large distances is probably due to the use of an anelastic attenuation rate. The standard deviations for the data at distances up to 100 km are much smaller than those of the data within a distance of 200 km. The standard deviations for the data within a 200-km distance are generally larger than the model prediction errors, while the standard deviations for the data within a 100-km distance are generally smaller than the model prediction errors, as shown in Figure 12b.

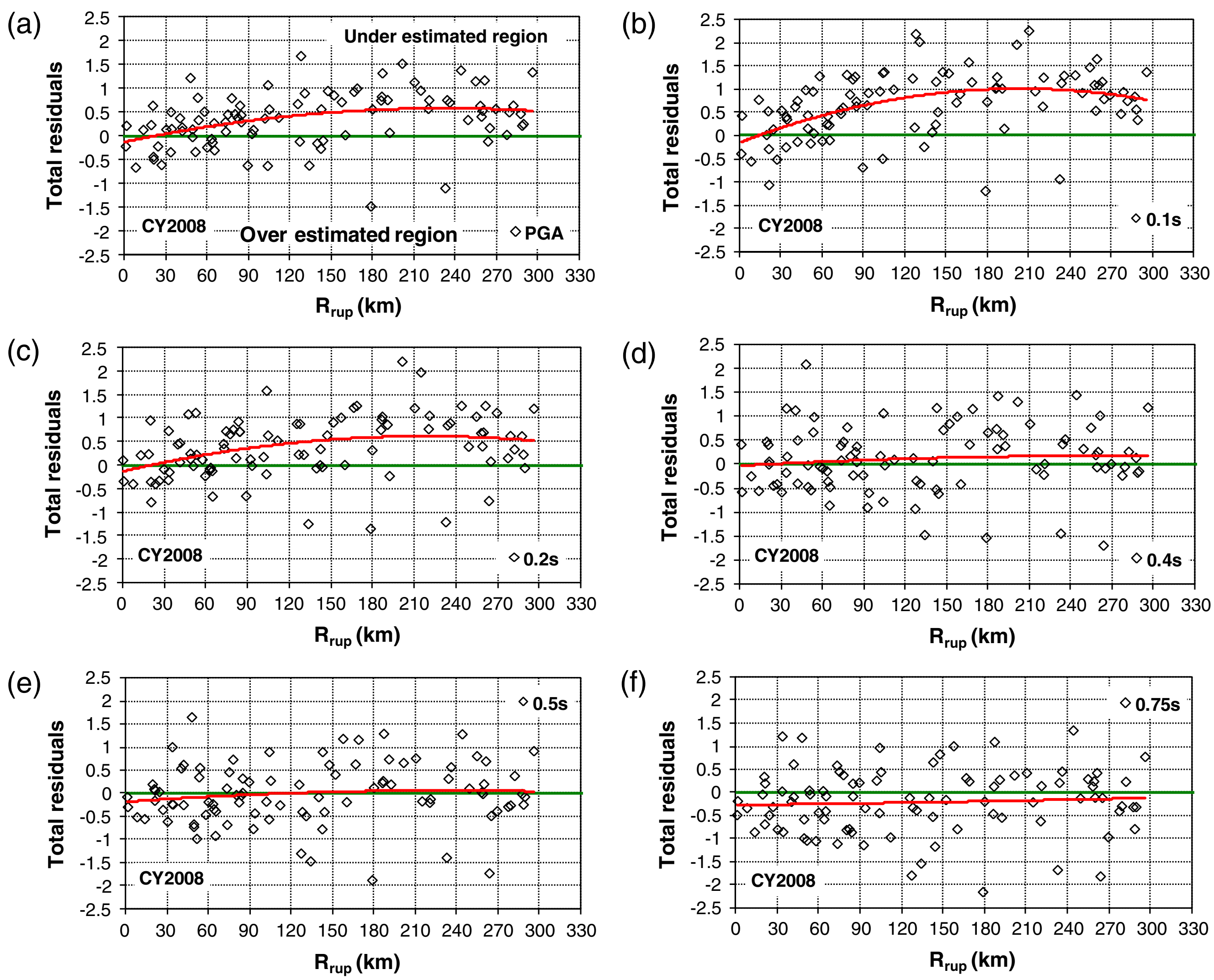

Figure 8. Distribution of residuals with source distance for the response spectra with respect to the Chiou and Youngs (2008) model (a) for PGA and for spectral periods of (b) 0.1 s, (c) 0.2 s, (d) 0.4 s, (e) 0.5 s, and (f) 0.75 s. The depth to a shear-wave velocity of 1000 m/s was computed from equation 1 in Chiou and Youngs (2008). This model is considered to be suitable in an M_w range of 4–8.5 for strike-slip earthquakes and 4–8.0 for reverse and normal faulting earthquakes within a distance range of 0–200 km. The applicable range for V_{S30} is between 150 and 1500 m/s and is between 0.01 and 10 s for spectral period. Surface rupture is assumed for all comparisons. The color version of this figure is available only in the electronic edition.

Comparisons with the Campbell and Bozorgnia (2008) Model

Figure 13 shows the residuals computed from the Campbell and Bozorgnia (2008) model (referred to as CB2008) for PGA and at spectral periods of 0.1 s, 0.2 s, 0.4 s, 0.5 s, and 0.75 s. The CB2008 model generally underpredicts the recorded spectra for periods less than 0.4 s in a distance range within 200 km. The model underpredicts the recorded spectra at 0.1 s and 0.2 s by a significant amount in the distance range of 30–200 km. At periods of 0.5 and 0.75 s, the CB2008 model has excellent predictions at all distance ranges, and the distribution of residuals is not significantly biased with respect to source distance, even though CB2008 does not contain a term for anelastic attenuation rate. For the data over 250 km at short periods, the CB2008 model predicts the data very well, though this distance range represents a large distance extrapolation from data used in the NGA models.

Figure 14a shows a reasonably good fit to the data at all distance ranges at a spectral period of 1.0 s, considerably better than for those of the other spectral periods in Figure 14b–f. The model generally overpredicts long-period spectra as shown in Figure 14d–f, particularly in the distance range of 50–200 km. The predictions within a source distance of about 30 km are generally reasonable, and the distribution of residuals is generally not significantly biased with respect to the source distance. The CB2008 model generally overpredicts the recorded spectra by a factor of just below 2 at long periods and at distances over 50 km. The predictions for data over a 200-km distance are generally very similar to, or better than, those for the data in a distance range of 100–200 km.

Figure 15 shows the distribution of residuals with respect to the inferred V_{S30}. For spectral periods up to 0.5 s, the distribution of the residuals is not biased with respect to the inferred V_{S30}. At spectral periods of 1.0 s, 2.0 s, and 3.0 s, the data from a site with low inferred V_{S30} are significantly overpredicted. At the 5.0-s spectral period, the data from stations with a V_{S30} over 600 m/s are much better predicted than the CY2008 model (Fig. 11f), though the residuals for the two models have similar distribution at the other spectral periods.

Figure 16a shows the residual factor and the 95% confidence limits for the records within a 100-km distance. At the 0.1-s spectral period, the largest residual factor for this model is about 2.1 for the data within a 100-km distance and is 2.4 for the data within a 200-km distance. The CB2008 model predicts the Wenchuan data fairly well within a spectral period range of 0.4–1 s. At periods beyond 1 s, the CB2008 model overpredicts the recorded data by a factor of just below 2, on average. Figure 16b shows the standard deviation of the Wenchuan records. For the data within a 100-km distance, the standard deviation is generally less than the model standard error, while for the data within a 200-km distance the standard deviation is generally larger than the model standard error.

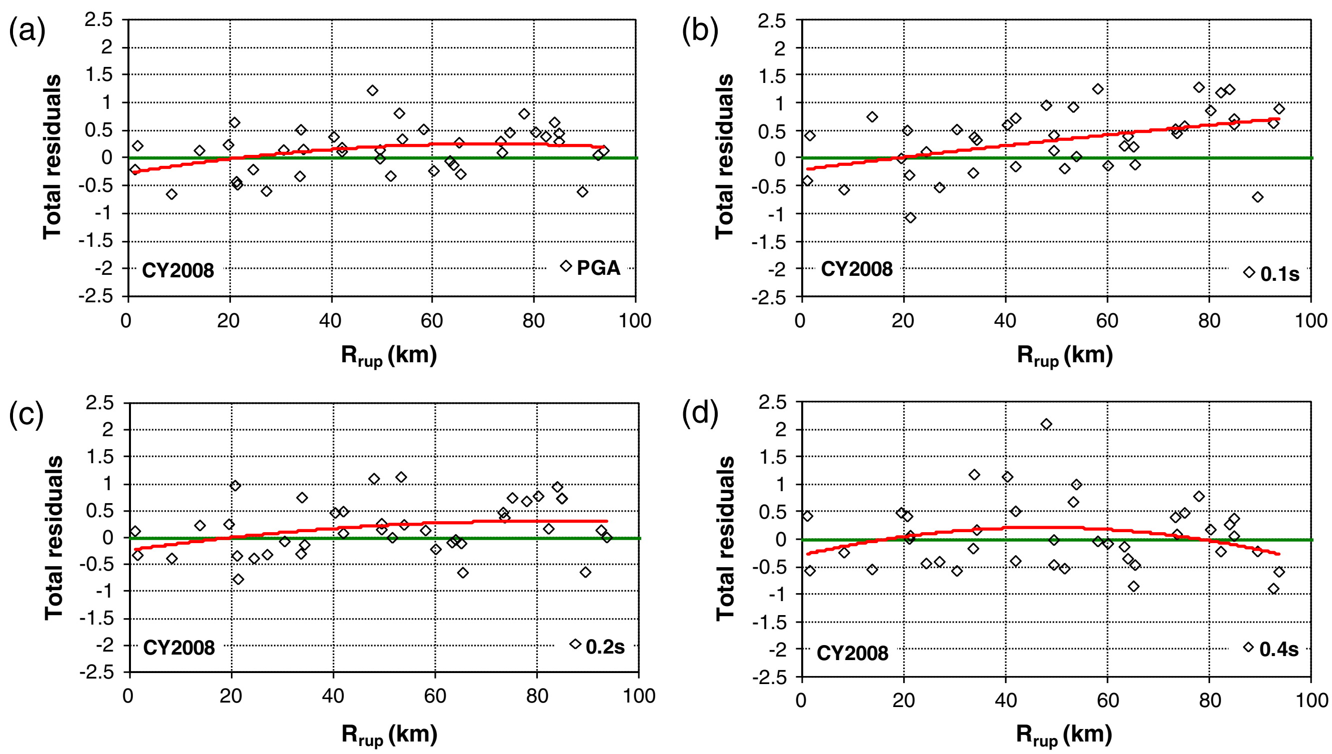

Figure 9. Distribution of residuals with source distance for the response spectra with respect to the Chiou and Youngs (2008) model (a) for PGA and for spectral periods of (b) 0.1 s, (c) 0.2 s, and (d) 0.4 s. The color version of this figure is available only in the electronic edition.

As described earlier, the complex fault initiation and rupture propagation among different fault segments may differ significantly, and the assumption of surface-rupture earthquake may not be suitable for all subevents. In the CB2008 model, the prediction at short period improved significantly when the depth to the top of the fault was selected as 1.0 instead of 0 (as suggested by K. W. Campbell, personal comm., 2009). The overpredictions at short periods are indeed significantly improved, though the improvement for other models is negligible. It is possible that the assumed surface rupture for all subevents is not appropriate, or the CB2008 model may be overly sensitive to this fault parameter.

Comparisons with the Boore and Atkinson (2008) Model

Figure 17 shows the total residuals for the Boore and Atkinson (2008) model (referred to as BA2008). The residuals were calculated using the closest distance from a site to the surface projection of the fault plane, R_{JB}, but the residuals were plotted against the closest distance to the rupture plane R_{rup} in Figures 17, 18, and 20. At PGA and spectral periods up to 0.4 s, the model generally underpredicts the recorded spectra at the source-distance range of 50–200 km and considerably underpredicts the recorded spectra at large distances beyond the model data range (0–200 km). The model predicts the ground motion at short distances (e.g., 50 km) reasonably well. The overall model prediction improves with increasing spectral period, and excellent prediction can be found at the 0.75-s spectral period.

Figure 18a,b,f shows reasonable predictions by the BA2008 model and also that the distribution of residuals is not significantly biased. The model tends to overpredict the recorded spectra at the 2.0-s and 3.0-s spectral periods as shown in Figure 18c,d, in a distance range of 0–200 km. The model also predicts the recorded spectra very well at distances from 200–300 km at the 1.0-s and 2.0-s periods, even though this distance range represents a large extrapolation

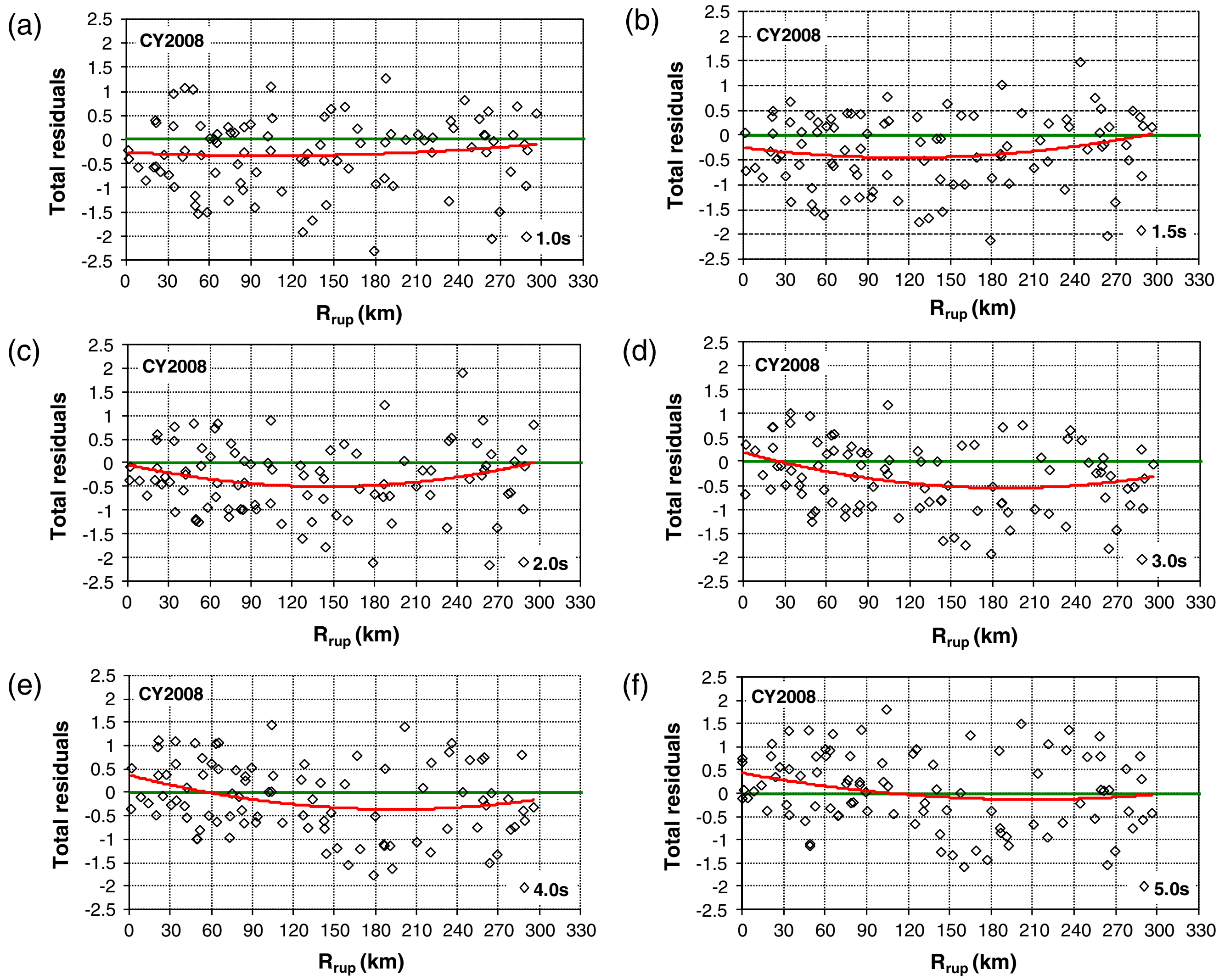

Figure 10. Distribution of residuals with source distance for the response spectra with respect to the Chiou and Youngs (2008) model for spectral periods of (a) 1 s, (b) 1.5 s, (c) 2 s, (d) 3 s, (e) 4 s, and (f) 5 s. The color version of this figure is available only in the electronic edition.

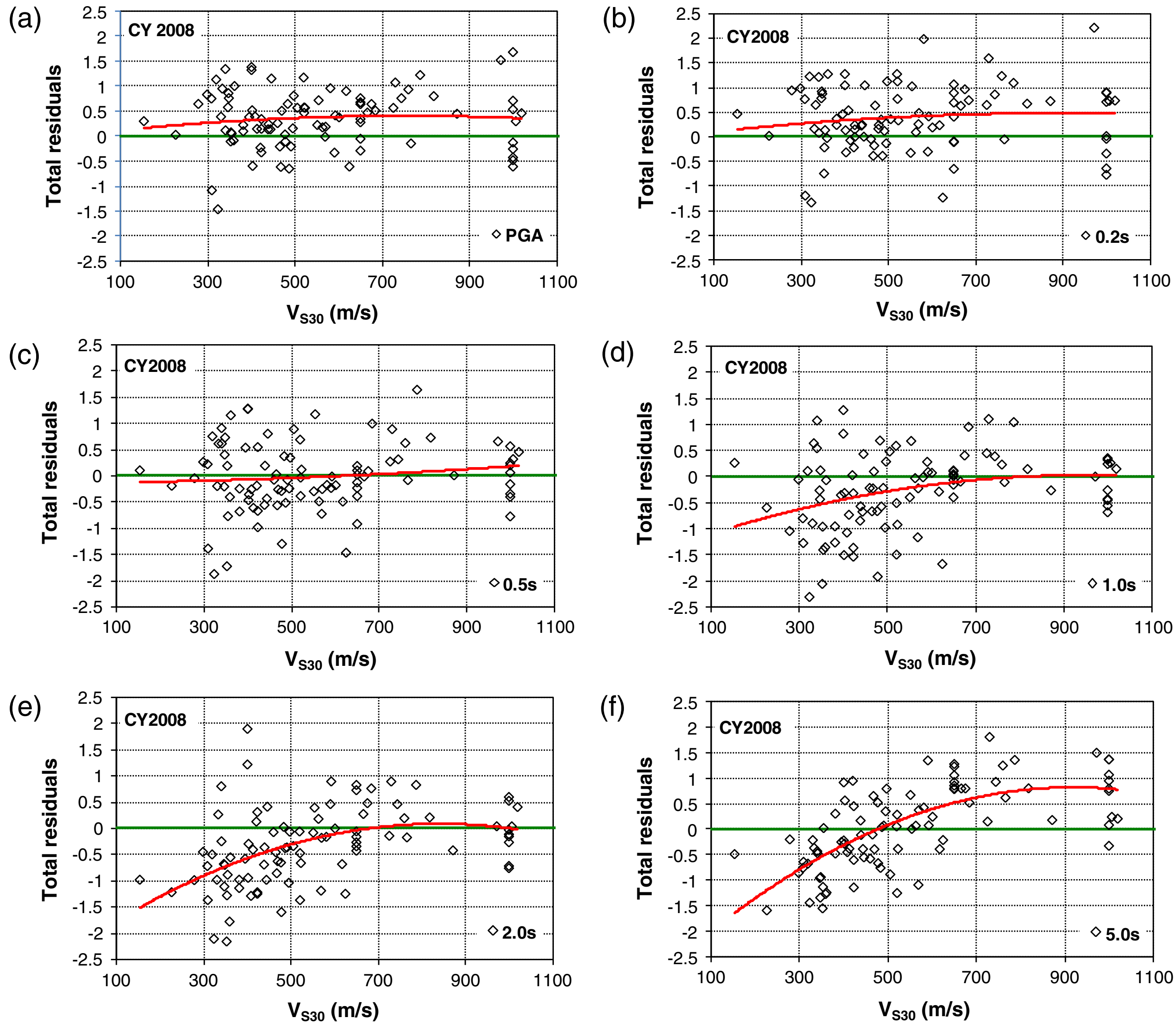

Figure 11. Distribution of residuals with V_{S30} for the response spectra with respect to the Chiou and Youngs (2008) model for (a) PGA and for spectral periods of (b) 0.2 s, (c) 0.5, (d) 1.0 s, (e) 2.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

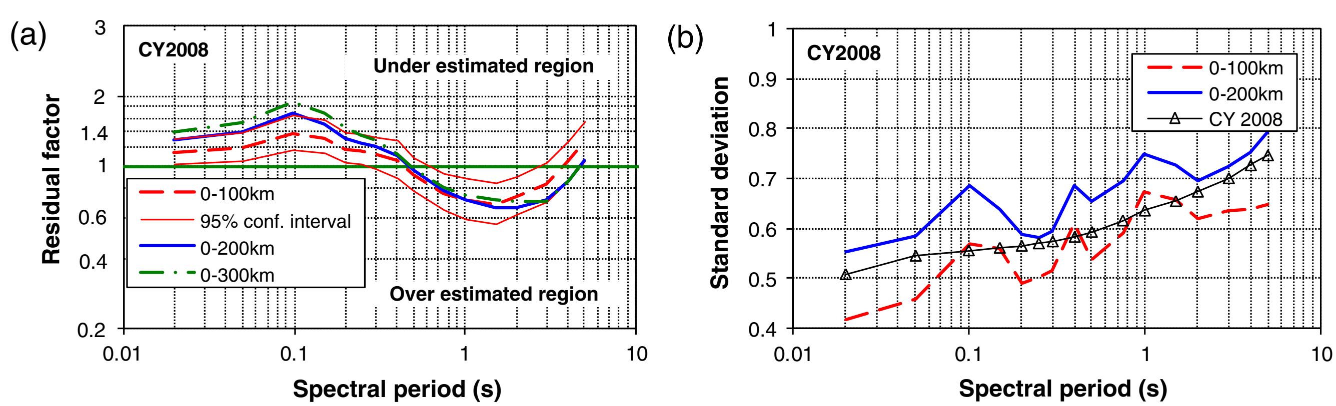

Figure 12. (a) Residuals factor and (b) standard deviation for the Chiou and Youngs (2008) model for source distances of 0–100 km and 0–200 km. The 95% confidence limits for the data within a distance of 100 km are also presented in (a). The color version of this figure is available only in the electronic edition.

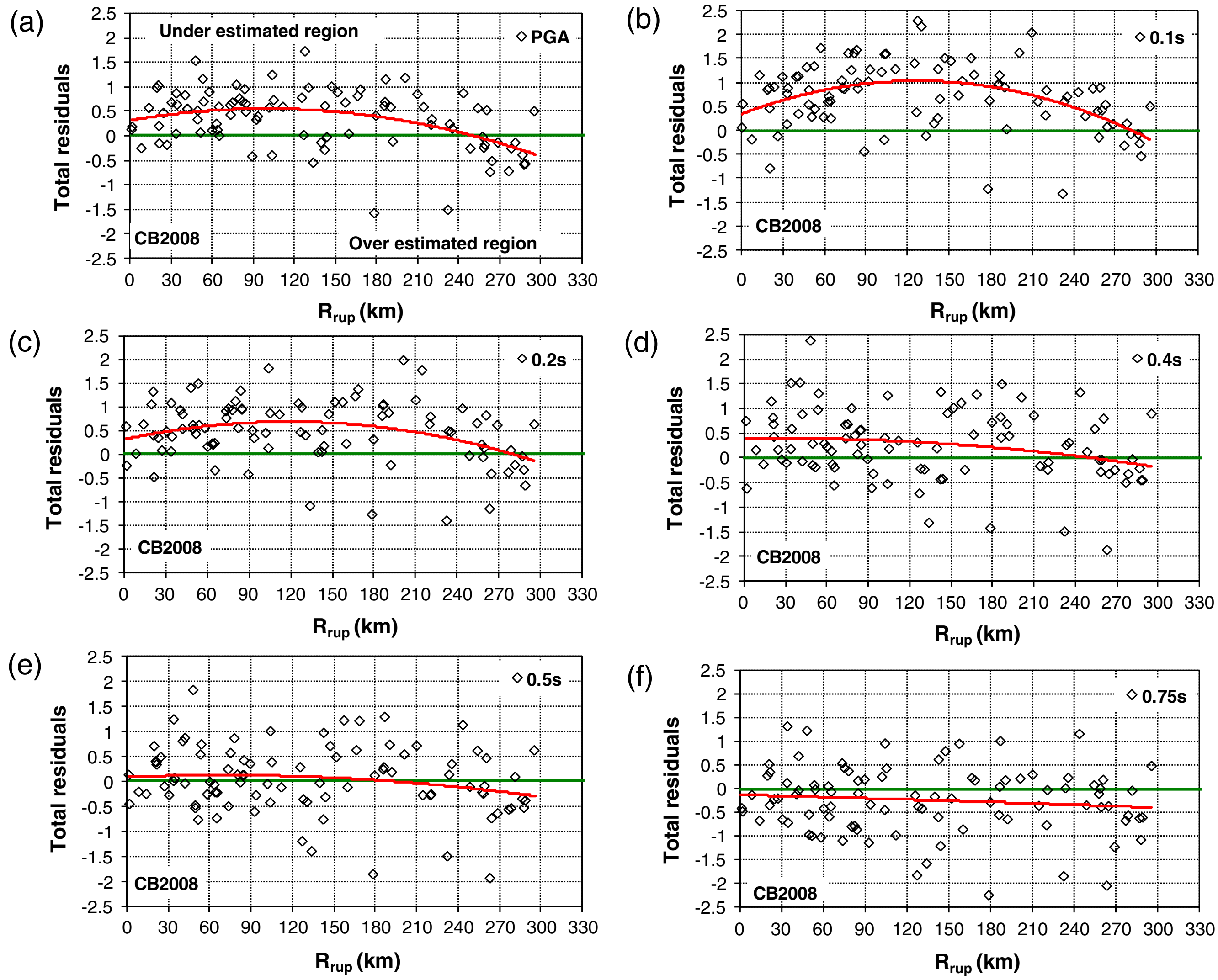

Figure 13. Distribution of residuals with source distance for the response spectra with respect to the Campbell and Bozorgnia (2008) model for (a) PGA and for spectral periods of (b) 0.1 s, (c) 0.2 s, (d) 0.4 s, (e) 0.5 s, and (f) 0.75 s. The depth to the 2.5 km/s shear-wave velocity horizon was taken as 1 km (the term for sediment basin effect is 1.0). The CB2008 model is applicable for M_w ranging from 4.0 up to 7.5–8.5 (depending on focal mechanisms), distances ranging from 0–200 km, and period ranging from 0.01 to 10 s. Surface rupture is assumed for all comparisons. The color version of this figure is available only in the electronic edition.

from the distance range of the data used in the BA2008 model. The use of anelastic attenuation rate in the BA2008 model may contribute to the reasonable prediction at large distances.

Figure 19 shows the distribution of residuals with the inferred V_{S30}. Similar to the other NGA models compared in the present study, the residuals are unbiased with respect to V_{S30} for periods up to 0.5 s, and the model overpredicts the data from the soil sites with $V_{S30} < 300$ m/s at long periods (1 s or longer).

Figure 20a presents the residual factors and the 95% confidence limits for the Wenchuan records within a 100-km distance, and again the model predicts the recorded data very well in a spectral period range of 0.5–1.0 s, similar to the other NGA models. The recorded data at short periods are greatly underpredicted, with the largest residual factor being about 1.6 for the reco.M.rds within a distance of 100 km and 2.2 for the records within a distance of 200 km. The standard deviation for the Wenchuan records is generally smaller than that of the BA2008 model for the data within a 100-km distance and is larger than the model prediction error for the data within a 200-km distance.

Comparisons with the Abrahamson and Silva (2008) Model

Figure 21 shows the total residuals for the Abrahamson and Silva (2008) model (referred to as AS2008). This model gives an excellent prediction for PGA and spectra at 0.2 s, 0.4 s, and 0.5 s and a reasonable prediction at the 0.75-s spectral periods. At 0.1 s, the model generally underpredicts the recorded spectra. Figure 22 shows that the AS2008

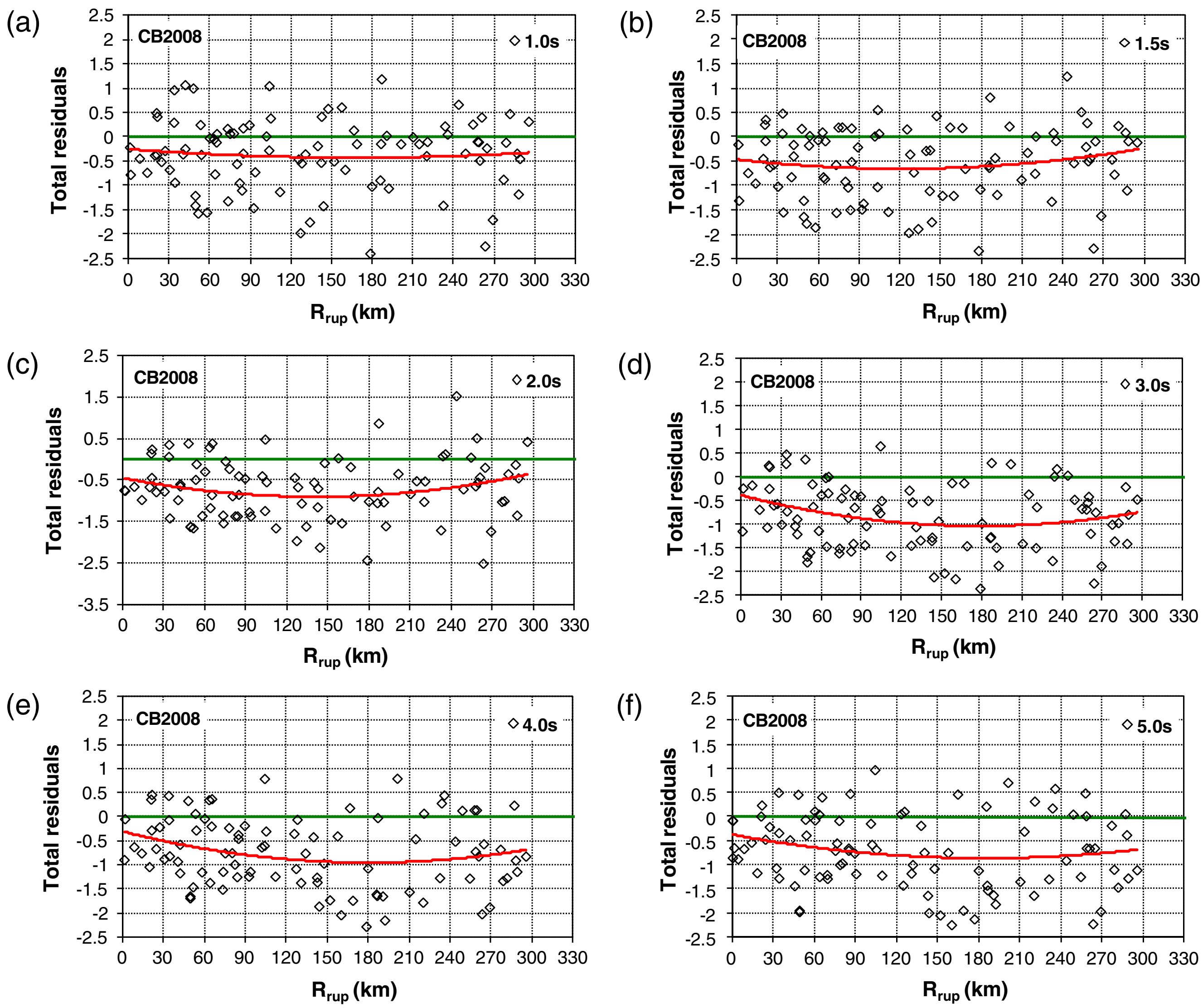

Figure 14. Distribution of residuals with source distance for the response spectra with respect to the Campbell and Bozorgnia (2008) model for spectral periods of (a) 1.0 s, (b) 1.5 s, (c) 2.0 s, (d) 3.0 s, (e) 4.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

model on average overpredicts the recorded spectra considerably at spectral periods of 1.0 s or longer. The predictions are very reasonable for records within about 50 km at periods of 3.0 s or longer. The worst prediction tends to be in a distance range of 60–200 km, and the prediction improves slightly at large distances over 200 km, even though the data used by AS2008 model are within a 200-km distance.

Figure 23 shows the distribution of residuals with the inferred V_{S30}, and the distribution is not seriously biased for all periods except for 5.0 s. At the 5.0-s period, the data with a V_{S30} less than 300 m/s are significantly overpredicted. Note that the distribution of residuals with respect to V_{S30} is not biased as strongly as to the other NGA models up to the 2-s period; that is, the trend lines are nearly parallel to the horizontal axis of the each figure. This may suggest that the biased distribution of residuals with respect to V_{S30} for the other NGA models is not due to the systematic error in the estimates of V_{S30}.

Figure 24a presents the residual factors and the 95% confidence limits for the Wenchuan records within a 100-km distance and the residual factor for the data within 200 km. The model predicts the recorded data very well in a spectral period range of 0.4–0.75 s, similar to the other NGA models. The recorded data at short periods are much underpredicted, with the largest residual factor being about 2.0 for the records within a distance of 100 km and 2.1 for the records within a distance of 200 km. At periods over 0.75 s, the AS2008 model overpredicts the recorded spectra significantly, and the smallest residual factor is 0.51 at the 1.5-s period for the data within a 100-km distance. The standard deviation within a distance of 200 km is generally similar to that of the AS2008 model. For the data in the distance range of

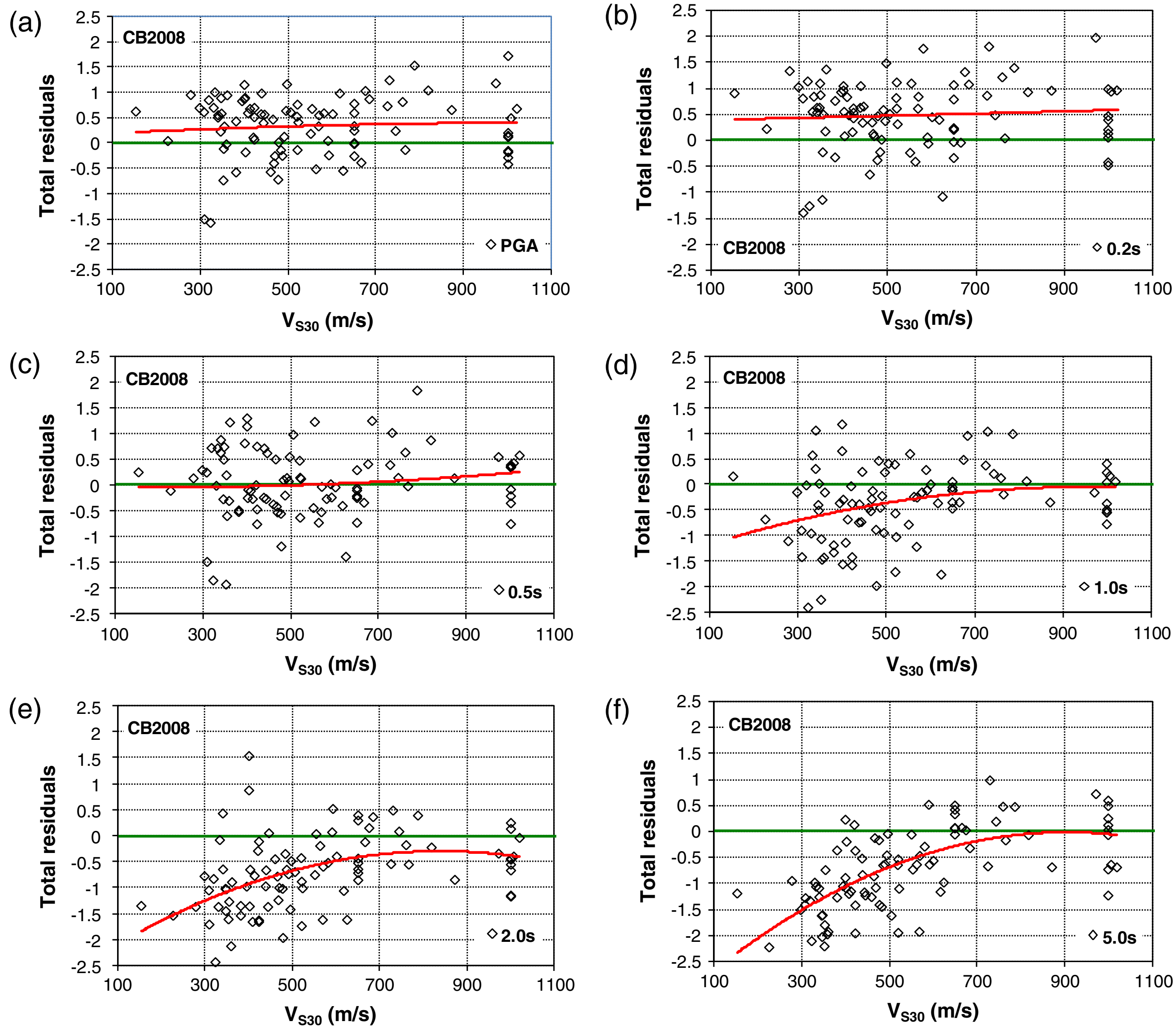

Figure 15. Distribution of residuals with V_{S30} for the response spectra with respect to the Campbell and Bozorgnia (2008) model for (a) PGA and for spectral periods of (b) 0.2 s, (c) 0.5 s, (d) 1.0 s, (e) 2.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

0–100 km, the standard deviations computed for the Wenchuan records are significantly less than those of the AS2008 model and those for the data in a source distance range of 0–200 km.

Summary of Comparison and Discussions

To summarize our comparison, Figure 25 shows the residual factors and the standard deviations for the Wenchuan earthquake records computed for five attenuation models. Note that the residual factors reflect the average level of model prediction but do not show the effect of biased prediction at different distance ranges or average shear-wave velocity at the top 30 m.

Figure 25a shows the residual factors for the data within a distance of 100 km computed from five attenuation models. Of the five models, the Zhao, Zhang *et al.* (2006) (Z2006) model has the best prediction for the spectra within 0.3 s on average, with a residual factor very close to 1.0. In the period range of 0.3–0.6 s, all five attenuation models predict the recorded spectra very well. At periods over 0.6 s, the residual factors from the Z2006 and the Abrahamson and Silva (2008) (AS2008) models are very similar. Over a 1-s period, the Chiou and Youngs (2008) (CY2008) model has the best prediction of the Wenchuan records. At about a 2-s period, the Z2006 model has the smallest residual factor of 0.44, suggesting the poorest overprediction.

Figure 25b shows the standard deviations of the residuals for Wenchuan records within a distance of 100 km

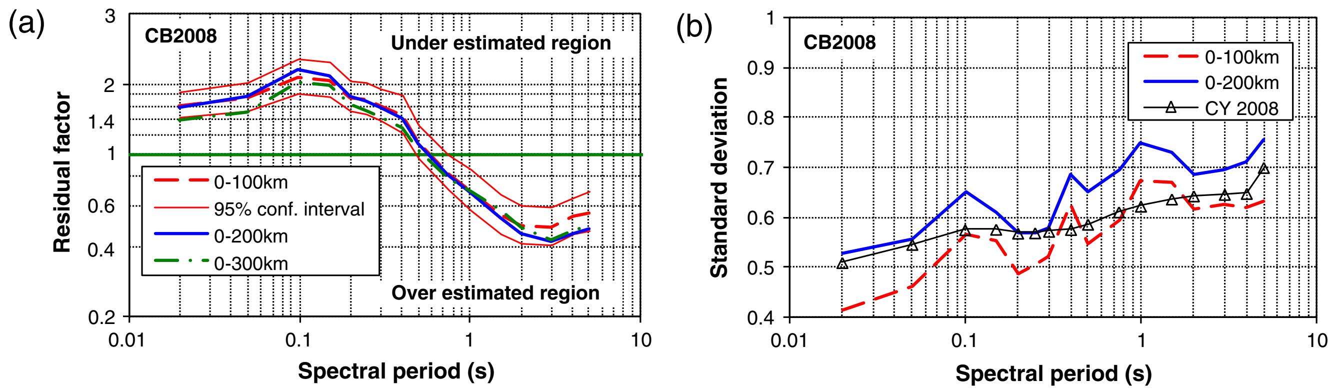

Figure 16. (a) Residuals factor and (b) standard deviation for the Campbell and Bozorgnia (2008) model for source distances of 0–100 km and 0–200 km. The 95% confidence limits for the data within a distance of 100 km are also presented in (a). The color version of this figure is available only in the electronic edition.

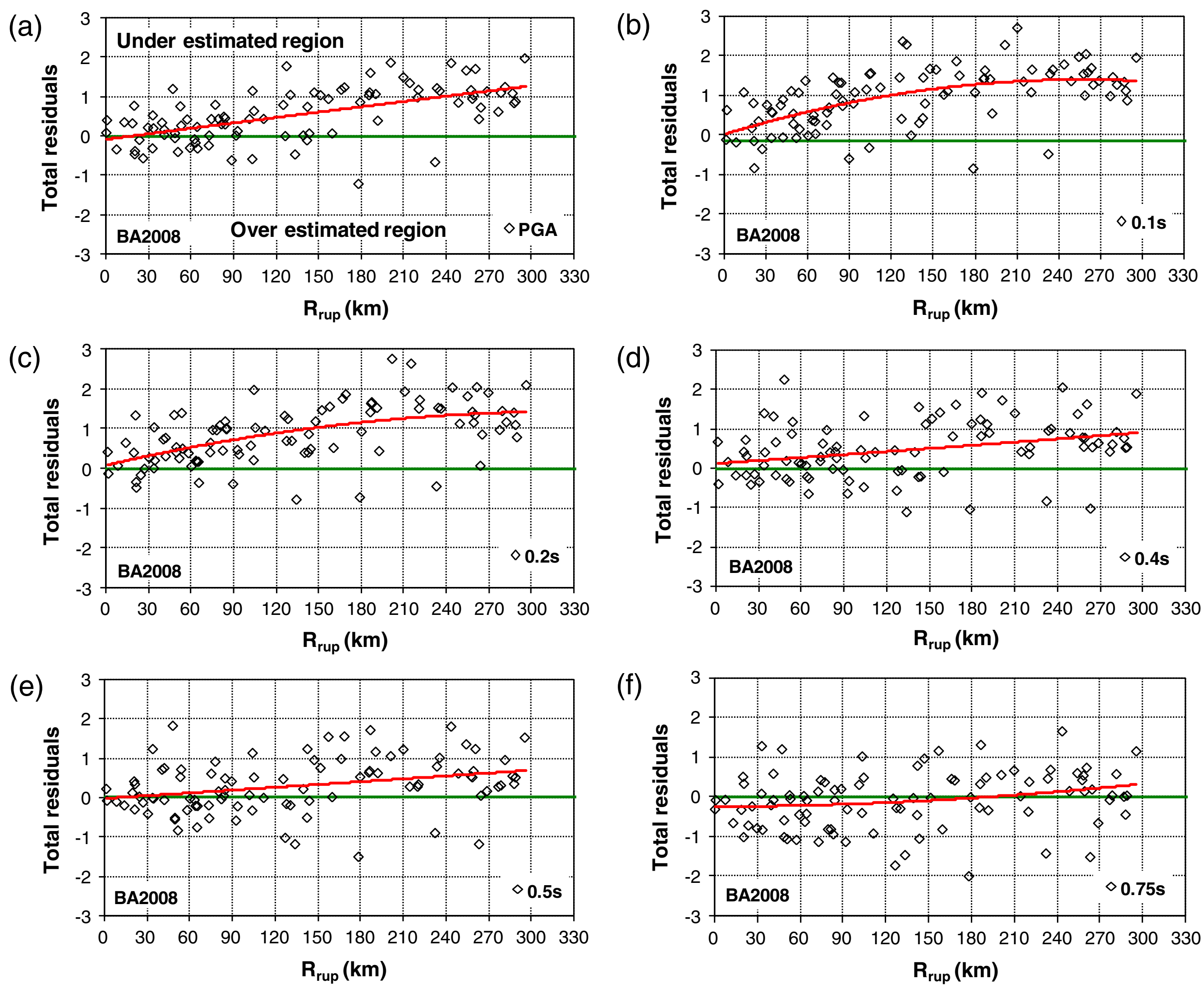

Figure 17. Distribution of residuals with source distance for the response spectra with respect to the Boore and Atkinson (2008) model for (a) PGA and for spectral periods of (b) 0.1 s, (c) 0.2 s, (d) 0.4 s, (e) 0.5 s, and (f) 0.75 s. The BA2008 models are applicable for M_w 5–8, $R_{JB} < 200$ km, and $V_{S30} = 180$–1300 m/s and for period range of 0.01–10 s. Surface rupture is assumed for all comparisons. The color version of this figure is available only in the electronic edition.

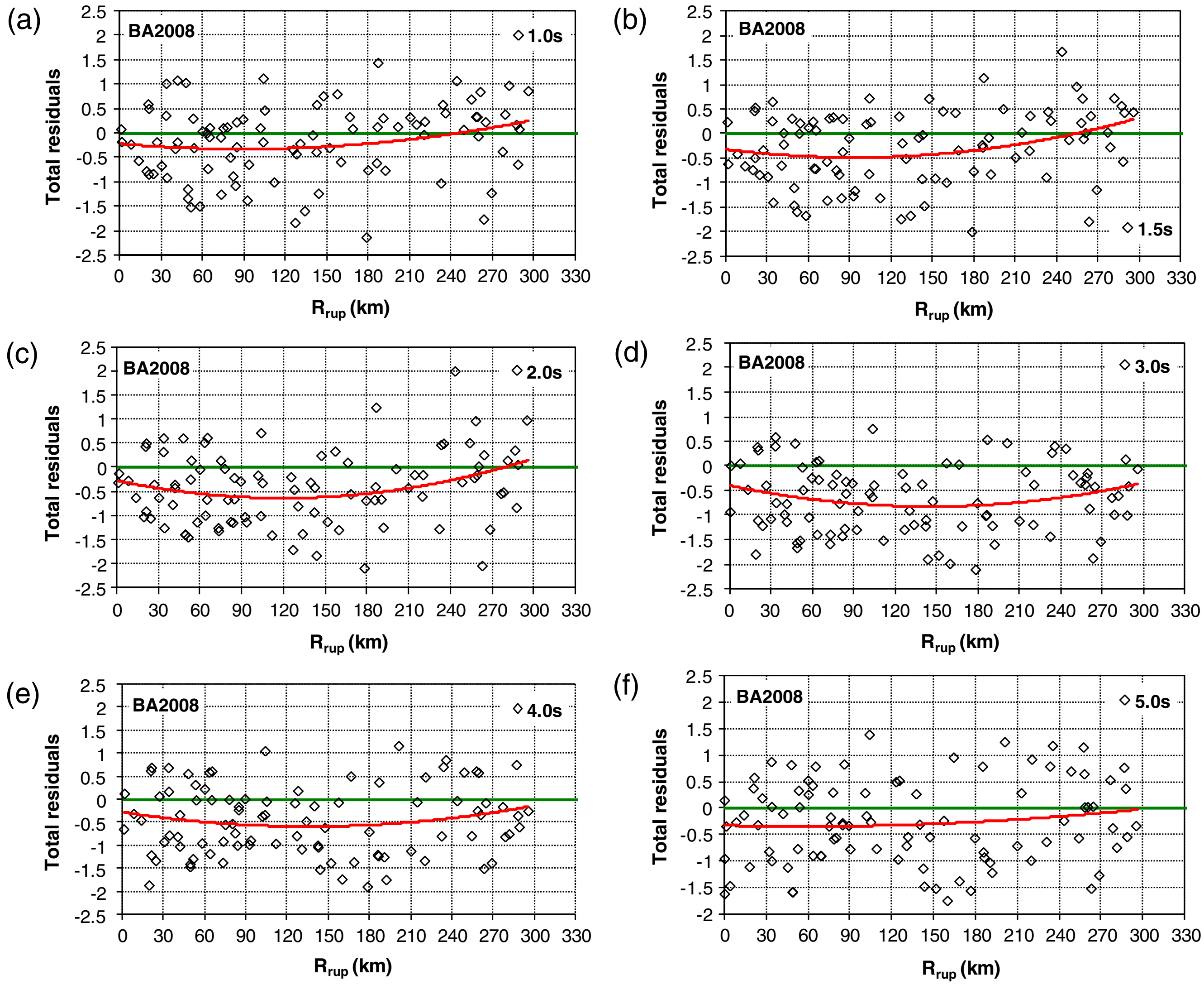

Figure 18. Distribution of residuals with source distance for the response spectra with respect to the Boore and Atkinson (2008) model for spectral periods of (a) 1.0 s, (b) 1.5 s, (c) 2.0 s, (d) 3.0 s, (e) 4.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

with respect to the five attenuation models. The standard deviations of the four NGA models are very similar at all periods, apart from the AS2008 model, which has a considerably smaller standard deviation than the other NGA models at periods over 1 s. At periods over 0.6 s, the Z2006 model has the smallest standard deviation but has a marginally larger standard deviation than the other models at short periods less than 0.2 s.

Figure 25c shows the residual factors and Figure 25d shows the standard deviations for the records within a source distance of 200 km. For PGA and for spectral periods up to 0.4 s, the Z2006 model has the best estimate of the recorded spectra, with the largest residual factor of only 1.3 (at 0.1 s). The CY2008 model has the next best prediction while the Campbell and Bozorgnia (2008) (CB2008) model has the largest residual factors at short periods. The residual factors for the Boore and Atkinson (2008) (BA2008) and AS2008 models are similar at spectral periods less than 0.15 s. At spectral periods over 0.2 s, the CB2008 and BA2008 models have very similar residual factors. At periods over 0.25 s, the residual factors from the AS2008, Z2006, and CY2008 models are very similar. At long periods, the CY2008 model has the residual factor closest to 1.0, while the Z2006, CB2008, and BA2008 models overpredict the data by a similar amount. Figure 25d shows that the standard deviations for the total residuals with respect to the five models are very similar, varying between 0.5 and 0.8. At periods over 1 s, the Z2006 model has the lowest standard deviation.

All models tend to significantly underpredict short-period spectra at source distances over 100 km, though some of the models predict the short-period spectra within a source distance of 50 km reasonably well (Z2006 and CY2008 for

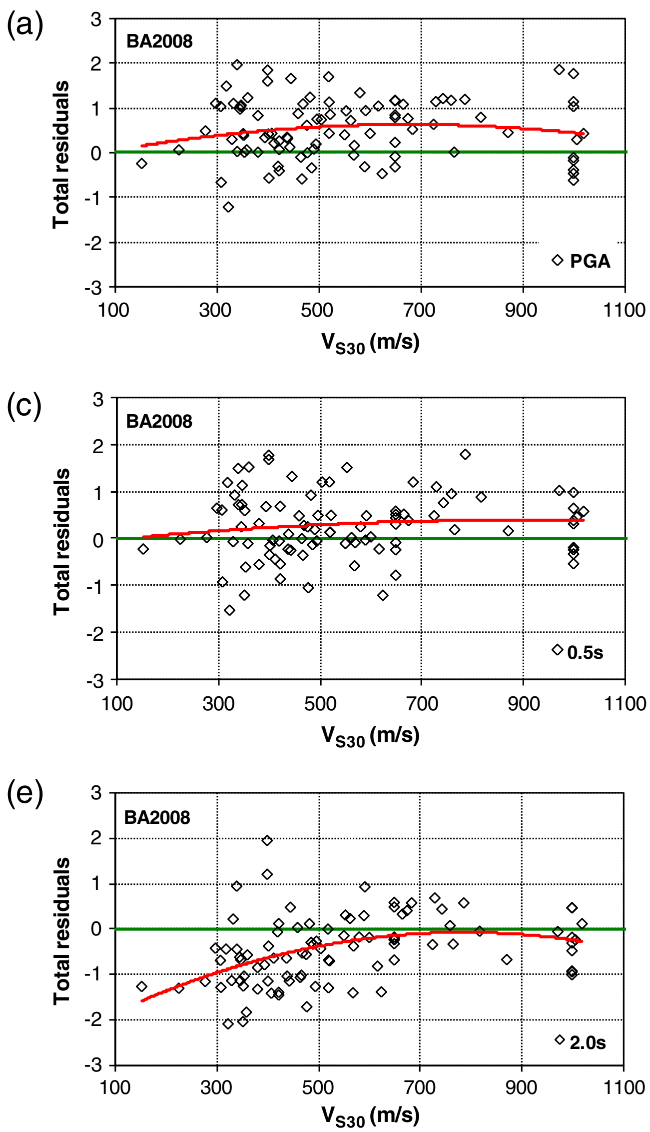

Figure 19. Distribution of residuals with V_{S30} for the response spectra with respect to the Boore and Atkinson (2008) model for (a) PGA and for spectral periods of (b) 0.2 s, (c) 0.5 s, (d) 1 s, (e) 2 s, and (f) 5 s. The color version of this figure is available only in the electronic edition.

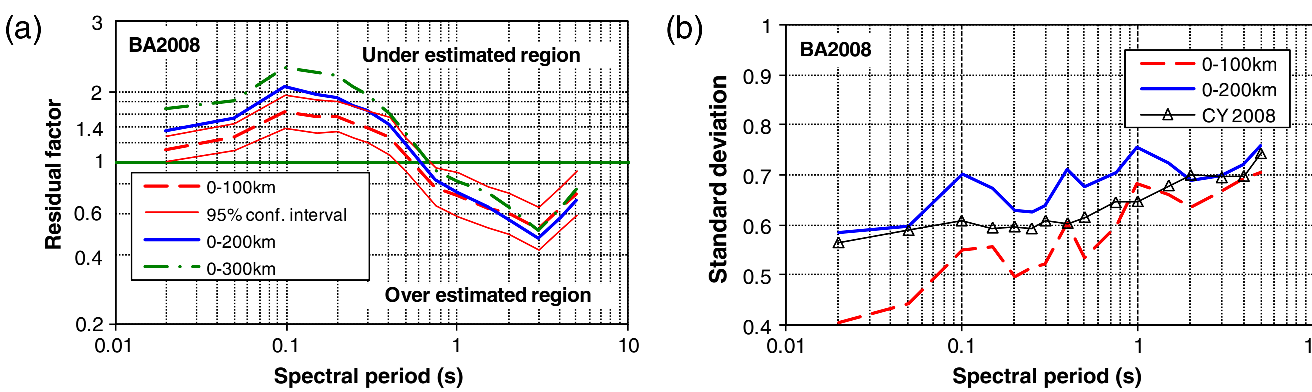

Figure 20. (a) Residuals factor and (b) standard deviation for the Boore and Atkinson (2008) model for source distances of 0–100 km and 0–200 km. The 95% confidence limits for the data within a distance of 100 km are also presented in (a). The color version of this figure is available only in the electronic edition.

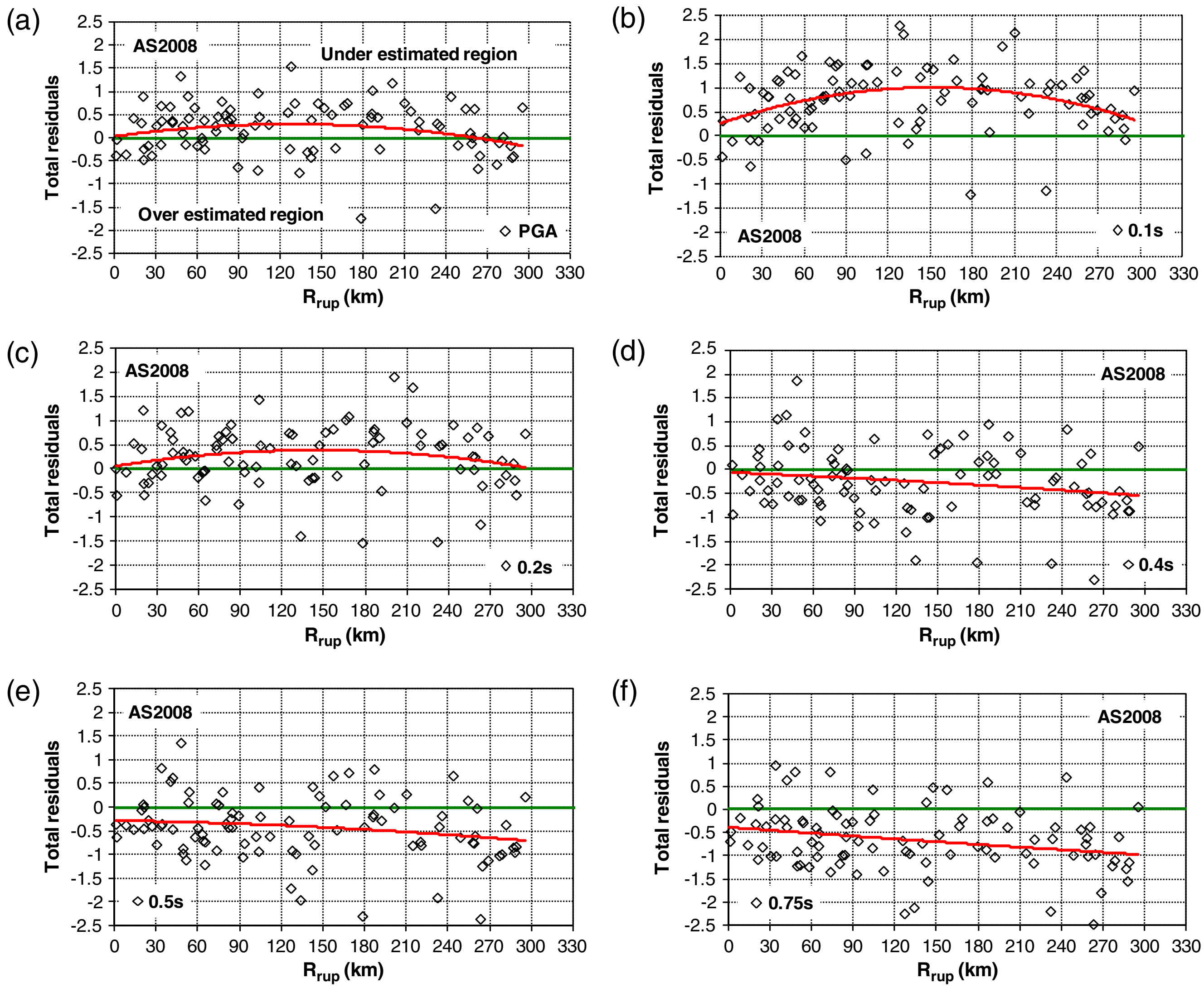

Figure 21. Distribution of residuals with source distance for the response spectra with respect to the Abrahamson and Silva (2008) model for (a) PGA and for spectral periods of (b) 0.1 s, (c) 0.2 s, (d) 0.4 s, (e) 0.5 s, and (f) 0.75 s. The depth-to-shear-wave velocity 1 km/s was taken as 50 m, and the results are slightly worse if 100 m is selected. The model is applicable to magnitudes 5–8.5, distances 0–200 km, and periods of 0–10 s. Surface rupture is assumed for all comparisons. The color version of this figure is available only in the electronic edition.

PGA and the 0.1–0.4-s period and BA2008 for PGA). The tendency to underestimate short-period ground motions may be caused by the relatively large stress drop for the 2008 Wenchuan earthquake compared with those of other shallow crustal earthquakes (e.g., the 1992 Landers, 1995 Kobe, and 1999 Chi-Chi earthquakes). A common feature for all models is that the PGA and short-period spectra within a source distance range of 100–200 km are severely underpredicted, by a factor of close to 1.5 or larger. If the stress drop is the only factor, the short-period ground motions from the records within 50 km should also be overpredicted. For short-period ground motions, the reasonable prediction at short distances, and the underprediction at other distances, may suggest that the relatively large stress drop is not the only factor. Magnitude scaling and the terms for the magnitude-dependent geometric spreading may also be possible factors for the overprediction at short periods in the distance range of 100–200 km.

All models predict the Wenchuan data quite well at 0.5-s, 0.75-s, and 5.0-s periods, and all the NGA models generally predict the recorded spectra well at 1-s periods, within a distance of 200 km. The standard deviations computed from all models are reasonable for the data within a distance of 200 km, varying between 0.5 and 0.8.

We also carried out a set of statistical tests on the residuals computed for the Wenchuan records within a 200-km distance for each pair of attenuation models. Table 1 shows the probability of an *F*-test on the hypotheses that the residuals between each pair of models have the same standard deviations. The values in bold and italic in Table 1 suggest

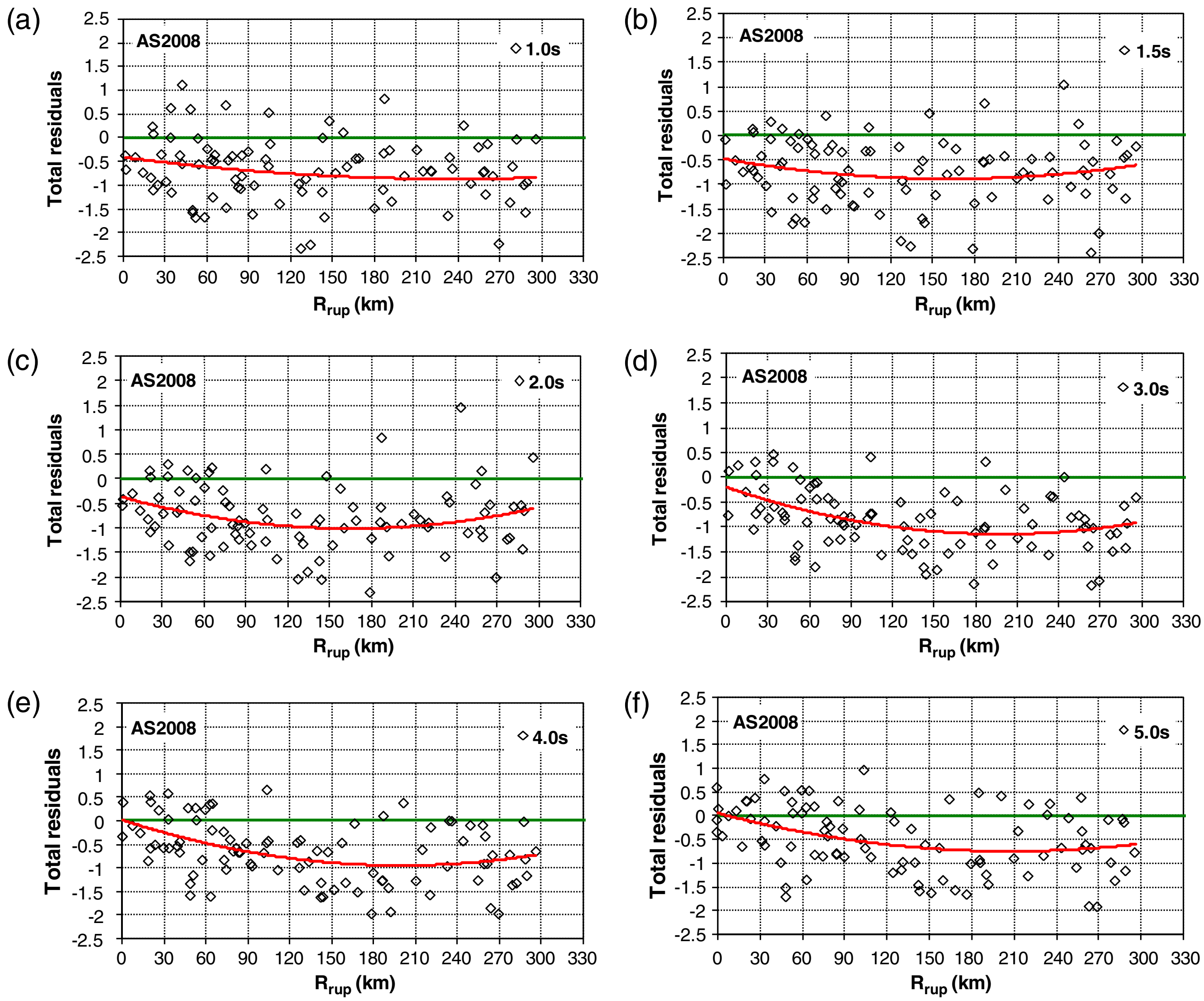

Figure 22. Distribution of residuals with source distance for the response spectra with respect to the Abrahamson and Silva (2008) model for spectral periods of (a) 1.0 s, (b) 1.5 s, (c) 2.0 s, (d) 3.0 s, (e) 4.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

that the standard deviations between each pair of models differ statistically. The *F*-test results suggest that the standard deviations derived from the five attenuation models do not differ statistically, except for those between the Z2006 and the CY2008 models at periods of 3 s and 4 s, with the Z2006 model having a much smaller standard deviation. At the 4-s spectral period, the standard deviation of the Z2006 model and the BA2008 model differ statistically.

Table 2 shows the probability of the Student's *t*-test on the hypotheses that the residuals of each pair of models have the same mean values. A significance level of 5% is used for all comparisons. The values in bold and italic in Table 2 suggest that the mean residuals between each pair of models differ statistically at a significance level of 5%. On average, the predictions of the Z2006 model do not differ statistically from those of the CY2008 model for PGA and spectral periods up to 1 s, apart from the 0.1-s period at which the Z2006 model has a statistically better prediction. The CY2008 model has statistically better average predictions than the Z2006 model in the period range of 1.5–5 s. The results in Table 2 suggest that the average predictions of the Z2006 model are statistically better than those of the CB2008 and the BA2008 models for PGA and at spectral periods up to 0.5 s, while the Z2006 model has a statistically better average prediction than the CB2008 model at the 5-s spectral period. The Z2006 model also has statistically better predictions on average than the BA2008 model at spectral periods of 0.05, 0.1, and 0.15 s, and the average residuals for the two models do not differ statistically at the other periods.

Table 2 suggests that the CY2008 model has statistically better average predictions than the CB2008 model for the Wenchuan data at PGA and in the spectral period ranges of

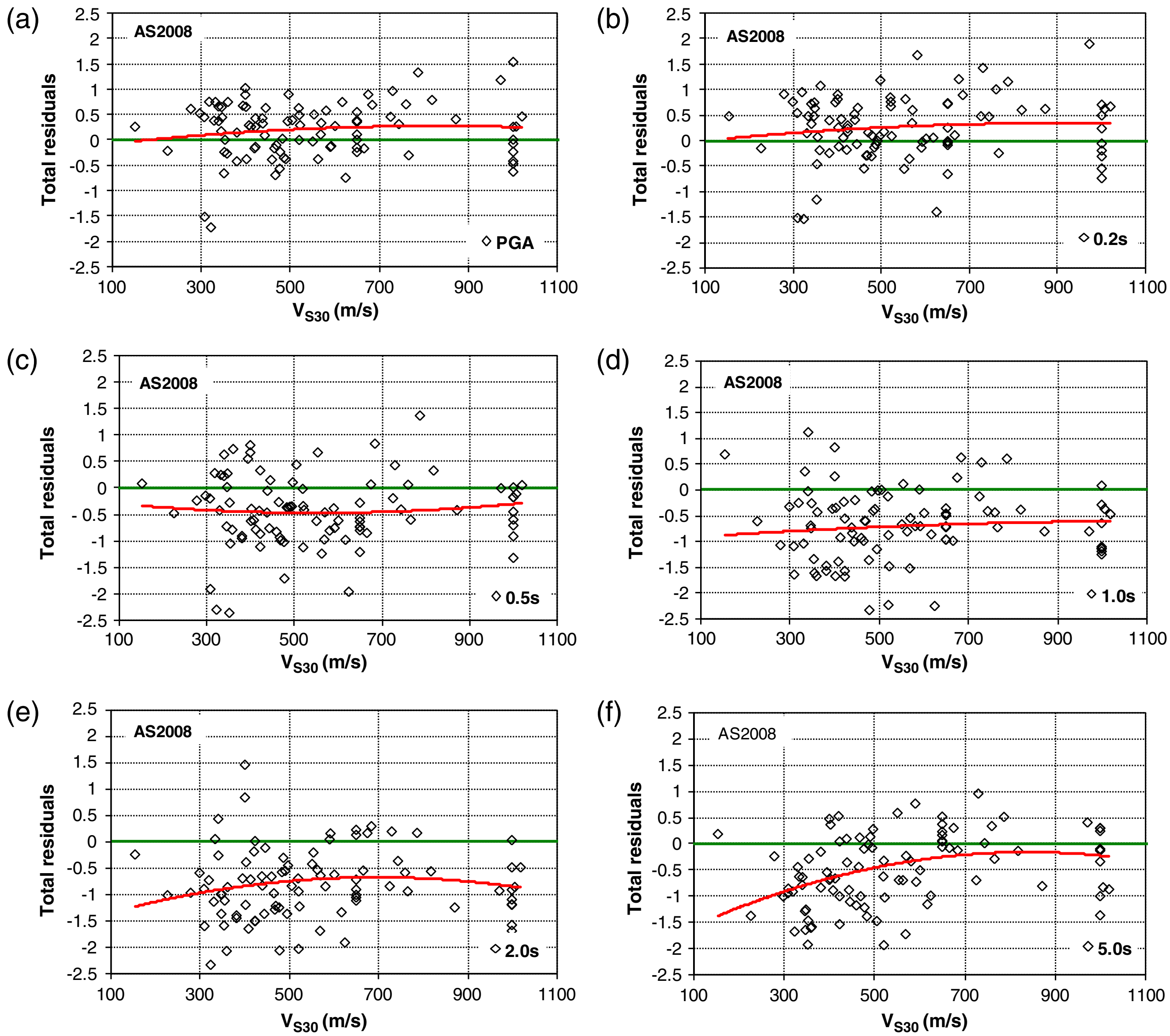

Figure 23. Distribution of residuals with V_{S30} for the response spectra with respect to the Abrahamson and Silva (2008) model for (a) PGA and for spectral periods of (b) 0.2 s, (c) 0.5 s, (d) 1.0 s, (e) 2.0 s, and (f) 5.0 s. The color version of this figure is available only in the electronic edition.

0.05–0.4 s and 2.0–5.0 s. The CY2008 model predicts, on average, the Wenchuan data in spectral period ranges of 0.15–0.4 s and 2.0–5.0 s statistically better than does the BA2008 model. The average predictions from the CY2008 model are statistically better than those from the AS2008 model at spectral periods of 0.4 s or larger, while the AS2008 model has a statistically better prediction than the CY2008 model at 0.3 s. The mean values of residuals from the CB2008 model and the BA2008 model do not differ statistically at all spectral periods. The AS2008 model has statistically better average predictions than the CB2008 model for PGA and spectra in the period ranges of 0.15–0.4 s and 4.0–5.0 s but has a worse prediction than the CB2007 model at periods of 0.5–1.0 s, while the average predictions for other periods are similar. The AS2008 model also has statistically better average predictions than the BA2008 model in a period range of 0.2–0.3 s but a worse prediction than the BA2008 model between 0.4 s and 1.0 s, while the two models have statistically similar average predictions for the other periods.

All NGA models overpredict the spectra at long periods over 1 s for sites with a V_{S30} less than about 600 m/s. This is unlikely to be caused by systematic errors in estimating V_{S30} for these sites. For a site with a $V_{S30} = 300$ m/s, the site's natural periods are likely to be in a range of 0.3–0.6 s for many stations (the soil layer could be fairly thin and shallow among the valleys in hilly areas). If V_{S30} for these sites is significantly overestimated or underestimated, the residuals at periods close to the site's natural period will be significantly biased.

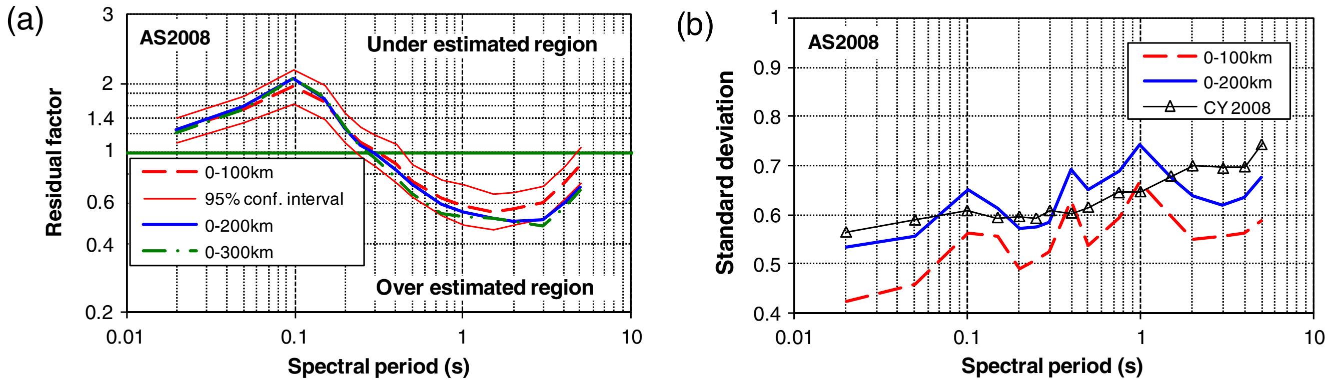

Figure 24. (a) Residuals factor and (b) standard deviation for the Abrahamson and Silva (2008) model for source distances of 0–100 km and 0–200 km. The 95% confidence limits for the data within a distance of 100 km are also presented in (a). The color version of this figure is available only in the electronic edition.

At periods significantly longer than site periods, site effects due to surface soil layers are much less than that at the site's natural periods.

Note that the Wenchuan earthquake is the largest earthquake, in terms of magnitude and number of records, that has ever been recorded. The large magnitude represents a large extrapolation from the magnitude range of some attenuation models. Every large earthquake has its own characteristics that might be difficult to capture with empirical models because they do not have terms for many seismological parameters, such as stress drop. The overall predictions of all of the models considered here are reasonable, considering the usually large variabilities associated with the empirical models.

The data from the 2008 Wenchuan earthquake provides a rare opportunity to test the predictions of recently developed models at the upper end of the magnitude range of strong-motion data. Note that the preliminary comparisons carried out in this study are based on an approximate fault model and inferred shear-wave velocity profiles of the recording stations. Further detailed comparisons can be performed when an improved fault-rupture model and shear-wave velocity profiles are available.

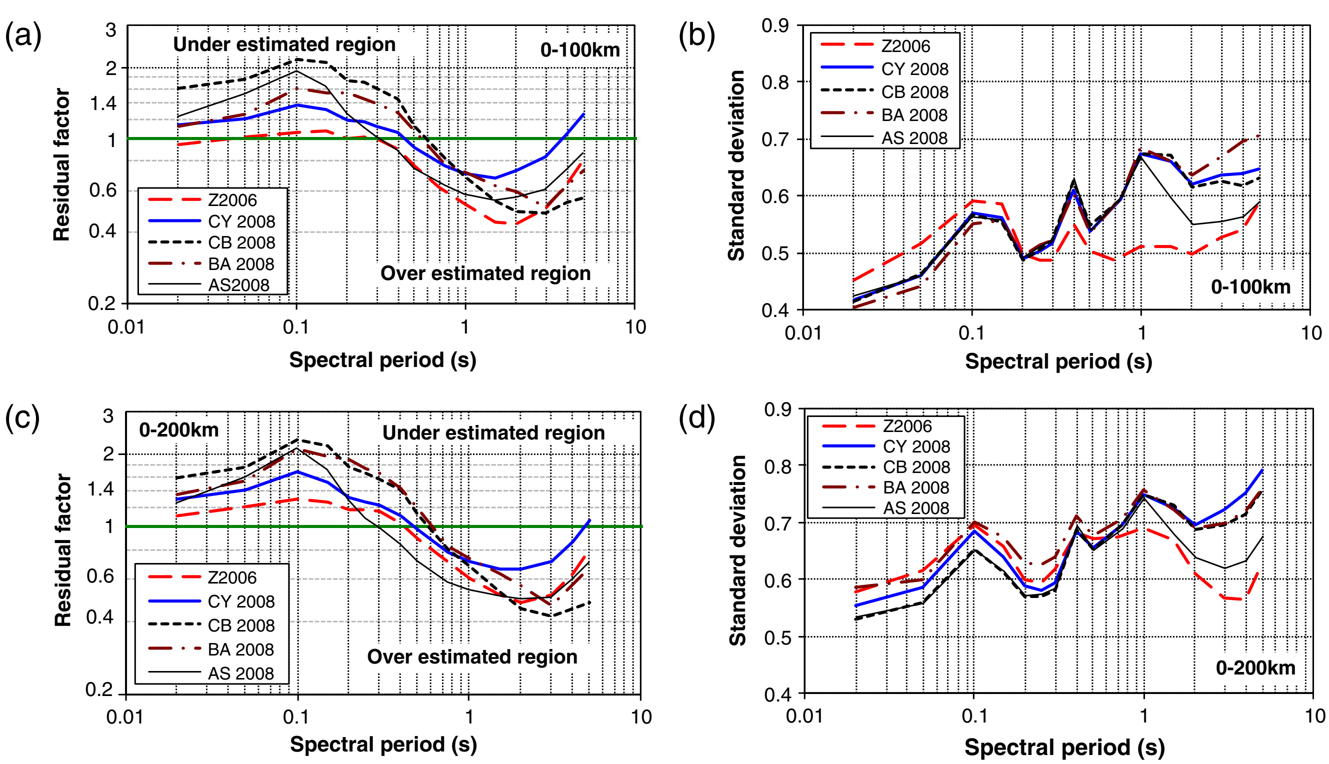

Figure 25. (a and c) Residuals factors and (b and d) standard deviations for data in source-distance ranges of 0–100 km (top row) and 0–200 km (bottom row). The color version of this figure is available only in the electronic edition.

Table 1
Probabilities of *F*-Test on the Hypotheses that Residuals of Each Pair of Models Have the Same Standard Deviations for Data within a 200-km Source Distance

Period (s)	Zhao/CY	Zhao/CB	Zhao/BA	Zhao/AS	CY/CB	CY/BA	CY/AS	CB/BA	CB/AS	BA/AS
PGA	0.73	0.47	0.91	0.53	0.71	0.64	0.78	0.40	0.93	0.46
0.05	0.68	0.42	0.83	0.42	0.69	0.84	0.70	0.55	0.99	0.55
0.1	0.90	0.59	0.96	0.58	0.68	0.86	0.67	0.56	0.99	0.55
0.15	0.79	0.55	0.87	0.57	0.74	0.67	0.76	0.44	0.98	0.46
0.2	0.88	0.69	0.68	0.71	0.81	0.57	0.83	0.41	0.98	0.43
0.25	0.87	0.74	0.66	0.80	0.87	0.55	0.93	0.44	0.94	0.49
0.3	0.76	0.61	0.77	0.67	0.84	0.55	0.91	0.43	0.94	0.47
0.4	0.99	0.96	0.75	0.90	0.98	0.76	0.91	0.78	0.94	0.84
0.5	0.84	0.81	0.95	0.81	0.97	0.79	0.97	0.76	1.00	0.76
0.75	NA*	NA	NA	NA	1.00	0.90	0.95	0.90	0.95	0.85
1	0.51	0.50	0.47	0.55	1.00	0.95	0.95	0.95	0.94	0.89
1.5	0.52	0.49	0.54	0.93	1.00	0.98	0.58	0.93	0.54	0.60
2	0.30	0.34	0.32	0.73	1.00	0.95	0.49	0.97	0.55	0.52
3	0.05	0.09	0.09	0.46	1.00	0.78	0.22	0.98	0.34	0.33
4	***0.02***	0.06	***0.05***	0.34	1.00	0.73	0.17	0.94	0.34	0.30
5	0.06	0.13	0.13	0.56	0.68	0.73	0.20	0.98	0.36	0.35

*The Zhao, Zhang *et al.* (2006) model does not have 0.75-s period.

The differences among the spectra predicted by the different models are considerable. For example, at a spectral period of 0.1 s, the difference in the residual factors between the CB2008 model and the CY2008 model is a factor of 1.4 (the ratios of residual factors) for data within a source distance of 100 km. This means that predicted spectra from the CB2008 model, on average, are 40% higher than those from the CY2008 model for an earthquake similar to the Wenchuan earthquake in magnitude and focal mechanism. At 5 s, the differences in the predicted spectra between the CB2008 and the CY2008 models are a factor of about 2.3. Even though a single earthquake does not necessarily produce the median ground motions that empirical models are designed to predict, such a considerable difference among different models represents a challenge for empirical models to predict recorded ground motion well at the upper end of the earthquake magnitude range in a strong-motion dataset.

Data and Resources

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Table 2
Probabilities of *Student*-Test on the Hypotheses that Residuals of Each Pair of Models Have the Same Mean Values for Data within a 200-km Source Distance

Period (s)	Zhao/CY	Zhao/CB	Zhao/BA	Zhao/AS	CY/CB	CY/BA	CY/AS	CB/BA	CB/AS	BA/AS
PGA	0.13	***0.00***	***0.04***	0.21	***0.01***	0.55	0.79	0.08	***0.01***	0.39
0.05	0.14	***0.00***	***0.02***	***0.01***	***0.01***	0.37	0.19	0.12	0.31	0.70
0.1	***0.03***	***0.00***	***0.00***	***0.00***	***0.01***	0.07	0.05	0.36	0.47	0.95
0.15	0.11	***0.00***	***0.00***	***0.01***	***0.00***	***0.03***	0.24	0.28	***0.04***	0.27
0.2	0.28	***0.00***	***0.00***	0.39	***0.00***	***0.00***	0.81	0.60	***0.00***	***0.00***
0.25	0.49	***0.00***	***0.00***	0.38	***0.00***	***0.00***	0.11	0.85	***0.00***	***0.00***
0.3	0.69	***0.00***	***0.00***	0.11	***0.01***	***0.00***	***0.04***	0.80	***0.00***	***0.00***
0.4	0.60	***0.01***	***0.01***	0.08	***0.02***	***0.03***	***0.02***	1.00	***0.00***	***0.00***
0.5	0.49	***0.03***	***0.01***	0.07	0.14	0.06	***0.01***	0.63	***0.00***	***0.00***
0.75	NA*	NA	NA	NA	0.57	0.61	***0.02***	0.96	***0.01***	***0.00***
1	0.21	0.14	0.12	0.36	0.83	0.76	***0.04***	0.93	0.09	***0.02***
1.5	***0.04***	0.19	0.07	0.94	0.46	0.79	***0.03***	0.64	0.74	0.06
2	***0.00***	0.42	0.14	0.74	***0.05***	0.19	***0.01***	0.53	0.41	0.26
3	***0.01***	0.60	0.37	0.77	***0.00***	***0.00***	***0.00***	0.74	0.12	0.55
4	***0.01***	0.09	0.34	0.52	***0.00***	***0.00***	***0.00***	0.52	***0.02***	0.72
5	***0.03***	***0.00***	0.17	0.26	***0.00***	***0.00***	***0.00***	0.12	***0.00***	0.77

*The Zhao, Zhang *et al.* (2006) model does not have a 0.75-s period.

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