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Nonlinear site response from the 2003 and 2005 Miyagi-Oki earthquakes

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We estimate nonlinear site response by comparing site response estimates from the 16 August 2005 Mj=7.2 and 26 May 2003 Mj=7.0 Miyagi-Oki earthquakes with site response estimates from aftershocks of the 2003 event. Site response is solved by a spectral inversion technique to separate source, path, and site components. The constraint motion in the inversion is a regional attenuation model derived from fitting the spectra of data recorded at borehole KiK-net stations in the region and a theoretical source spectrum for each event determined using the same borehole stations. Site response is calculated at the surface of the KiK-net and K-NET stations. In general, the average aftershock site response is larger than for the two mainshocks, especially at a higher frequency. When comparing site response with input ground motion level, the predominant frequency and the site response values tend to decrease as the level of input ground motion increases.

Key words: Nonlinear site response, ground motion level, PGA, 2003 and 2005 Miyagi-Oki earthquakes.

1. Introduction

While nonlinear soil behavior during strong ground shaking and nonlinear site response have been discussed in the literature for quite some time, it is only in the last decade that we have recorded large enough data sets from significant earthquakes for the quantitative analysis of nonlinear effects. Near-source recordings from recent large earthquakes have shown that nonlinear site response can have a major influence on the observed ground shaking (e.g., Idriss, 1991; Field *et al.*, 1997, 1998; Bonilla *et al.*, 2005). Several studies have estimated at what level of shaking one should expect a noticeable nonlinear site response. For example, Idriss (1991) indicates that if PGA is more than 0.4 g at soft soil sites, the effect will be noticeable. Midorikawa (1993) and Beresnev (2002) also estimate nonlinear site response if peak ground acceleration (PGA) exceeds 0.2 g or peak ground velocity (PGV) exceeds 15 cm/s.

The 16 August 2005 MW=7.2 and the 26 May 2003 MW=7.0 Miyagi-Oki earthquakes (Satoh, 2004a, b) both generated large PGA at many K-NET and KiK-net stations in Japan. The 2003 event had many stations with PGA greater than 1.0 g. The 2005 earthquake did not produce PGA values above 1.0 g, although some stations still recorded PGA larger than 0.3 g. As mentioned by Midorikawa (1993) and Beresnev (2002), many of the observed PGA levels from these two earthquakes are large enough that we might expect to see nonlinear behavior.

In this study, we estimated site response at K-NET and KiK-net sites using the observed strong motion records of the 2003 event, the observed strong motion records of the 2005 event, and the observed weak motion aftershock events following the 2003 mainshock. Site response is solved by the spectral inversion technique to separate source, path, and site components, based on the method developed by Tsuda *et al.* (2006a). We then calculated the ratio of site response between each of the strong motion events and the average weak-motion site response to look for evidence of nonlinear behavior. The average strong motion site response in different frequency bands is examined with respect to the level of ground shaking at each site as well as the effect of input motion on the shift in predominant frequency.

2. Data

In the Iwate and Miyagi prefectures (close proximity to the large events) there is a total of 42 K-NET and 39 KiK-net stations. To examine the strong-motion site response we selected data from stations with a PGA larger than 100 cm/s^2 for the 2003 and 2005 events. To examine the weak-motion site response we used 14 aftershocks of the 2003 event with $M_W>4.0$, each with a focal depth between 60 and 75 km. The distribution of stations used in this study as well as the epicenters of the large events are shown in Fig. 1. We use S-wave time windows of 20 s for the 2003 event and 30 s for the 2005 event; each window starts approximately 1 s before the first S-wave arrival. A 10-s window is used for the aftershock data.

3. Site Response Estimation Including Two Large Events

Site response is usually estimated relative to a reference station that is assumed to have a response close to unity for the frequency band of interest. However, if the reference station itself has its own site response that is significantly different from unity, we then have less confidence in the site response estimate at other stations. Thus, we applied a method to estimate site response independent of the reference station (Tsuda *et al.*, 2006a). Tsuda *et al.* (2006b) de-

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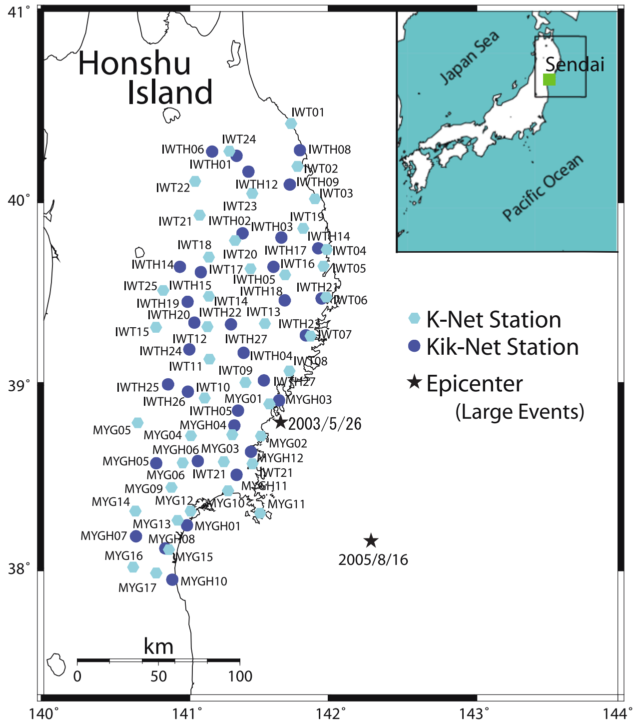


Fig. 1. Station distribution of K-net (light-blue hexagon) and Kik-net (dark-blue circle) stations used in this study. The epicenter of two mainshocks (star) is also shown.

rived site response based on weak motion data for K-NET and KiK-net stations located in the Iwate and Miyagi prefecture. These site response estimates compared well with a previous study based on conventional, reference-dependent methods (Satoh, 2005) in the frequency range where the reference site response was considered to be close to unity. The non-reference site technique is based on a spectral inversion where the constraint motion in the inversion is a regional attenuation model derived from fitting the spectra of data recorded at borehole KiK-net stations in the region and a theoretical source spectrum for each event determined using the same borehole stations. The method for solving the source parameters is described in detail in Tsuda *et al.* (2006a). We considered the points with maximum slip determined by Yamanaka and Kikuchi (2003) and Yamanaka (2005) as the hypocenter for each event. We also accounted for the effect of a frequency-dependent radiation pattern (Kamae *et al.*, 1991), assuming that the theoretical radiation of seismic waves occurs in the low frequency range and isotropic radiation occurs in high frequency range when estimating the source parameters for the two large events. This is deemed necessary to account for the finite fault radiation effects of these larger earthquakes. Finite fault radiation effects are not considered for the weak motion aftershocks. Table 1 shows the results of the estimation of the source parameters. While our estimation of the source spectrum assumes a point source, a comparison with the moment estimated from finite fault studies of the source (Table 1) indicates that we are estimating the source spectrum correctly (note that the teleseismic estimate of Moment for the 2005 event from other agencies ranges from 4.7 to 8.2e+19 Nm). Using the path attenuation effects from Tsuda *et al.* (2006b) for the 2003 event and those of Satoh and Tastumi (2002) for the 2005 event, and the source spectrum derived from the parameters shown in Table 1, the mainshock site response is then determined for the two large events as the ratio of the observed ground acceleration spectrum to the theoretical acceleration spectrum (using Boatwright (1978) source spectral formulation and the attenuation, source parameters, and radiation effects mentioned above).

Table 1. Focal parameters used to determine moment and corner frequency for the two large events. The location of the hypocenter and Mo (finite fault) have been determined by Yamanaka and Kikuchi (2003) and Yamanaka (2005) for the 2003 and 2005 events, respectively. The Mo (point source) and corner frequency estimates are those determined in this study.

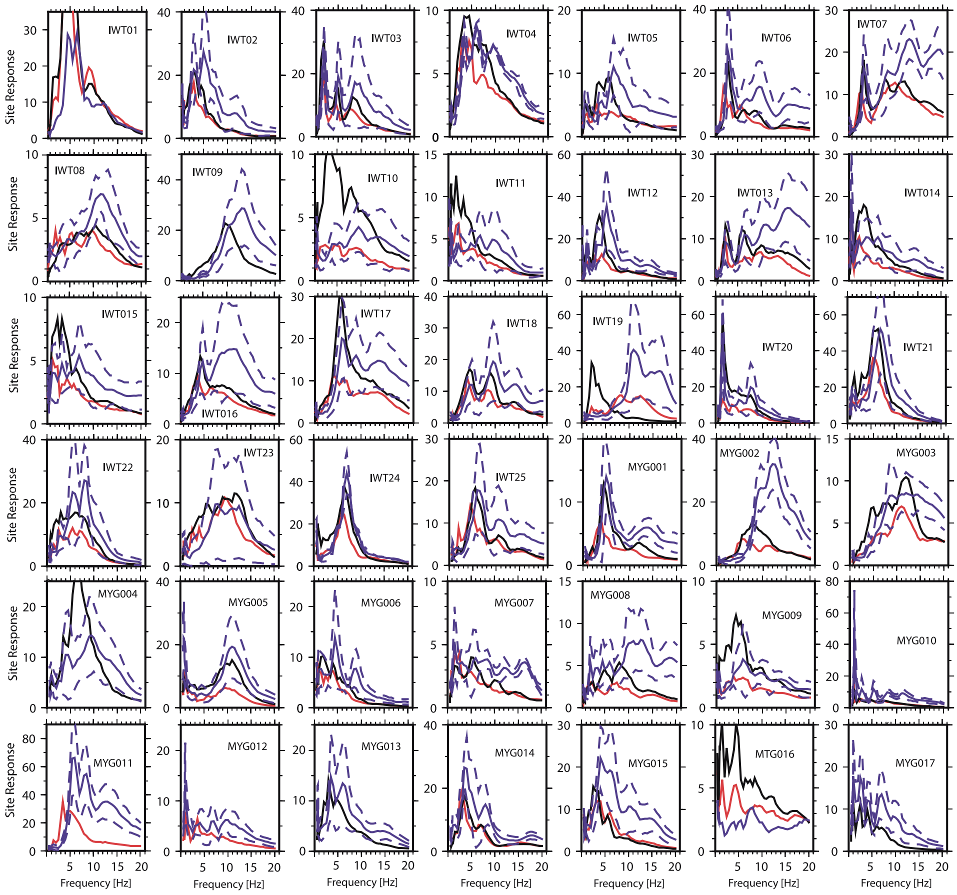
	2003/5/26	2005/8/16
Hypocenter	(142.07E, 38.16N)	(141.66E, 38.85N)
Focal depth (km)	54.0	76.0
Mo (finite fault) (Nm)	3.8E+19	4.1E+19
Mo (point source) (Nm)	4.2E+19	8.9E+19
fc (Hz)	0.27	0.13

4. Comparison of Site Response

In Fig. 2 we plot the site responses from the two large earthquakes as well as the site response based on the 2003 aftershock data (Tsuda *et al.*, 2006b) for the K-NET and KiK-net stations with a PGA$\geq$100 gal for either large event. As discussed in Satoh (2004b), many K-net and KiK-net stations have large site response values, a result also supported by the analysis in this study. The site response from the two large earthquakes is smaller than the average weak motion aftershock response at many of the sites, especially as frequency increases. In addition, many sites also show a shift to a lower frequency for the predominant site resonance. These two observations are consistent with typical nonlinear site response effects (Bonilla *et al.*, 2005; Field *et al.*, 1997, 1998). A more detailed analysis using the exact site characterization of each site and the input ground motion incident to the site is needed to explain why some sites show these effects and others do not.

We next calculate the ratio of the mainshock site response to the average aftershock site response. This ratio is usually below unity when nonlinear effects exist (smaller site response values). However, this ratio can also be greater than unity even when nonlinear effects do exist because of the shift to a lower frequency for the predominant site resonance. A clear example of this effect is shown in Fig. 3(a, b) where both the shift in frequency and decrease in amplitude are clear. The average ratio of all stations for the 2003 and 2005 events are shown in Fig. 3(c) and (d), respectively. The average site response ratio from the 2003 event (which had larger PGAs) shows an overprediction by the weak motion site response (ratio$<$1) for frequencies above 5 Hz. The average site response ratio from the 2005 event shows an overprediction by the weak motion site response above 8 Hz. The ratio for both these events is greater than unity in the low frequency range, which is consistent with a shift of energy to a lower frequency. In addition, the low frequency ratio for the 2005 event is larger than for that for the 2003 event. This can be interpreted as a smaller degree

(a) K-NET



(b) KiK-net

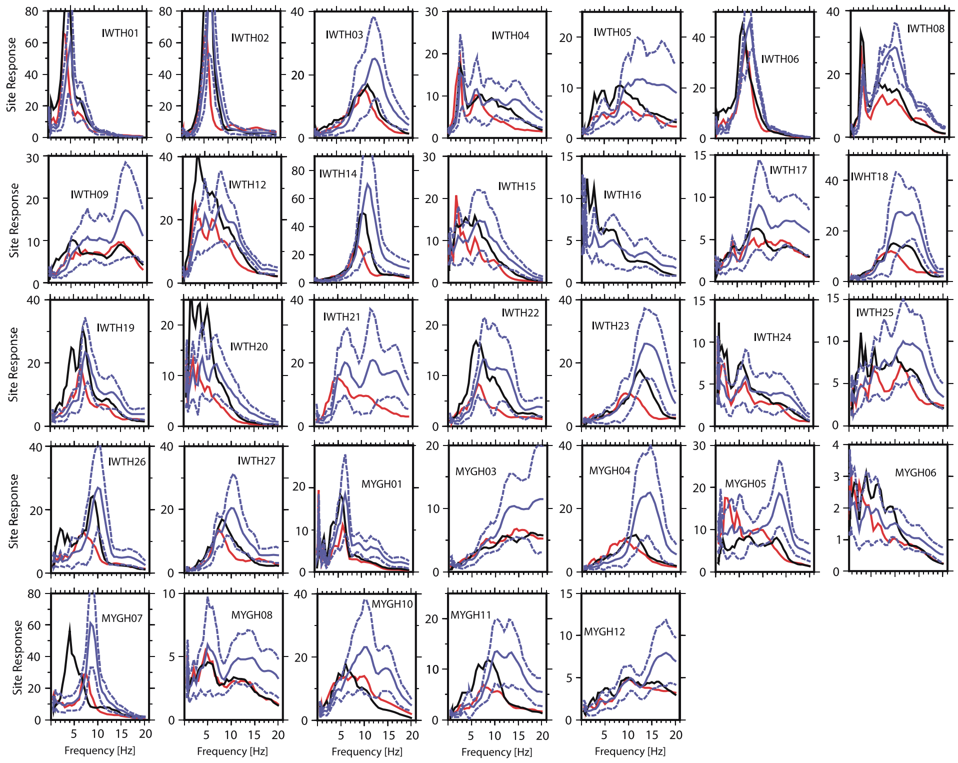


Fig. 2. Site response derived from data for K-NET and KiK-net (surface) stations. The blue lines correspond to the site response from Tsuda *et al.* (2006b) (average $\pm 1\sigma$; the red line corresponds to the site response from the 2003 event; the black line corresponds to the site response from the 2005 event.

Table 2. Average predominant frequency ratio for the two large events based on PGA values.

	2003 Event			2005 Event		
PGA (g)	Number of stations	Averaged ratio	1σ	Number of stations	Averaged ratio	1σ
0.1–0.2	17	0.932	0.095	26	0.9140	0.1034
0.2–0.3	15	0.882	0.115	15	0.8112	0.1020
0.3–0.4	16	0.825	0.085	7 ($\geq$0.3 g)	0.7325	0.1875
0.4–	20	0.770	0.133			

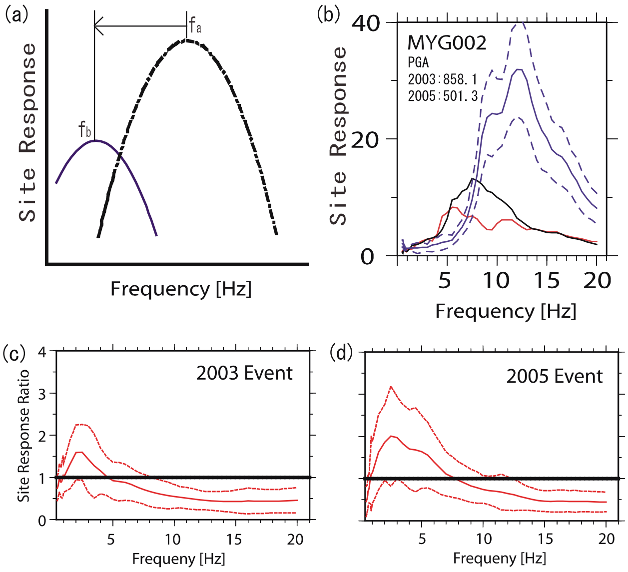


Fig. 3. (a) Schematic diagram of the shift of predominant frequencies. (The predominant frequency from weak motion (fa) changes to the predominant frequency from strong motion (fb)). (b) Example of a shift of predominant frequencies dependent on the PGA values (cm/s^2). Site response ratio for the 2003 event (c) and the 2005 event (d) averaged for the K-NET and KiK-net stations with PGA$\geq$100 (cm/s^2). The black dotted line corresponds to the case when the site responses from weak motion and from strong motion are equal.

of nonlinearity in the 2005 event due to the smaller input ground motion levels, which leads to less of a decrease in the site response estimate due to nonlinearity.

In order to more quantitatively examine the site response from each of these events, we examine the individual site response ratios at each site by averaging them into frequency bands to look for a general frequency dependence of the site response and potential correlation with observed PGA. In Fig. 4 the blue and red circles correspond to the frequency averaged site response ratio at each site from the 2005 event and the 2003 event, respectively. As we move from the lower to higher frequency bands, the site response ratio decreases, as expected, based on the same reasoning used in the interpretation of Fig. 3. There is a great deal of scatter when the site response ratio is correlated into the lower frequency ranges with input PGA. In the lowest range (0.5–1.0 Hz), we expect things to be on average close to unity without much scatter as at these wavelengths the material should behave in a linear fashion (Fig. 4(a)). In the ranges from 1 to 5 Hz and from 5 to 10 Hz, more scatter is expected as each site has a unique soil profile (some very thin soft layers, some thicker); in addition, given that we would expect energy to be transferred to a lower frequency

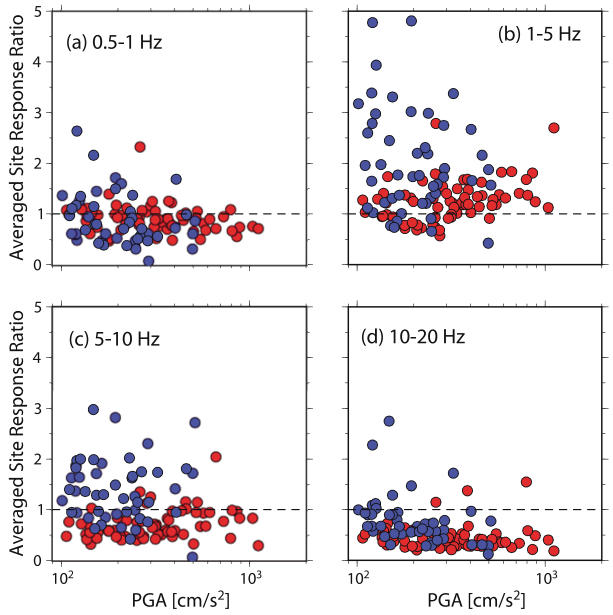


Fig. 4. Site response ratio averaged in four frequency bands: (a) 0.5–1.0 Hz, (b) 1–5 Hz, (c) 5–10 Hz, and (d) 10–20 Hz as a function of PGA (maximum value for either horizontal component). Red corresponds to stations from the 2003 event and blue corresponds to stations from the 2005 event.

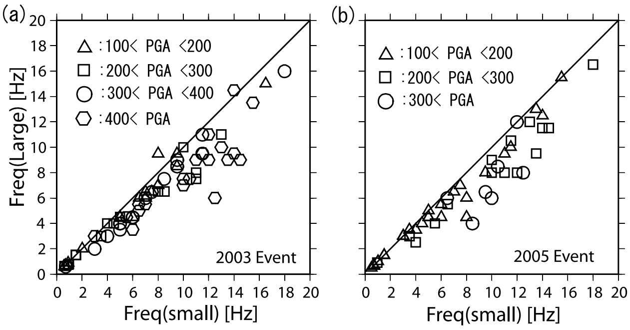


Fig. 5. The comparison of predominant frequencies between weak motion case and strong motion case: (a) 2003 event, (b) 2005 event.

when the soil behaves in a nonlinear fashion, these ratios could be either greater or less than unity depending on the predominant site response mode. The difference between the 2005 and 2003 results (blue and red, respectively) does make sense in that the 2003 event, with larger input motions and consequently more expected nonlinearity, has its points predominantly below unity in the 5- to 10-Hz range (Fig. 4(c)). The 2005 event, with smaller input PGA and hence a smaller degree of nonlinearity, still has significant scatter in the 5- to 10-Hz range. In the highest range from

10–20 Hz (Fig. 4(d)), both events exhibit significant nonlinearity, especially as you move to larger input PGA.

We then examine the shift of predominant frequencies of the site response in Fig. 5. First, we picked the predominant frequencies with peak site response values from the weak motion data. Then, we checked how those frequencies changed in the two strong motion data. We compared the ratio between the strong motion frequency and weak motion frequency, averaged over stations in similar ranges of input PGA. The results, shown in Table 2, indicate that the ratio is clearly decreasing with increasing PGA, which confirms that the predominant frequency of strong motion site response is decreasing. These results clearly demonstrate that nonlinear behavior begins at 0.2 g or perhaps less, becoming more significant as you move from 0.3 to 0.4 g.

5. Discussion and Conclusion

While it may not be easy to understand the details of nonlinear effects in such a general way by grouping many stations together as well as multiple events, we do need to understand these effects on average if there is any hope of including nonlinear effects in hazard mapping as we move to larger input motions. The next logical step in this study will be to start to separate the stations based on site classification as well as by input motion level and to look for trends within each site class. As many of these sites have very shallow soft layers, a classification such as Vs30 will probably not work very well. In the future we plan to examine these data using a Vs10 classification to look for correlations.

In conclusion, the ratio of these responses and the shifts of predominant frequencies of site response to the lower frequency are consistent with a nonlinear site response when the PGA is larger than 0.2 g. This effect becomes larger as input motion increases. The seismicity rate in the Miyagi-Oki region is very high, and this region can be expected to have another large earthquake in the near future. Thus, incorporating the nonlinear soil behavior in ground motion predictions should be an important component of any future earthquake scenario for this region.

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