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Confirmation of Nonlinear Site Response: Case Study from 2003 and 2005 Miyagi-Oki Earthquakes

Kenichi Tsuda, Ralph J. Archuleta and Jamison Steidl

Department of Earth Science and Institute for Crustal Studies, University of California Santa Barbara, Santa Barbara, CA, 93106, USA

Abstract

We have confirmed the nonlinear site response from observed data of the 2003 (Mw 7.0) and 2005 (Mw 7.2) Miyagi-Oki earthquakes. Both events produced large peak ground accelerations (PGA), suggesting that a nonlinear site response could exist. We calculated the surface site responses for K-NET and KiK-net stations using weak motion data with source and path parameters determined by a spectral inversion of KiK-net borehole records. We compared these site responses to those derived from strong motion data. This comparison suggests that nonlinear site response occurred at many stations. We also did 1D simulations of wave propagation that incorporated soil nonlinearity. The results of the nonlinear simulation agreed better with the observed data at surface than the results of the linear elastic case.

Key words: (Linear and Nonlinear) Site Response, 2003 and 2005 Miyagi-Oki Earthquakes, Strong Shaking

1. Introduction

Nonlinear site response has been discussed in the seismological society since the seminal paper of Seed and Idriss (1970). However, linear theory has generally been used to estimate site response (e.g., Borcherdt, 1970; Aguirre *et al.*, 1994). With more data being recorded in the near source areas of recent large earthquakes it has become clear that nonlinear site response can have a major effect (e.g., Idriss, 1991; Aki, 1993; Iwasaki and Tai, 1996; 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 PGA exceeds 200 gal, or peak ground velocity (PGV) exceeds 15 cm/s.

The 16 August, 2005 M_W 7.2 Miyagi-Oki and the 26 May, 2003 M_W 7.0 Miyagi-Oki earthquakes (Satoh, 2004a, b) both generated large PGA at many K-net and Kik-net stations. The 2003 event had many stations with PGA greater than 1.0 g. While the 2005 inter-slab earthquake did not produce PGA values above 1.0 g that had been recorded from the 2003 intra-slab earthquake, some stations still recorded PGA larger than 0.3 g. In Figure 1, we plot data for both earthquakes and the empirical attenuation relationship of Shi and Midorikawa (1999). Many of the PGA from these earthquakes exceed the empirical curve, especially for smaller distances. Because this area could have another large earthquake in the near future, the data from these two earthquakes provide a good opportunity to examine site responses for the range of large accelerations that may be produced by future earthquakes.

In this study, we derive site response from observed data over a broad range of events. To understand the nonlinear site response in more detail we compute the full nonlinear 1D wave propagation.

2. Data

Among the many K-net and Kik-net stations, we selected 16 K-net and 19 Kik-net stations located in Iwate and Miyagi prefectures close to the epicenter of the events. These stations produced large PGA (=

* e-mail: kenichi@crustal.ucsb.edu

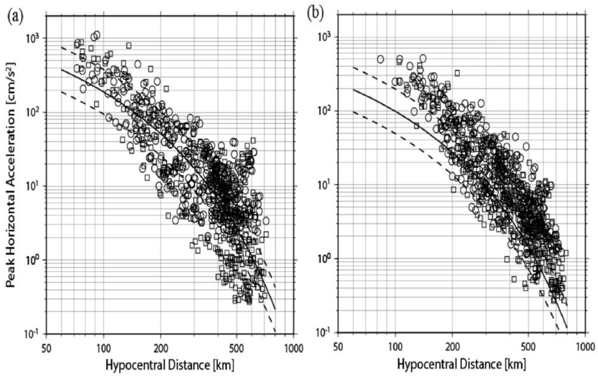

Fig. 1. The relationship of recorded peak horizontal accelerations as a function of hypocentral distance from 2003 (a) and 2005 (b) Miyagi-Oki main shocks. The circles and open squares correspond to the peak horizontal acceleration at K-net and Kik-net stations, respectively. A solid curve shows the empirical attenuation relationship for the mean peak horizontal acceleration (Shi and Midorikawa, 1999). The dashed lines correspond to the empirical relation±factor of two.

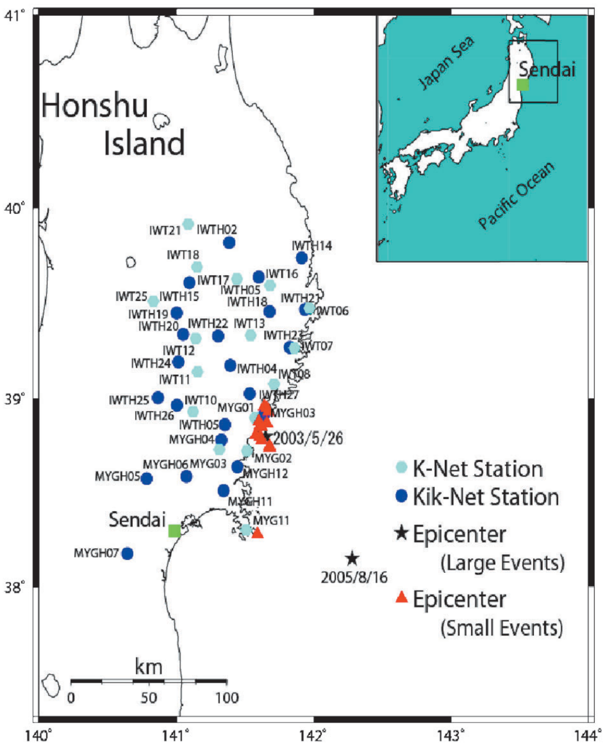

Fig. 2. Station distribution of K-net (light-blue hexagon) and Kik-net (dark-blue circle) stations used in this study. The epicenters of main shock (star) and 14 aftershocks (triangles) are also shown.

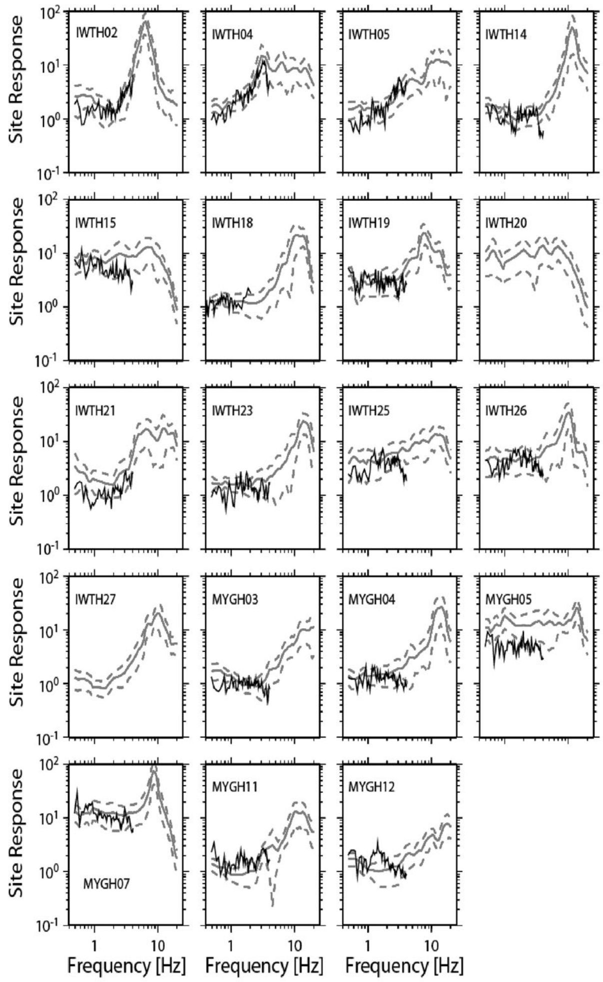

Fig. 3. Surface site response derived from observed data for Kik-net 19 stations in blue lines (average±1σ). Black lines correspond to the site response results from the conventional inversion analysis by Satoh (2005).

300 gal) for the 2003 event. Because we did not have many records from the aftershocks of the 2005 event, we selected 14 aftershocks of the 2003 event with M_W larger than 4.0, and each with a focal depth between 60 and 75 km. We show the distribution of stations used in this study as well as the epicenter of main-shock and aftershocks (Figure 2). We use S-wave time windows of 10s for aftershocks, 20s for the 2003 event, and 30 s for the 2005 event; each window starts approximately 1 sec before the first S-wave arrival.

3. Method

We used the spectral inversion method (Tsuda *et al.*, 2006a, b). Because this method is independent of the reference site, it is possible to determine the absolute site response from the seismological basement to the surface. For path attenuation, we used the model determined by Tsuda *et al.* (2006b). This

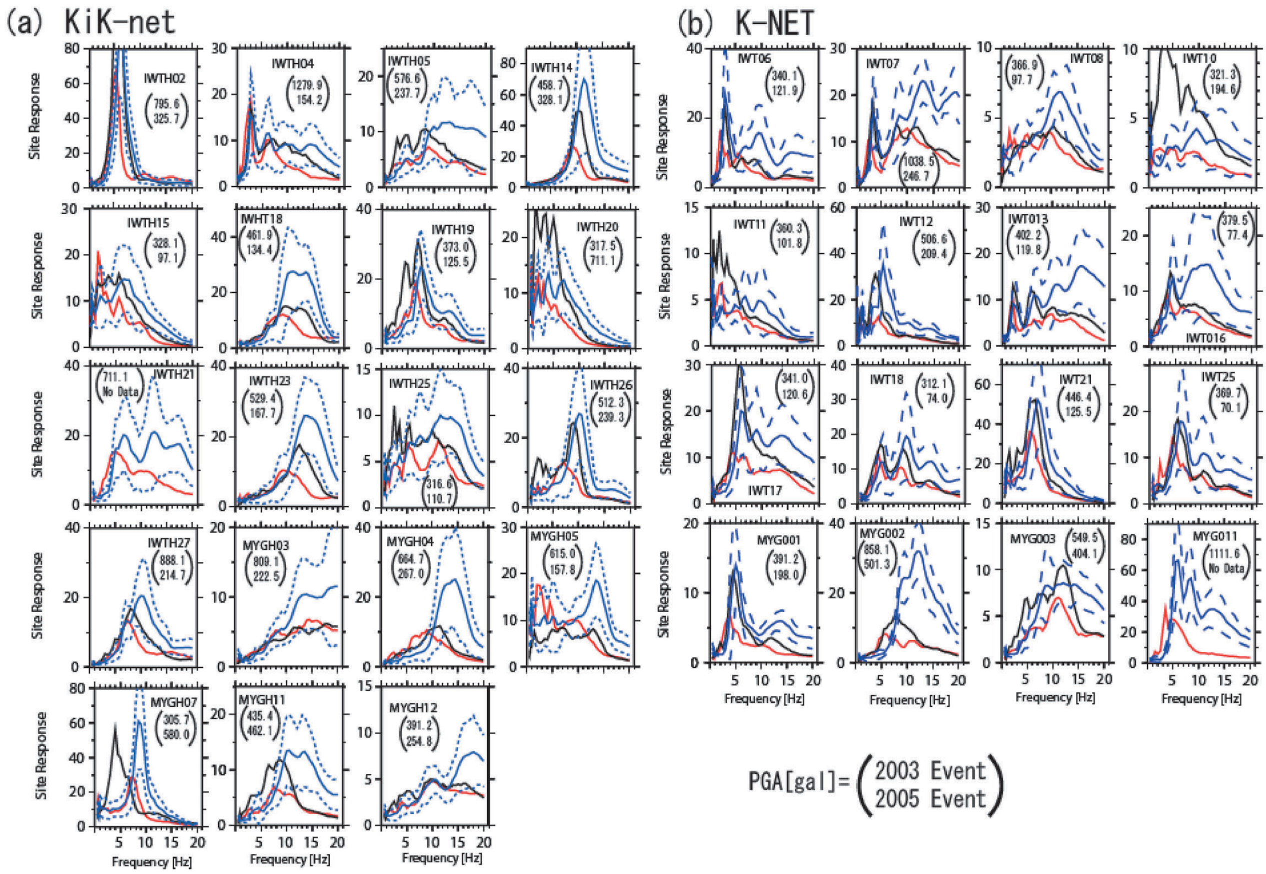

Fig. 4. Surface site response derived from data for (a) KiK-net and (b) K-NET stations. The blue lines correspond to the site response from aftershocks (average$\pm 1\sigma$); the red line corresponds to the site response from the 2003 event; the black line corresponds to the site response from the 2005 event. The two PGA (gal) listed for each station is the maximum value from the 2003 and 2005 events, respectively.

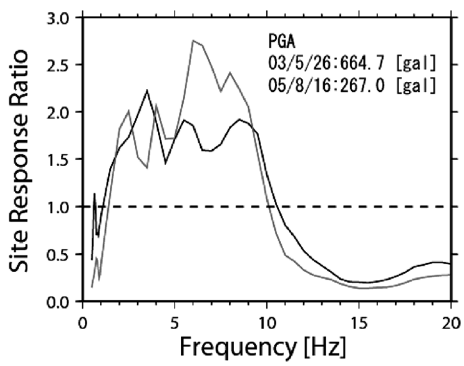

Fig. 5. Site response ratio (weak motion case/strong motion case) of Kik-net MYGH04 station for 2003 event (red) and 2005 event (black), respectively.

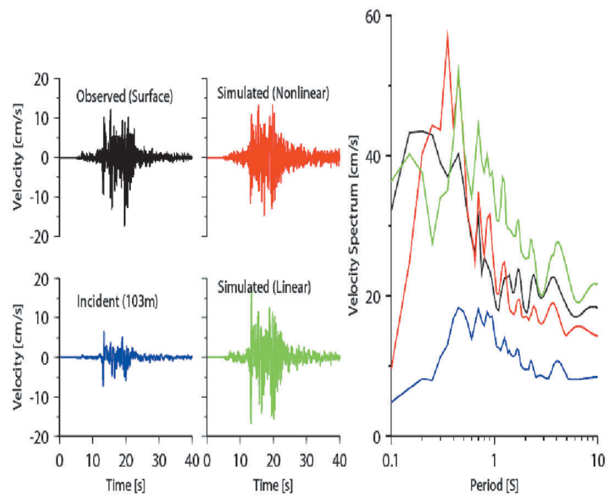

Fig. 6. Nonlinear simulated synthetic (red line), Linear simulated synthetic (green line), and observed (black line) at the surface and at a depth of 103 m (blue line) Time histories and corresponding velocity response spectrum (h=5%) at Kik-net station (MYGH04)

attenuation model correlates with those of other studies for the inter-plate event. (e.g., Satoh *et al.*, 1997; Satoh and Tatusmi, 2002)

To determine the site response from the two large events, we applied the same method as Tsuda *et al.* (2006b) with consideration to the effects of the focal mechanism. The hypocenters of these events are set to the point that has maximum slip among the fault planes based on the rupture model of Yamanaka and Kikuchi (2003) for 2003 event and Yamanaka (2005) for 2005 event.

4. Results

We derive surface site responses using weak motion data. We show the site responses at KiK-net stations used for this study (Figure 3). We also show the site response derived by an inversion method that depends on a reference site—(Satoh, 2005). Because her reference site has its own site response above 4 Hz, the site responses are only given up to 4 Hz. In this frequency range, our site responses correlate well with her results.

In Figure 4, we plot the site responses from the two large earthquakes. As can be seen, the site responses from two large earthquakes are generally smaller than the weak motion response, and the predominant frequency is generally shifted to a lower frequency. This is a characteristic of a nonlinear site response.

To check how different the nonlinearity might be between two levels of strong shaking, we take the ratio of site responses from a large event to the average of the small events. As an example we show the response for station MYGH04 where the PGA is 664.7 [gal] and 267.0 [gal] from the 2003 and 2005 events, respectively. We compare the two responses in Figure 5—the smaller the ratio is, the more nonlinearity there exists. Note that the response is high at low frequencies and low at high frequencies, indicating that the nonlinear site response is decreasing the overall level of site response, and shifting the curve to a lower frequency, which increases the ratio at low frequencies and decreases the ratio at high frequencies.

To investigate the nonlinearity further, we simulated seismic wave propagation with a nonlinear stress-strain relationship (Bonilla *et al.,* 2005). First, we re-determined the 1-D velocity profiles using an iterative inversion method of weak motion data (Assimaki and Steidl, 2005). We then calculated the synthetic seismogram from the strong motion case. Because we did not have detailed information about water table and laboratory data for this site, we used generic values for soil parameters to specify nonlinear hysteretic response (Hartzell *et al.*, 2004). We compare the synthetics with data from the 2003 event (Figure 6). The results for linear elastic response consistently overestimate the observed data for the entire period range above 0.4 s. The nonlinear response does well for periods greater than 0.5 s, but misfits the below 0.5 s.

5. Summary

The comparison of site responses from weak motion data with site responses from two large earthquakes shows that nonlinear site response existed during strong shaking. The synthetic 1D simulation of seismic wave propagation that accounts for soil nonlinearity provides a better representation of the observed records than a linear elastic response. Because the area of off-Miyagi prefecture is forecast to have another large earthquake in the near future, predictions of strong ground motion should take account of nonlinear soil response.

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References

Aki, K. (1993). Local site effects on weak and strong ground motion, *Tectonophysics,* 218, 93–111.

Aguirre, J., K. Irikura, and K. Kudo. (1994). Estimation of strong ground motion on hard rock and soft sediment sites in Ashigara valley using the empirical Green's function method, *Bull. Disast. Prev. Res. Inst., Kyoto Univ.* 44, 45–68.

Assimaki, D., and J. Steidl. (2005). Inverse analysis of weak and strong motion down hole array data from the Mw 7.0 Sanriku-Minami earthquake, *Soil Dynamics and Earthquake Engineering.* (in review).

Beresnev, I.A. (2002). Nonlinearity at California generic soil sites from modeling recent strong-motion data, *Bull. Seism. Soc. Am.,* 92, 863–870.

Borcherdt, R.D. (1970). Effects of local geology on ground motion near San Francisco Bay, *Bull. Seism. Soc. Am.* 60, 29–61.

Bonilla, L. F, R. Archuleta, and D. Lavalèe. (2005). Hysteretic and dilatant behavior of cohesionless soils and their effects on nonlinear site response: field data observations and modeling, *Bull. Seism. Soc. Am.* (Accepted for publication)

Field, E. H., P. A. Johnson, I. A. Beresnev, and Y. Zeng. (1997). Nonlinear ground-motion amplification by sediments during the 1994 Northridge earthquake, *Nature* 390, 599–602.

Field, E. H., S. Kramer, A.-W. Elgamal, J.D. Bray, N. Matasovic, P.A. Johnson, C. Cramer, C. Roblee, D.J. Wald, L.F. Bonilla, P.P. Dimitriu, and J.G. Anderson. (1998). Nonlinear site response: Where we're at. Proceedings of the VIIth International Symposium on the Observations of the Continental Crust through Drilling 69 no. 3.

Hartzell, S., L. F. Bonilla., and R. A. Williams. (2004). Prediction of nonlinear soil effects, *Bull. Seism. Soc. Am.*, 94, 1609–1629.

Idriss, I.M. (1991). Earthquake ground motions at soft soil sites, Special Session in Honor of H.B. Seed, *Proc. Second Int. Conf. on Recent Advances in Geotech. Earthq. Eng. and Soil Dyn.,* St. Louis.

Iwasaki, Y. and Tai, M. (1996). Strong motion records at Kobe Port Island, *Special Issue of Soils and Foundations,* V1, 29–40.

Midorikawa, S. (1993). Nonlinearity of site amplification during strong ground shaking, *Zishin.* 46, 207–216. (Japanese with English abstract)

Satoh, T. (2005). Influence of fault mechanism, depth, and region on stress drops of small and moderate earthquakes in JAPAN, *Structural Eng./Earthquake Eng., JSCE,* 200. (accepted for publication)

Satoh, T. (2004a). Short-period spectral level of intraplate and interplate earthquakes occurring off Myagi prefecture, *Journal of JAEE,* 4, 1–4. (Japanese with English abstracts)

Satoh, T. (2004b). Study on causes of large peak accelerations of the 2003 Miyagiken-oki earthquake based on strong ground motion records, J.Struct.Cnstr. Eng., AIJ, 581, 31–38. (Japanese with English abstract)

Satoh, T., and Y. Tatsumi. (2002). Source, path, and site effects for crustal and subduction earthquakes inferred from strong motion records in Japan, J. Struct. Constr. Eng., AIJ, 556, 15–24. (Japanese with English abstract)

Satoh, T, H. Kawase., and T. Sato. (1997). Statistical spectral model of earthquakes in the Eastern Tohoku district, Japan, based on the surface and borehole records observed in Sendai, *Bull. Seism. Soc. Am.* 87, 446–462.

Seed, H.B. and I.M. Idriss (1970). Analysis of ground motions at Union Bay, Seattle during earthquakes and distant nuclear blasts, *Bull Seism. Soc. Am.* 60, 125–136.

Si, H., and S. Midorilkawa. (1999). New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition. *J. Struct. Constr. Eng.,* AIJ, 523, 63–70. (Japanese with English abstract)

Tsuda, K., Archuleta, R., and Koketsu, K. (2006a). Quantifying spatial distribution of site response by use of the Yokohama High-Density Strong Motion Network, *Bull. Seism. Soc. Am.* 96, 926–942.

Tsuda, K., Archuleta, R., Steidl, J., and Assimaki, D. (2006b). Site response estimation for 2003 Miyagi-Oki earthquake Sequence considering nonlinear site response, *Bull. Seism. Soc. Am.* 96, 1474–1482.

Yamanaka, Y., and M. Kikuchi. (2003). May 26, Miyagi-oki earthquake (Mj＝7.0), EIC *Seismological Notes,* 135, (http://wwweic.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/2005/EIC168.html) (Japanese)

Yamanaka, Y. (2005). August 16, Miyagi-oki earthquake(Mj＝7.2), EIC *Seismological Notes,* 168. (http://wwweic.eri.u-tokyo.ac.jp/sanchu/Seismo_Note/2005/EIC168.html) (Japanese)

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