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Modelling of source terms separated from observed response spectra to reduce variability in GMPE

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Abstract

We investigated the characteristics of strong ground motions separated from acceleration Fourier spectra and acceleration response spectra of 5% damping calculated from weak and moderate ground motions observed by K-NET, KiK-net, and the JMA Shindokei Network in Japan using the generalized spectral inversion method. As a reference our separation method uses the outcrop motions at a rock site, YMGH01, where we extracted the site response due to shallow weathered layers. We include events with JMA magnitude equal to or larger than 4.5 observed from 1996 to 2011. From the corner frequencies of Fourier source spectra and CMT seismic moment values, we calculate Brune's stress parameters to find a clear magnitude dependence, in which smaller events tend to spread over a wider range while maintaining the same maximum value. We confirm that this is exactly the case for several mainshock-aftershock sequences. The average stress parameter for crustal earthquakes, ~0.8MPa, is much smaller than those of subduction zone earthquakes, either plate-boundary or intraplate, ~5MPa, which can be primarily explained by their depth dependence.

Next we compare the strong motion characteristics based on the 5% damping acceleration response spectra and find that the separated characteristics of strong ground motions are different, especially in the lower frequency range less than 1Hz. These differences comes from the difference between Fourier spectra and response spectra in the observed data; that is, predominant components in high frequency range of Fourier spectra contribute to increase the response in lower frequency range with small Fourier amplitude because strong high frequency component acts as an impulse to a Single-Degree-of-Freedom system.

By using the separated source terms for 5% damping response spectra we can obtain regression coefficients with respect to the moment magnitude, which lead to a new Ground Motion Prediction Equation. Although stress drops for crustal earthquakes are 1/7 of the subduction-zone earthquakes, we found that linear regression works quite well. After this linear regression we correlate residuals from this linear relationship as a function of obtained stress drops of corresponding events from Fourier spectra. We find quite a good linear correlation in a wide frequency range from 0.3 Hz to 20 Hz, which yields reduction of variability higher than 50 % from the original one in terms of the standard deviation. When we applied the same kind of correction to Fourier source terms we can see reduction in high frequency range but cannot see any reduction in the frequency range below 1 Hz, as expected. To use derived correction based on the stress drop for a future event we can use average stress drops for different types of events together with the source depth correction.

Keywords: strong motion, generalized inversion, stress drop, GMPE, response spectra

1. Introduction

The objective of this study is to investigate the possibility of reducing uncertainty associated with the source term of ground motion prediction equations (GMPEs) for response spectra by introducing its stress drop dependence. To do so we need first obtain quantitative and systematic estimates of stress drops of observed earthquakes. Then we need to obtain the source term of the response spectral GMPE and uncertainty estimate of that GMPE relative to the observed response spectra used as constraint. Finally we will calculate variance reduction by introducing the correction factor with respect to the stress drops for each earthquakes. This is a single-source estimate of variance of GMPE, similar to the single-station estimate of variance.

First we used Fourier acceleration spectra (FAS) of strong ground motions observed by K-NET, KiK-net (Aoi et al., 2000 [1]; Okada et al. 2004 [2]), and JMA Shindokei Network in Japan to separate source, path, and site factors based on a generalized spectral inversion method, initially proposed by Andrews (1982 [3], 1986 [4]). The separation method that we used here is the same method proposed by Kawase and Matsuo (2004) [5]. We include all sources larger than M_{JMA}4.5 observed from 1996 to 2011. Our results are in good agreement with the results by Kawase and Matsuo on the characteristics estimated from Fourier spectra, but ours show higher stability. By using the same method, we also separated the strong motion characteristics based on the acceleration response spectra (RS) with 5% damping successfully. However, the separated characteristics of strong ground motions of both results are different, especially in the lower frequency range less than 1Hz and higher frequency range more than 10 Hz. These differences comes from the difference between Fourier spectra and response spectra found in the observed data. Our GMPE for RS is based on the generalized inversion and not based on the regression analysis as in the ordinary GMPEs (e.g., NGA-West, Abrahamson et al., 2014 [6]).

From the separated FAS source term we calculated the so-called Brune's stress drops (Brune, 1970 [7]). We found that the stress drops have a magnitude dependence where the higher values are the same irrespective of magnitude but their lower bound tends to increase as the magnitudes become smaller. The same is true for mainshocks and aftershocks sequence. We also found that systematic increase of stress drop as a function of source depths.

By using these stress drop estimates for individual earthquakes and source terms separated from RS we can correlate residuals (logarithm of ratios) of individual earthquakes from the average linear relationship on magnitude with the stress drops. The correlation is quite strong and the correction based on the stress drop of each earthquake is quite significant to reduce the uncertainty. Thus we would like to propose to account for the effect of stress drop on the source term in future GMPEs.

2. Separation of source, path, and site factors

As the first stage of analysis we used Fourier acceleration spectra (FAS) of strong ground motions observed by K-NET, KiK-net, and JMA Shindokei Network in Japan to separate source, path, and site factors based on a generalized spectral inversion method. The separation method that we used here is the same method proposed by Kawase and Matsuo (2004) [5]. We include all sources larger than M_{JMA}4.5 observed from 1996 to 2011. In Figure 1 magnitude-distance distribution of used data is plotted for three different types of earthquake for two category of source depths. See details on the data and method of separation in Nakano et al. (2015) [8].

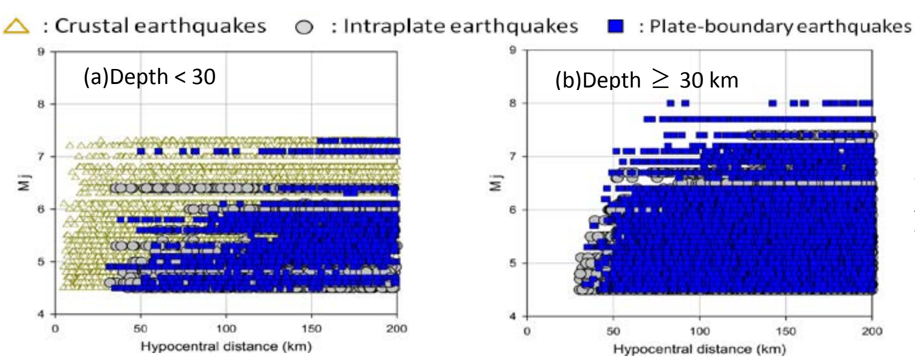

Figure 1 JMA magnitude versus hypocentral distance relationship of all the used data with source depths (a) shallower than or (b) equal to/deeper than 30 km.

We limited earthquakes with source depth D ≤60 km and hypocentral distance from earthquake i to site j Xij ≤200 km, and records with peak ground acceleration PGA ≤ 2 m/s to avoid deviation by site nonlinearity. We use only surface data for KiK-net because it would be redundant to use both surface and borehole data at the same location (note that we can obtain borehole site factors after the inversion). Selection using these criteria resulted in analysis of 972 K-NET sites, 601 KiK-net sites, and 532 JMA Shindokei Network sites, 2,105 sites in total. The data covered 967 events with 446 subducting plate-boundary (type B) events, 294 subducting intraplate (type I) events, and 227 crustal (type C) events. There were 77,213 earthquake–station pairs. This dataset is approximately four times the size of that used in Kawase and Matsuo (2004) [5]. We used YMGH01 for constraint where no site effect would exist after correcting the theoretical site amplification from the bedrock (with S-wave velocity of 3.45 km/s) to the surface. We checked site factors for other hard-rock sites and found that the corrected YMGH01 shows actually the lowest and most stable characteristics among them.

Our results are in good agreement with the results by Kawase and Matsuo [5] on the characteristics estimated from Fourier spectra, but ours show higher stability. Figure 2 compares site factors separated from this study with those by Kawase and Matsuo [5]. The same kind of similarities can also be seen in source spectra and path attenuation characteristics.

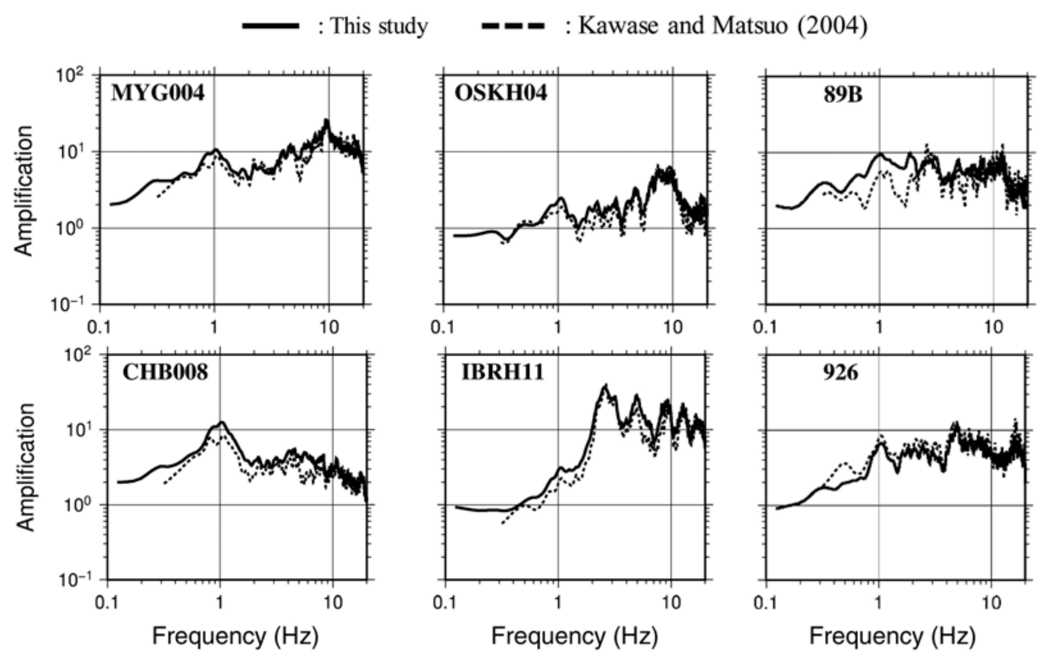

Figure 2. Examples of separated site factors by Nakano et al. [8] and Kawase and Matsuo [5].

3. Stress drop estimate

From the separated FAS source term we calculated the so-called Brune’s stress drops [7]. We tested whether it is statistically the same as those in Kawase and Matsuo (2004) by using t-test. We found that only crustal earthquakes do not pass the test, but basically they share the same average and standard deviation values for all three types of events. We also applied t-tests to the data before and after the Off the Pacific Coast of Tohoku Earthquake of March 11, 2011, to realize that differences were not significant for all earthquake scales and types. This means that there are barely any effects of the Off the Pacific Coast of Tohoku Earthquake on the stress drops of small earthquakes including aftershocks in the source region in Tohoku, Japan.

When we plot estimated stress drops as a function of their magnitude, we found that the stress drops have a magnitude dependence where the higher values are constant irrespective of magnitude but their lower bound tends to decrease as the magnitudes become smaller. The same is true for mainshocks and aftershocks sequence, which are not shown here though. Figure 3 shows stress drop distributions as a function of seismic moment M0 for different magnitude ranges and different event types (types B, I, and C). As mentioned above we cannot see any systematic difference before and after the 2011 Tohoku earthuake, except for larger events in types B and I.

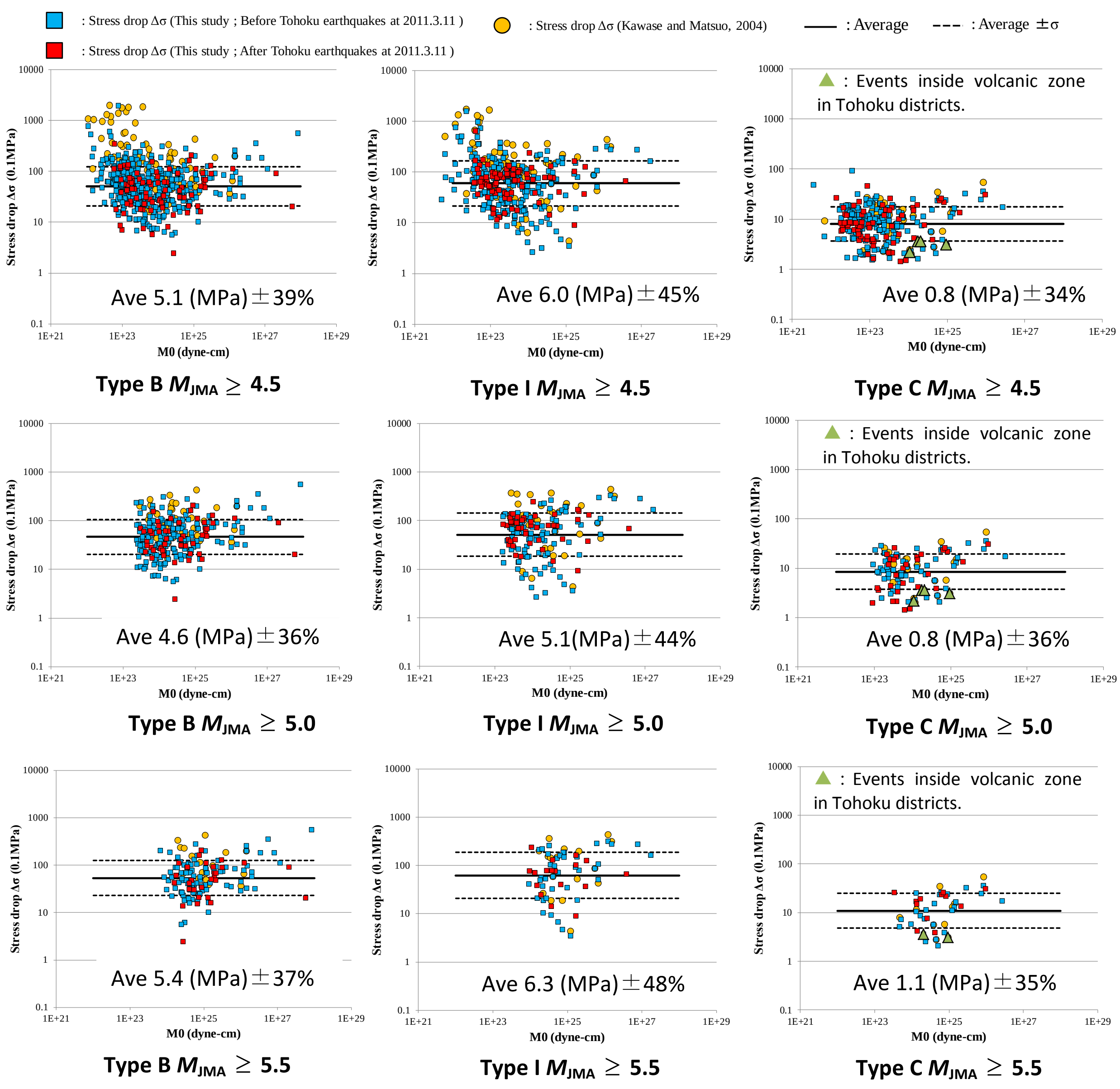

Figure 3 Brune's stress drops for three different event types and three magnitude ranges.

We also found that systematic increase of stress drop as a function of source depths on average. Here we use source depths determined by JMA, which is actually depths of rupture initiation. If we consider average source depth difference between crustal events and subduction events, we can explain the average stress drop difference between them, namely 0.8 MPa for crustal ones and around 5 MPa for subducion zone ones, as shown in Figure 3. In Fugure 4 we plot stress drops as a function of source depths. The depth dependence on type C events are stronger than those on types B and I events. Since the velocity increase in this range of crust and upper mantle does not seem to be as strong as the confining pressure increase, we believe that this depth dependence of stress drop would be a direct consequence of the confining pressure increase with depth.

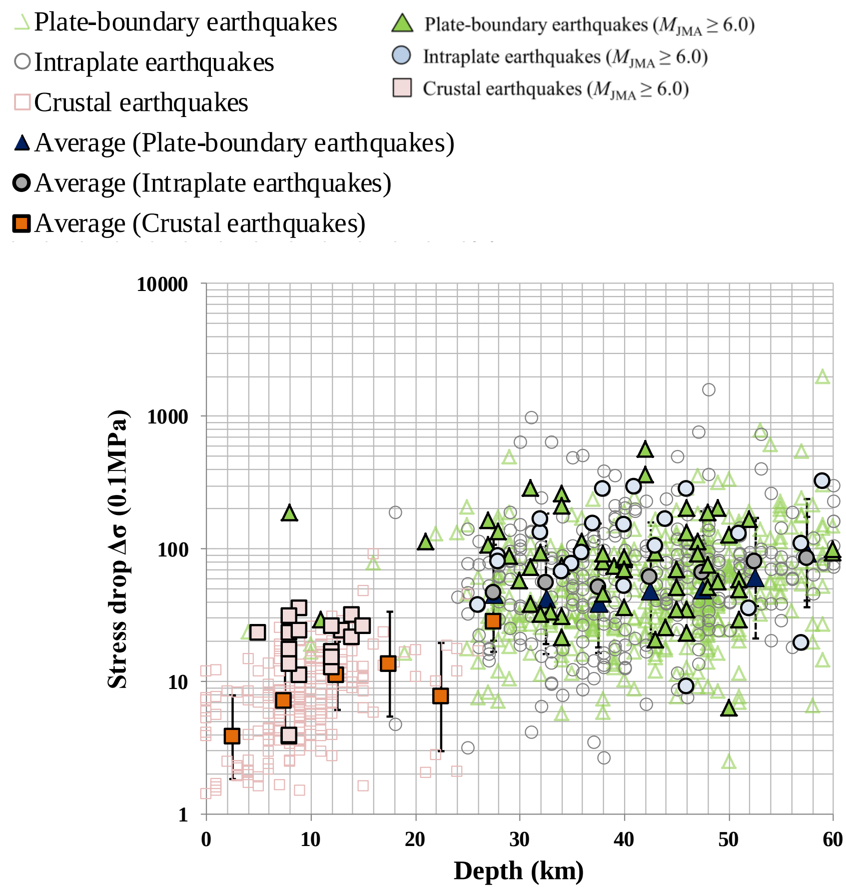

Figure 4. Relationship of stress drop and focal depth of events with different types. Types B and I events show gradual increase of stress parameters as source depths become larger. Solid dark-colored symbols with vertical bars are those for mean values (and plus/minus one standard deviation) in each 5 km bin for depth. Thick sold symbols are those with M_{JMA} larger than 6.0, which tend to be higher than the average as seen in Figure 3.

4. Response spectra and source term regression

By using the same method, we also separated the strong motion characteristics based on the acceleration response spectra (RS) successfully. However, the separated characteristics of strong ground motions of RS are different, especially in the lower frequency range less than 1Hz and higher frequency range more than 10 Hz. These differences comes from the difference between FAS and RS found in the observed data; that is, predominant components in a different frequency of FAS contribute to increase RS in lower and/or higher frequency with small amplitude because a strong (peak) component acts as an impulse to a Single-Degree-Of-Freedom system. In Figure 5 we compare the separated source factors in FAS and RS. As we can see the basic characteristics are quite similar, however, source factors in RS tend to become larger than those in FAS in lower frequency range. This is primarily because the amplitude in source factors are higher in high frequency range so that they contribute to increase the response of lower frequency oscillators.

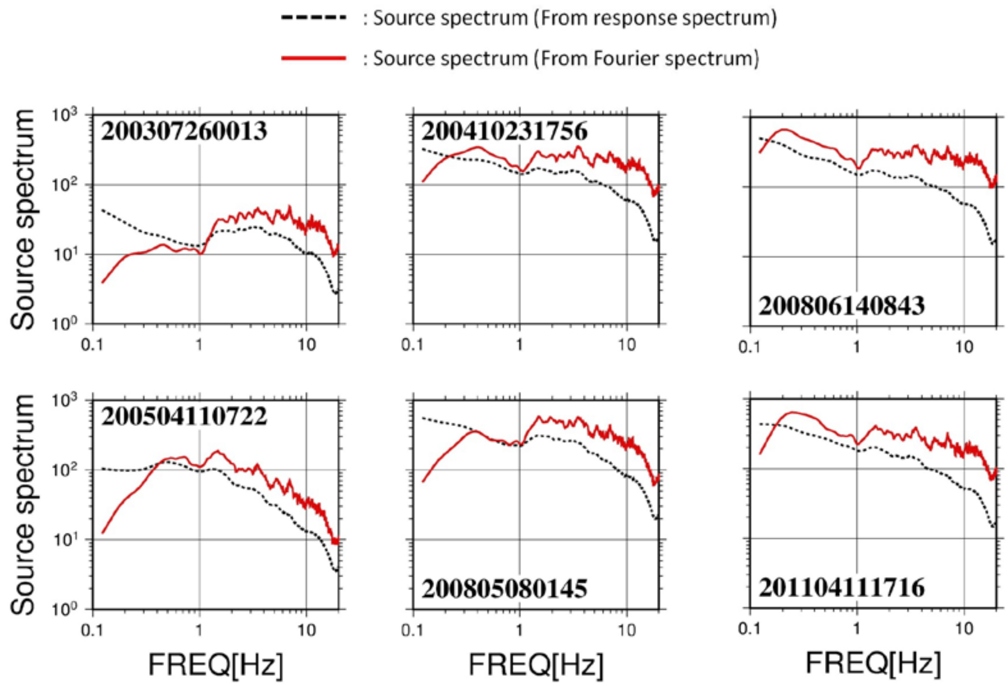

Figure 5 Comparison of source factors from FAS and RS (numbers are yyyymmddhhmm).

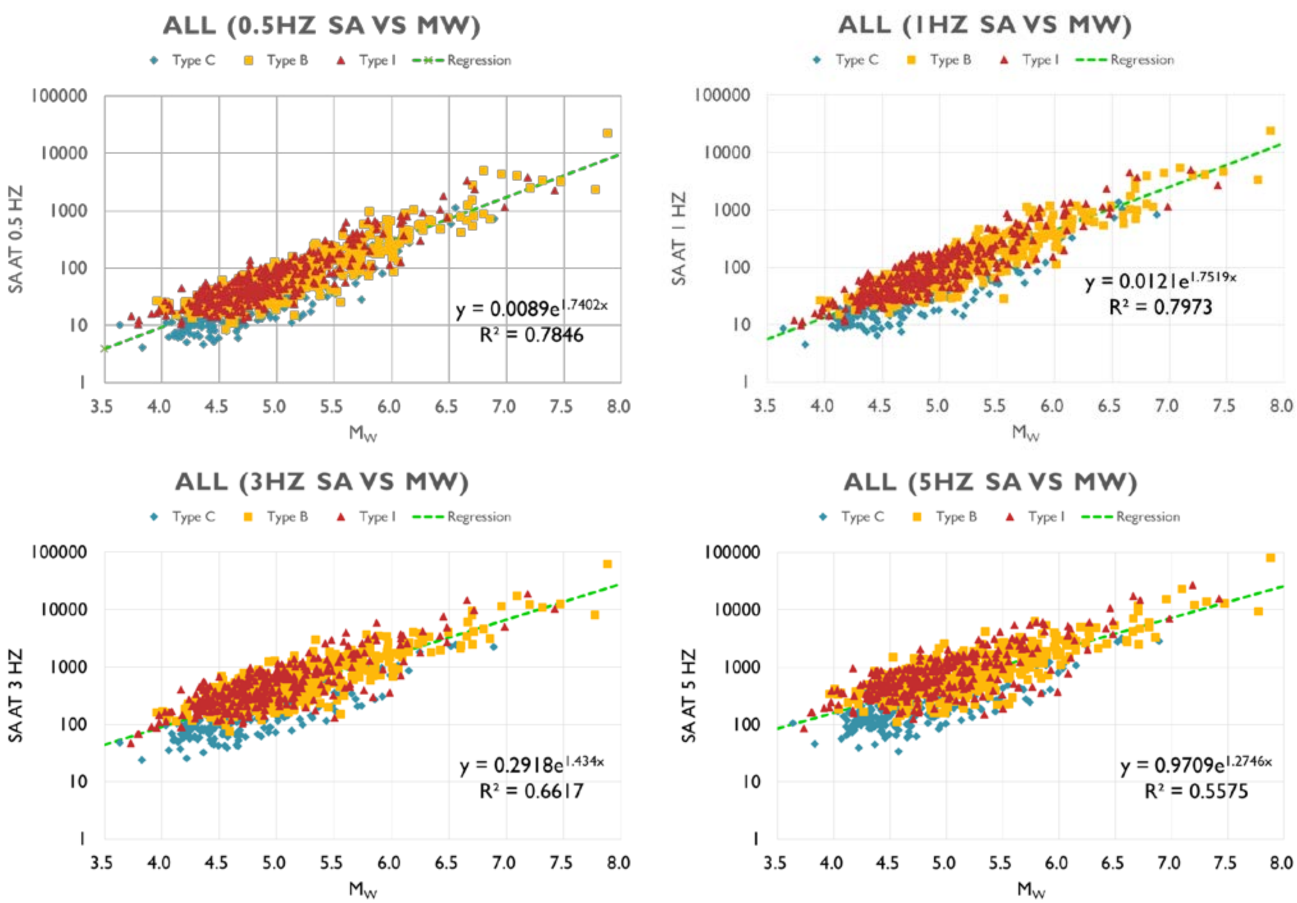

Figure 6 Linear regression coefficients and correlation coefficients of source terms for moment magnitude.

Our GMPE for RS is basically based on the generalized inversion and not based on the regression analysis as in ordinary GMPEs (e.g., NGA-West [6]). To translate separated source factors from RS into GMPE, we need to perform linear (or nonlinear) regression of the source term as a function of magnitude. To that end first we plot in Figure 6 source terms versus moment magnitudes for representative frequencies, namely, 0.5 Hz, 1 Hz, 3 Hz, and 5 Hz. The linearity is quite good so that we do not need to include any M-squared term. We also note that, even though we can get slightly higher correlation coefficients when we calculate a regression coefficient for each event type, correlations for all the events together are sufficiently high as shown in Figure 6.

To validate our linear regression coefficients we plot the linear term (aM_w) and constant (b) with respect to the oscillator frequency and compare them with those obtained by ordinary regression (Kanno et al., 2000 [9]) in Figure 7. The linear coefficients are quite similar to each other for wide frequency range and the constant coefficients are not so different except for very low frequency. Correlation coefficients R^2 are higher than 0.7 for frequency range from 0.3 Hz to 2 Hz. Such a high correlation is encouraging for GMPEs in general since M_w is a parameter to represent the lower-end characteristic of the source term.

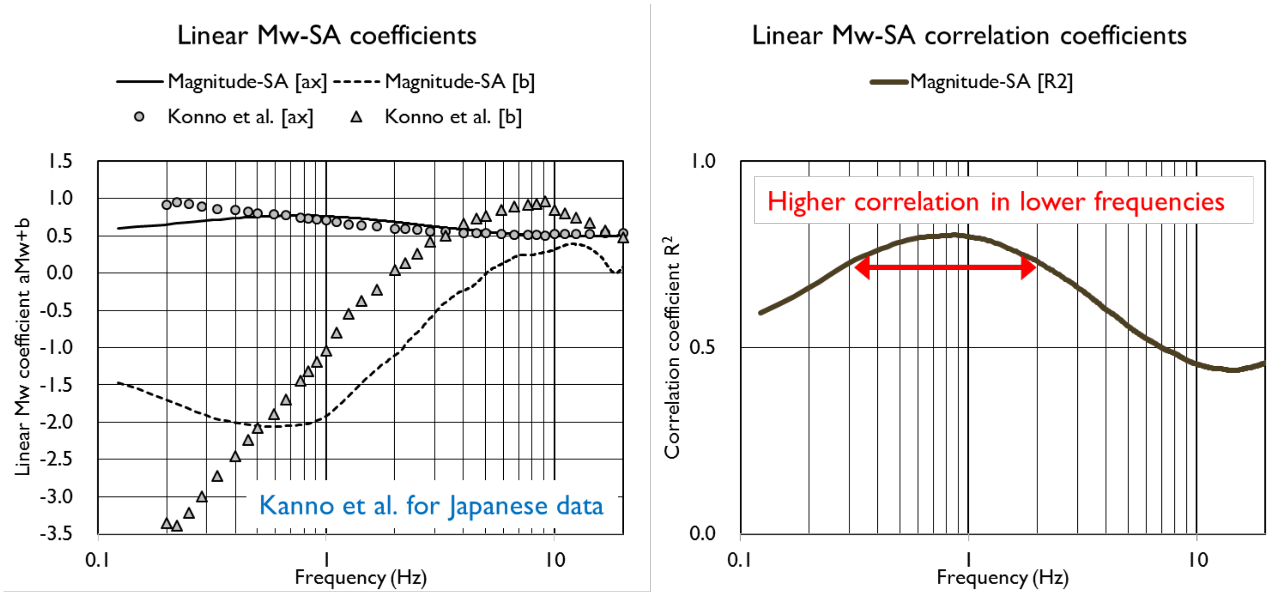

Figure 7 Magnitude coefficients (aM_w+b) and their correlation coefficients with respect to oscillator frequency

5. Residual reduction by stress drop correction

After linear correlation with respect to magnitude, we can obtain residuals from the average linear relationship for every events. Then we plot these residuals as a function of the estimated stress drop and obtain linear regression coefficient as shown in Figure 8 for representative frequencies. The residuals are quite well correlated with stress drops in a linear manner for a wide frequency range. The regression coefficients are quite high, especially for high frequency. This is quite natural since stress drops control high frequency power of the source spectra. Figure 9 summarize the coefficients of regression ($a\Delta\sigma$+b) for each frequency. Since the dependence on frequency is not so significant, we may use frequency-independent coefficients as shown in Figure 9 with gray lines.

In Figure 10 we plot standard deviations of residuals (variations) for each frequency with and without stress drop correction. We can see reduction of variation in RS prediction by more than 50% for a wide frequency range from 0.3 Hz to 20 Hz. If we use FAS and do the same analyses as we did for RS, the resultant reduction of residuals can be seen only in the frequency range higher than 0.5 Hz as shown in Figure 11, because the stress drop is the high frequency parameter that controls the high frequency level of the source factor.

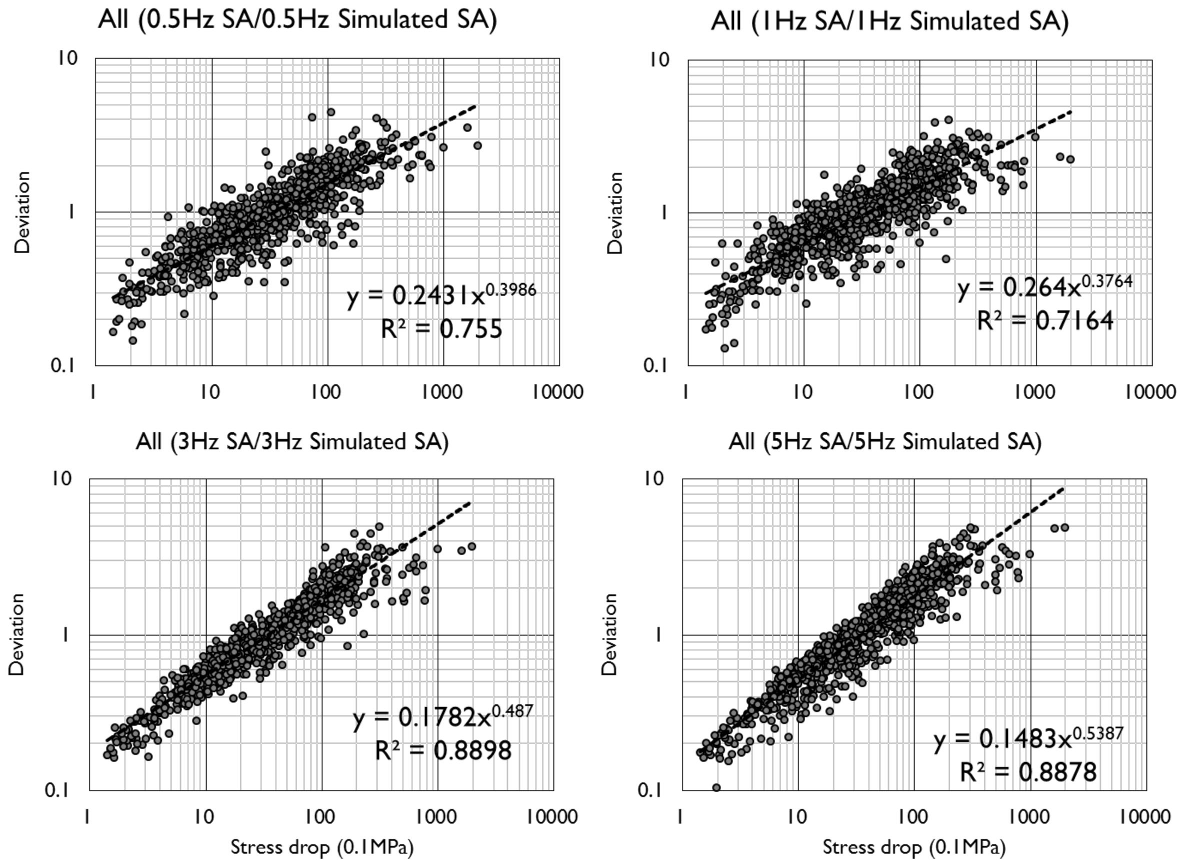

Figure 8 Linear relationship of residuals and estimated stress drops.

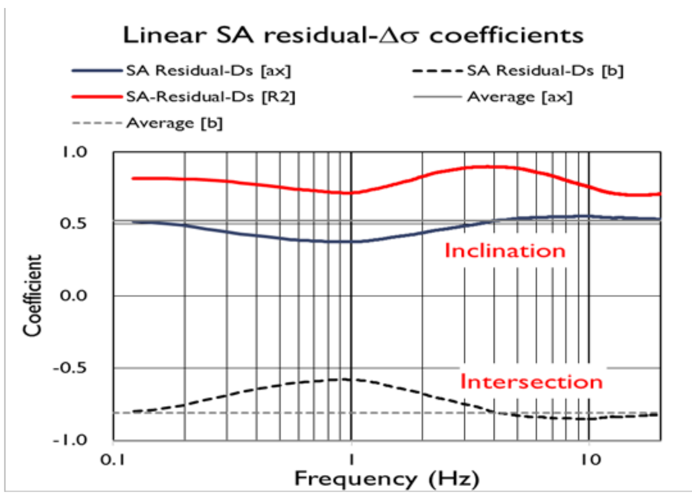

Figure 9 Summary of regression coefficients w.r.t. the stress drop Δσ and correlation coefficients R^2(red line).

6. Conclusions

In this paper first we separated the strong motion characteristics for Fourier spectra and 5% damping acceleration response spectra and obtained source terms of each event for both spectra. Then we estimated stress drops based on the source terms of Fourier spectra. Next we made linear regression analysis on the source terms

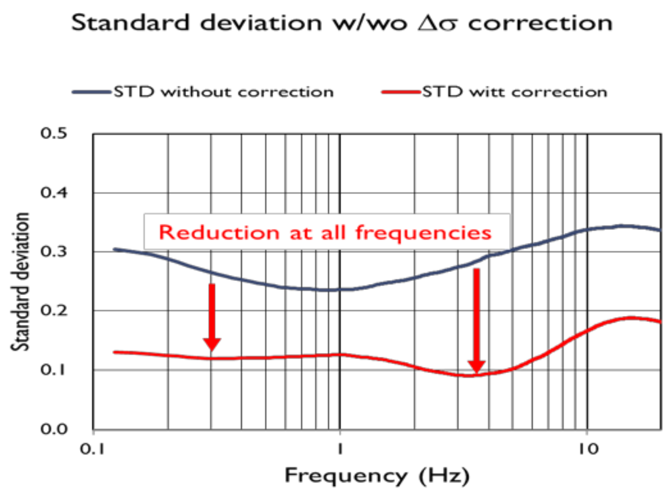

Figure 10 Standard deviation of source term residuals with and without stress drop correction for RS.

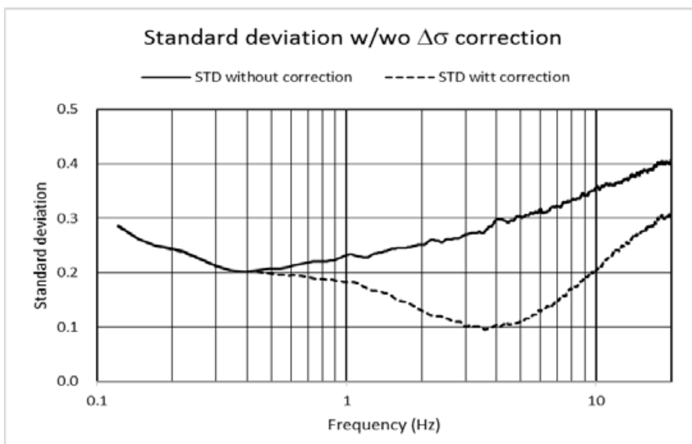

Figure 11 Standard deviation of source term residuals with and without stress drop correction for FAS.

of response spectra with respect to the moment magnitudes to get a new GMPE formula. Although stress drops for crustal earthquakes are 1/7 of the subduction-zone earthquakes, we can see linear regression works quite well for all the three types of events. After this linear regression we correlate residuals from this regression relationship as a function of the stress drop of the corresponding event estimated from Fourier spectra. We found quite a good linear relationship in a wide frequency range from 0.3 Hz to 20 Hz, which yields reduction of variability more than 50 % from the original one in terms of the standard deviation. When we applied the same kind of correction to the Fourier source terms we can see reduction in the high frequency range but cannot see any reduction in the frequency range below 1 Hz, as expected. The procedure here looks somewhat circular. However, if we treat the stress drop as a controlling parameter of GMPE, then our proposal just means to increase the numbers of parameters to better represent observed spectra.

In the practical application of the proposed stress drop correction on GMPEs for a future earthquake, we may use the average stress drop estimates for different types of event and different magnitude ranges as shown in Figure 3 together with their depth dependence as shown in Figure 4. We may see some regional variations for subduction zone earthquakes, which needs further scrutiny since numbers of events are still not sufficient to see spatial difference in a quantitative manner.

Acknowledgements

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