Implications of Mw 9.0 Tohoku-oki Japan earthquake for ground motion scaling with source, path, and site parameters

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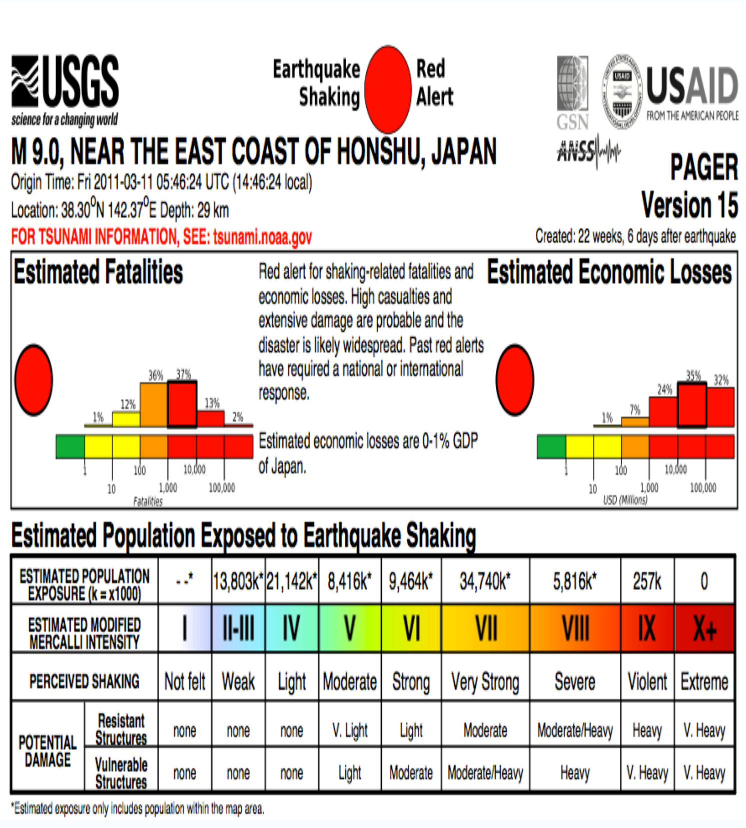
Motivation and Problem Statement:



The magnitude 9.0 Tohoku earthquake on March 11, 2011, which occurred near the northeast coast of Honshu, Japan, resulted from thrust faulting on or near the subduction zone plate boundary between the Pacific and North America plates. The March 11, 2011 earthquake was an infrequent catastrophe. It far surpassed other earthquakes in the southern Japan Trench of the 20th century, none of which attained M8. A predecessor may have occurred on July 13, 869, when the Sendai area was swept by a large tsunami that Japanese scientists have identified from written records and a sand sheet.

The M_w 9.0 Tohoku-oki Japan earthquake produced approximately 2000 ground motion recordings. We consider 1238 three-component accelerograms corrected with component-specific low-cut filters. The recordings have rupture distances between 44 and 1000 km, time-averaged shear wave velocities of V_{s30} = 90 to 1900 m/s, and usable response spectral periods of 0.01 to >10 sec. The data support the notion that the increase of ground motions with magnitude saturates at large magnitudes. High frequency ground motions demonstrate faster attenuation with distance in backarc than in forearc regions, which is only captured by one of the four considered ground motion prediction equations for subduction earthquakes. Recordings within 100 km of the fault are used to estimate event terms, which are generally positive (indicating model under-prediction) at short periods and zero or negative (over-prediction) at long periods. We find site amplification to scale minimally with V_{s30} at high frequencies, in contrast with other active tectonic regions, but to scale strongly with V_{s30} at low frequencies.

Ground Motion Networks and Data Processing:

In the present study, we utilized available data from the K-net and Kik-net arrays, PARI-net, and JMA-net. The available data were reviewed to identify through visual inspection recordings for which all three components demonstrated a clear onset of shaking, so as to exclude from the data set records that may have had a P-trigger. This process yielded 1238 triaxial accelerographs
Pacific Engineering and Analysis selected specific corner frequencies to optimize the usable frequency range and in total processed a total of 1238 three-component digital accelerograms. For Kik-net sites, only data from the ground surface stations are considered. The most important filter applied to the data is the low-cut filter, which removes low frequency noise effects. We take the minimum usable frequency as 1.25×fHP, where fHP is the high-pass (equivalent to low-cut) corner frequency used in the processing. Using the filtered records, we computed the intensity measures of peak acceleration (PGA), peak velocity (PGV), and pseudo acceleration response spectral accelerations at a range of periods between 0.01 and 10.0 sec.

Comparison to GMPEs:

We utilize ground motion prediction equations (GMPEs) for interface subduction zone earthquakes by Atkinson and Boore (2003, 2008), Zhao et al. (2006), and Abrahamson et al. (2012), which we refer to subsequently as AB 2003, ZEA 2006, and AEA 2012, respectively. The first two of these GMPEs were used to predict subduction zone ground motions in the USGS seismic hazard maps (Petersen et al. 2008). The AEA 2012 model has been identified for use in subsequent versions of the USGS maps. We also consider a Japan-specific model by Si and Midorikawa (2000) that utilizes Japanese data from crustal, inter-plate, and intra-plate events. That model, which applies to PGA and PGV only, was selected due to its widespread usage in Japan and is denoted SM 2000.

Magnitude scaling of spectral ordinates:

A key issue in ground motion prediction for interface subduction zone earthquakes is the functional form used for magnitude scaling. Many models produce essentially linear scaling of the logarithm of ground motion with magnitude (e.g., SM2000 model in Figure 7 and a linear form of ZEA2006 that is not used here), whereas others apply higher order terms that produce saturation of ground motion with increasing magnitude (e.g., AB2003 and AEA2012 models, as well as quadratic form of ZEA2006 model in Figure 1). In Figure 1 we plot ground motion intensity measures (IMs) at several spectral periods versus magnitude. The data plotted have rupture distances between 70 and 150 km and include all site conditions. The GMPE medians are for a distance of 100 km and an average site condition corresponding to Vs30=300 m/s. The data for the Maule and Tohoku events appears to support saturation of ground motions at large magnitudes for the IMs considered, especially for high frequency IMs.

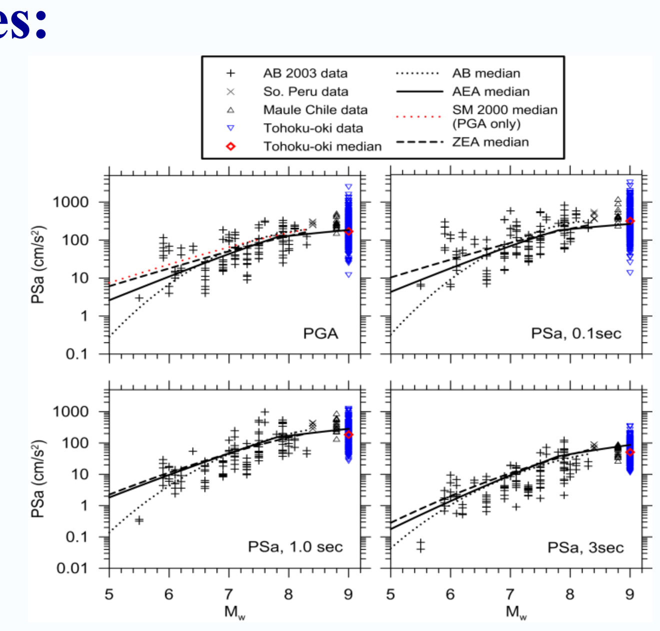


Fig 1. Scaling of spectral ordinates and PGA with magnitude from AB 2003 data set as well as Maule (Chile) and Tohoku-oki earthquake data for distances between 70 and 150 km. Median predictions from three GMPEs shown, which apply for reference soil conditions (approximate Vs30 = 300 m/s) and distance of 100 km.

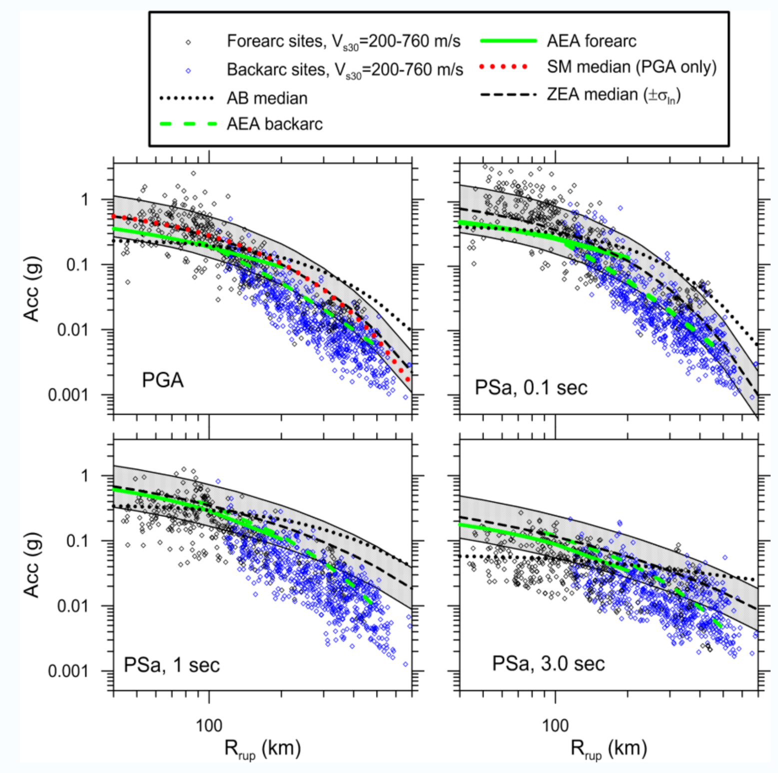


Figure 2. Same as Figure 3 except that data sorted into forearc and backarc sites and only data having V_{s30}=200 – 760 m/s are shown.

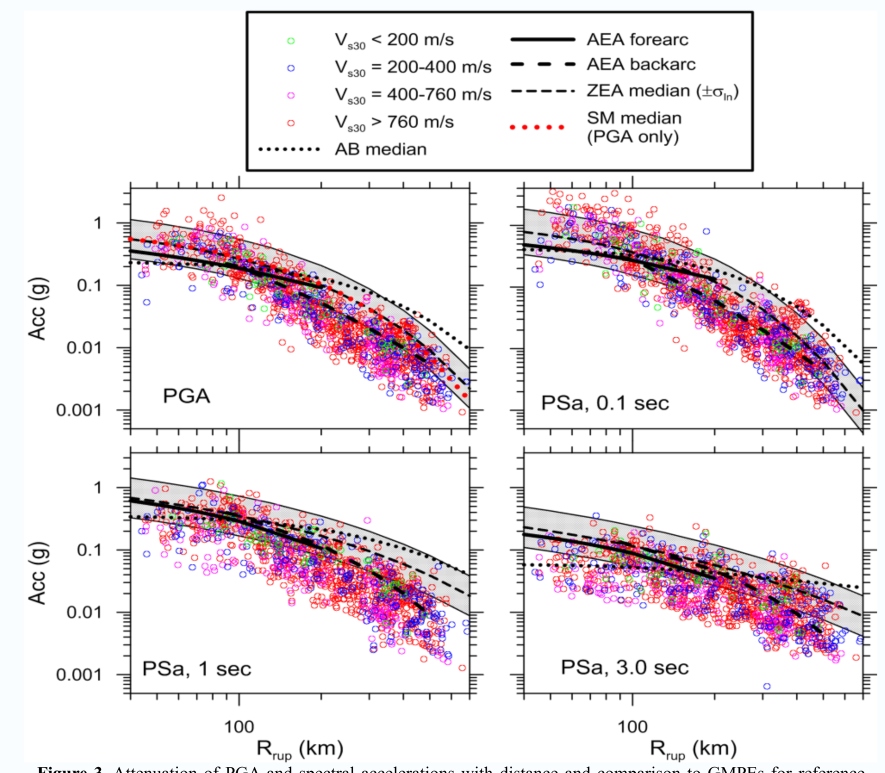


Figure 3. Attenuation of PGA and spectral accelerations with distance and comparison to GMPEs for reference condition equivalent to V_{s30}=300 m/s. For ZEA 2006 both the median (m) and median one standard deviation are shown, whereas for AB 2003, AEA 2012, and SM 2000 only medians are shown. The data are plotted as geometric means. ZEA 2006 applies to the geometric mean. AB 2003 applies to random component and no correction to the AB 2003 median has been applied. The SM 2000 median is divided by 1.1 to adjust from larger component to geometric mean per the recommendations of Beyer and Bommer (2006).

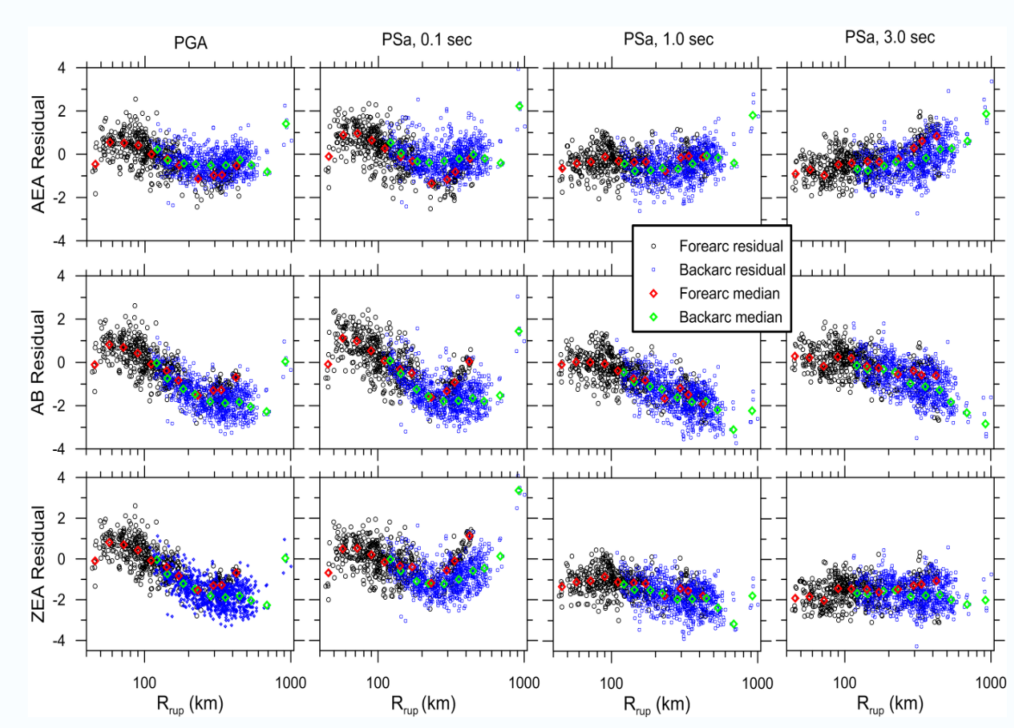


Figure 4. Total residuals of Tohoku-oki recordings within forearc and backarc regions relative to AB 2003, AEA 2012, and ZEA 2006 GMPEs along with mean residuals within distance bins

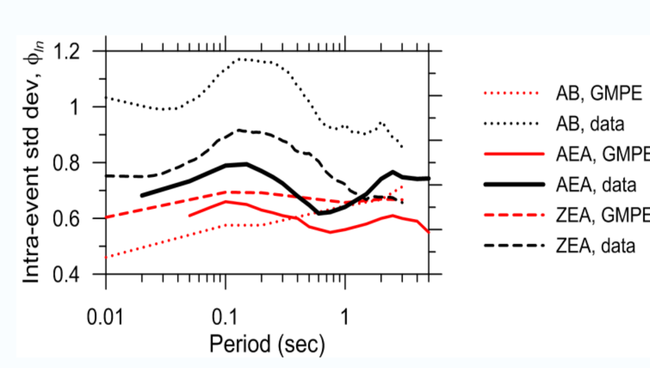


Figure 5. Intra-event standard deviation for Tohoku-oki earthquake data as compared to the AB 2003, AEA 2012, and ZEA 2006 intra-event standard deviations, f_{ln}. Dispersion computed using data over all distances.

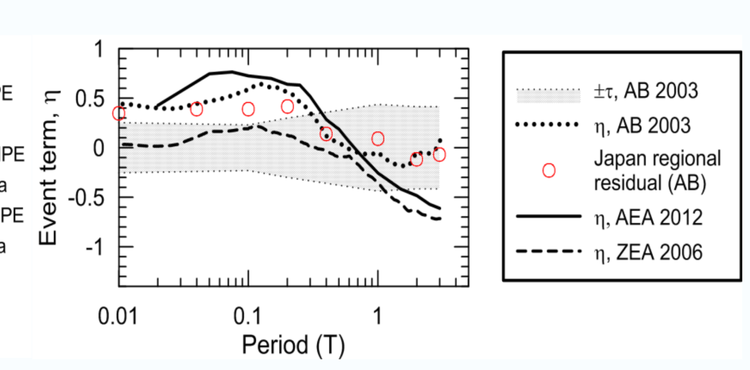


Figure 6. Estimated event terms of Tohoku-oki mainshock relative to the AB 2003, AEA 2012, and ZEA 2006 GMPEs. Also shown is the AB inter-event standard deviation (t) and the AB regional model bias for Japan (red circles). Estimated event terms were computed using data with R_{rup} < 100 km.

Site Effects:

Evaluation of site amplification, specifically in reference to the scaling of ground motions with V_{s30} is significantly important.

$$R_i^r = \ln(IM_i)_{rec} - \left(\ln(\mu_i^r)_{GMPE} + \eta\right)$$

where indicates the residual of recording i from a rock GMPE, is a rock GMPE median for the magnitude and distance corresponding to recording i, and η is the event term appropriate for the earthquake event and IM. The reference site condition is taken as reference rock for AB2003 (their site parameters S_C, S_D, and S_E are set to zero), V_{s30} = 1100 m/s for AEA2012, and hard rock for ZEA2006 (equivalent to NEHRP site category A).

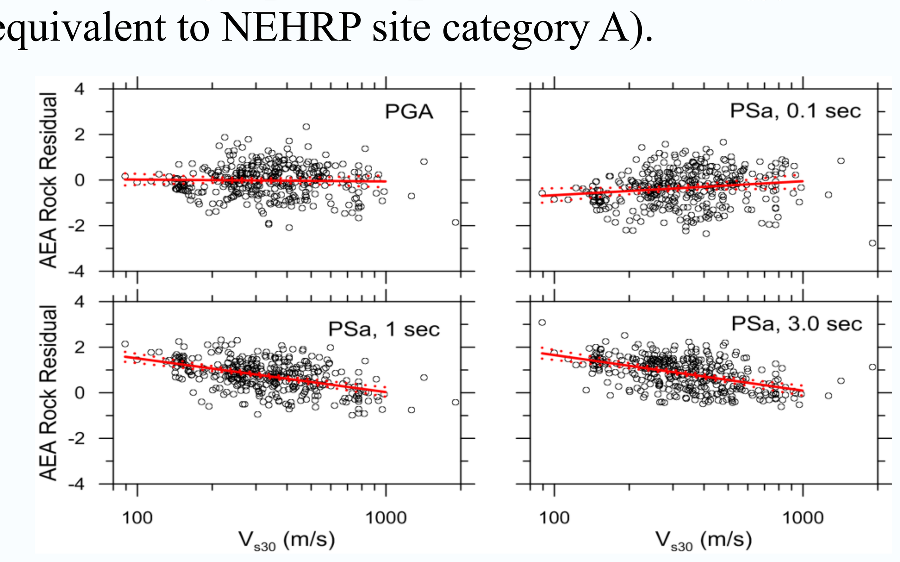


Figure 7. Reference rock residuals of Tohoku-oki recordings using AEA 2012 GMPE for rock site conditions. Residuals shown for forearc data with R_{rup} < 200 km along with linear regression fit and confidence intervals.

Slope parameter c	PGA	PSa, 0.1 sec	PSa, 1.0 sec	PSa, 3.0 sec
AB	-0.053	0.273	-0.770	-0.732
AEA	-0.035	0.266	-0.642	-0.678
ZEA	-0.045	0.282	-0.767	-0.724

Table 1. Values of slope parameter c from analysis of reference rock residuals for forearcc sites with R_{rup} < 200 km

The most important observation from the data trends in Figure 7 is the trend (or lack thereof) of reference site residuals with increasing V_{s30}. Low frequency ground motions show a statistically significant trend as indicated by the negative slope of the fit line (c < 0), whereas high frequency ground motions have a relatively weak, or even positive, trend. These trends are different from those observed in most previous research, based largely on data from California (e.g., Borcherdt, 1994; Choi and Stewart, 2005), which show significant trends with V_{s30} at low and high frequencies. This is a finding of considerable practical importance, as it suggests that the scaling of ground motions with V_{s30} is region-dependent.

Refrence: Jonathan P. Stewart, M.EERI, Saburoh Midorikawa, M.EERI, Robert W. Graves, M.EERI, Khatareh Khodaverdi,S.M.EERI, Tadahiro Kishida, M.EERI,Hiroyuki Miura,M.EERI, Yousef Bozorgnia, M.EERI, and Kenneth W. Campbell M.EERI, "Implications of Mw 9.0 Tohoku-oki Japan earthquake for ground motion scaling with source, path, and site parameters

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