Quantification of Degree of Nonlinear Site Response

S. Noguchi [1] and T. Sasatani [2]

[1] *Graduate Student, Faculty of Science, Hokkaido University, Sapporo, Japan*
[2] *Professor, Graduate School of Engineering, Hokkaido University, Sapporo, Japan*
Email: snoguchi@mail.sci.hokudai.ac.jp, sasatani@eng.hokudai.ac.jp

ABSTRACT :

We investigate nonlinear site response based on strong motion records form the 2003 off-Miyagi intraslab earthquake. First we identify the nonlinear site response using records obtained at KiK-net stations where vertical array has been installed. The nonlinear site response is identified by two methods; one is a spectral ratio of surface S-wave to borehole S-wave (surface/borehole) and the other is a spectral ratio of horizontal S-wave to vertical S-wave (S-H/V) for surface records. We confirm that two methods show similar results, so we extended nonlinear identification to records obtained at K-NET stations, where only a surface instrument has been installed, by using the S-H/V method. Next we define a degree of nonlinear site response (DNL) based on the surface/borehole and S-H/V spectral ratio; the DNL is summation of differences between the ratio for strong motion and that for weak motion. We find that the DNL values increase with observed PGA (Peak Ground Acceleration). Finally we make a comparison between the predicted and observed PGAs during the 2003 off-Miyagi Earthquake as a function of DNL. The strong motion prediction is done by using empirical Green's function method. A fairly good agreement is obtained at stations with small DNL. However, the agreement considerably decreases at stations with large DNL; the predicted PGA is much larger than the observed one. We conclude that the reduced observed PGA is due to nonlinear site response during strong ground motion.

KEYWORDS: Nonlinear Site Response, S-wave H/V, Strong Ground Motion Prediction, EGF Method

1. INTRODUCTION

It is very common phenomenon that the seismic response characteristics of surface soft soil become nonlinear when the site is struck by strong motion. From the results of dynamic soil test, it is known that damping factor h rises and shear rigidity of soil drops as the shear strain level rises. At the same time, shear wave velocity (Vs) related to shear rigidity also drops. The nonlinearity of site response is attributed to these changes of surface soil response due to strong ground motion (Midorikawa, 1993). Especially, the reduction of high frequency seismic waves by increased damping factor often becomes very significant. Because of that, the results of strong motion prediction are sometimes overestimated considerably, especially at PGA. It might be due to nonlinearity of site response contained in strong motion record. The overestimation is expected to be due to the assumption in prediction that the site response is linear regardless the strength of ground motion.

To investigate nonlinear site response, the data recorded at a vertical array are commonly used (e.g., Iai *et al*, 1995). The vertical array data is available at KiK-net stations. But at ground surface observation only stations like K-NET, nonlinear site response cannot be identified using above method. About this issue, Wen *et al*. (2006) suggested that the spectral ratio of horizontal to vertical for S-wave (S-H/V) at ground surface can be used as an indicator of nonlinear site response. We examine the availability of S-H/V using KiK-net vertical array data recorded during the 2003 off-Miyagi Earthquake. To test the behaviors of these ratios, we calculated theoretical response using a model structure using equivalent linear method.

Next, to check the characteristics of nonlinear site response quantitatively, we present the index of nonlinearity of site response DNL. We investigate the relation between DNL for S-H/V and strength of ground motion or soil parameter using data of KiK-net and K-NET. Finally, we compare the DNL with overestimated PGA of strong motion prediction. If the overestimation of PGA is due to nonlinear site response, the DNL would be correlated with the PGA overestimation.

2. IDENTIFICATION OF NONLINEAR SITE RESPONSE

2.1. Data

The 2003 off-Miyagi Earthquake (Mw7.0) occurring on May 26, 2003 is an intraslab earthquake. The hypocenter depth of the earthquake is 72km and located in subducting Pacific Plate. This earthquake generated strong ground motion over a wide region of fore-arc side of Tohoku in Japan (Fig.1). To investigate the influence of nonlinear site response on these strong motion data, we use data recorded at 67 sites of K-NET and 54 sites of KiK-net. These stations and their PGAs are shown in Fig.1.

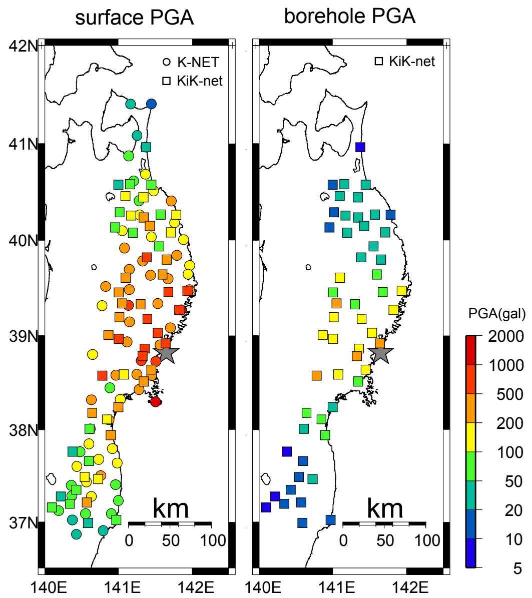

Figure 1 PGAs at K-NET and KiK-net stations during the 2003 off-Miyagi Earthquake. Gray stars mean the epicenter. Sites used in this analysis are only shown.

2.2. Changes of Spectral Ratio

To investigate the influence of nonlinear site response on a strong motion record, spectral ratio of S-wave horizontal spectrum at ground surface to that at borehole (surface/borehole) has been commonly used. On the other hand, Wen *et al*. (2006) showed that the S-wave spectral ratio of horizontal to vertical (S-H/V) at ground surface can be used as an indicator of nonlinear site response. According to Sato and Kanatani (2006), the change of bulk modulus is very little at saturated ground even with high strain level. They suggested that velocity and damping for compressional wave does not change significantly during strong motion. The compressional wave is expected to be dominant in vertical motion at ground surface. Therefore, vertical amplitude spectrum at ground surface can be used as reference spectra, and S-H/V is expected to be available for identification of nonlinear site response.

Here, to confirm availability of S-H/V method, we calculate the surface/borehole ratio and S-H/V using strong motion data recorded at KiK-net vertical array. A time window of S-wave spectrum is selected to be 20.48sec with 10% cosine taper at both ends. Fourier amplitude spectrum is calculated by FFT, and smoothed by 0.4Hz Parzen window. The horizontal amplitude spectra are derived from the square root of product of horizontal two components. Besides of them, we make 'reference' ratio of surface/borehole or S-H/V. The reference ratio is derived as an average of spectral ratios calculated using weak motions whose PGAs are less than 50gal. The time window for weak motion is selected to be 10.24sec.

A comparison of the surface/borehole or S-H/V for strong motion with reference is shown in Fig.2. In either surface/borehole or S-H/V panel, high frequency level over 10Hz for strong motion is reduced significantly compared to the reference. This is due to increase of damping factor *h* of surface soil during strong motion, and one of typical characteristics of nonlinear site response. At the other sites with high PGA, similar changes of the surface/borehole or S-H/V are also found. Furthermore, we calculate spectral ratio of surface/borehole or S-H/V for strong motion to the reference (strong/reference). The results are shown in Fig.2(c). The similarity of changes of surface/borehole and S-H/V becomes much clearer in the comparison of strong/reference. The similarity suggests that these changes of spectral ratios indicate the same phenomenon, which is the nonlinearity of site response due to strong motion.

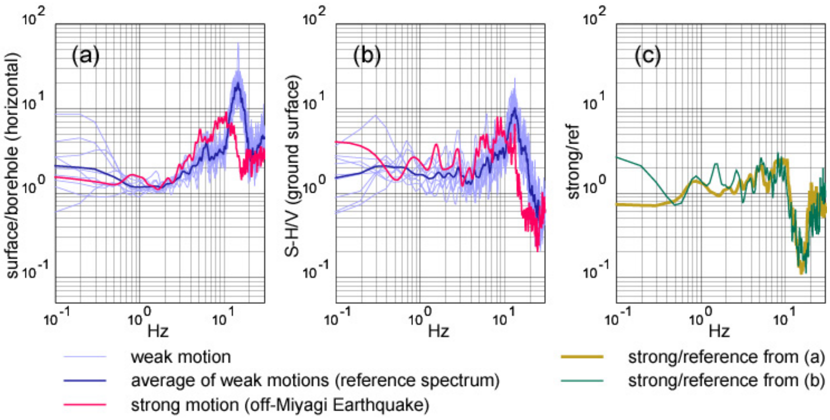

Figure 2 Comparison of spectral ratio for strong motion with reference. The strong motion data were recorded at KiK-net IWTH23 during the 2003 0ff-Miyagi Earthquake, whose horizontal PGA at ground surface is 559gal. (a) Surface/borehole spectral ratio of horizontal component, (b) S-H/V at ground surface, (c) The ratio of surface/borehole and S-H/V for strong motion to references.

2.3. Theoretical Spectral Ratio

In the section 2.2, the possibility is suggested that S-H/V can be used as an indicator of nonlinear site response. For this, it is needed to confirm that the S-H/V change is attributed to nonlinear site response same to surface/borehole. We calculated these ratios theoretically using model structure shown in Table 1. We use P-SV propagator matrix method by Aki and Richards (1980). The oblique SV-wave incidence into seismic basement is assumed for either S-H/V or surface/borehole. The incident angle is 30 degrees. We note that the surface/borehole depends on the structure between ground surface and borehole sensor, but S-H/V at ground surface depends on the whole structure.

To represent the damping, we use quality factor Q instead of damping factor h. Q and h are related as the following.

$$2h = \frac{1}{Q} = \frac{1}{Q_0 f^{\alpha}} + \frac{1}{Q_i} \tag{2.1}$$

Richards and Menke (1983) suggested that quality factor Q is represented by summation of scattering Q and intrinsic Q as above. Scattering Q is represented by $Q_0 f^{\alpha}$ in Eqn. 2.1. The dependency on frequency f was fixed at 1 in this analysis. On the other hand, Intrinsic Q represented by Qi in Eqn. 2.1 does not depend on f. In Table 1, $Qs0$ and Qsi represent $Q0$ and Qi in Eqn. 2.1. for S-wave. Similarly, $Qp0$ and Qpi represent $Q0$ and Qi

in Eqn. 2.1. for P-wave. To evaluate the nonlinearity of site response, we use equivalent linear method. One of characteristics of nonlinear soil response is decreasing of shear rigidity and *Vs*, and the other is increasing of damping factor *h* depending on strain level. The damping factor dealt in dynamic soil test does not depend on *f*, and corresponds to intrinsic *Q*. We simply assume reductions by 50% for *Vs* and *Qi* of soil (*Vs*<300m/s) to represent the nonlinear response; this is called nonlinear structure here.

The results are shown in Fig.3. The nonlinear/original is the ratio of the spectral ratio from nonlinear structure to that from original structure, and corresponds to the strong/reference in Fig.2(c). From the comparison of the nonlinear/original, the changes of S-H/V and surface/borehole at high frequencies are quite similar despite the difference of shapes of S-H/V and surface/borehole. These characteristics of each ratio are similar to the observed ones (Fig.2). It supports the assumption that the strong/reference for S-H/V indicates the change of response characteristics similar to that for surface/borehole.

Table 1 Model structure used to calculate theoretical surface/borehole and S-H/V shown in Fig.3. The structure between surface and GL-100m is used for surface/borehole, and whole structure is used for S-H/V.

No.	depth (m)	dencity (kg/m3)	Vp (m/s)	Vs (m/s)	Qs0	Qsi	Qp0	Qpi	
1	2	1500	500	120	10	5	20	5	
2	4	1700	1000	250	10	10	20	10	
3	20	1800	1500	250	10	10	20	100	
4	50	1900	1800	500	20	50	50	200	# engineering basement
5	100	2000	2100	700	20	100	50	200	# borehole seismometer GL-100m
6	200	2200	2500	1100	50	200	100	500	
7	500	2300	3300	1700	100	0	200	0	
8	1000	2450	4000	2200	200	0	500	0	
9	-	2700	5900	3400	0	0	0	0	# seismic basement

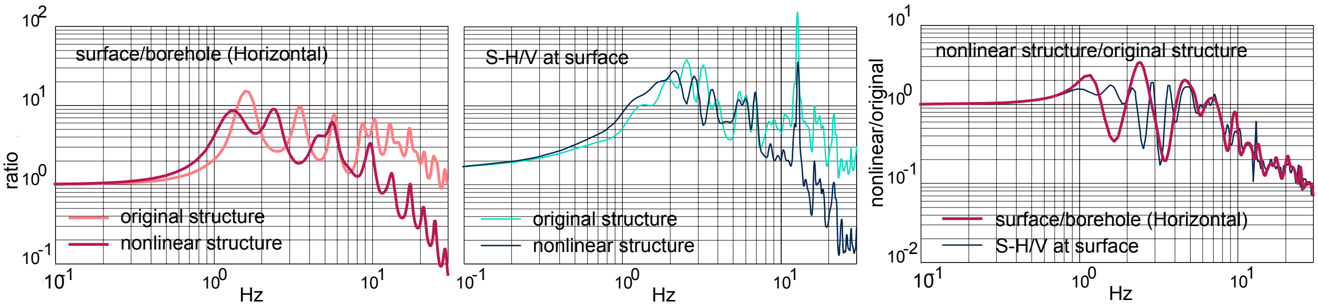

Figure 3 Theoretical spectral ratios calculated using model structure shown in Table 1. Oblique SV-wave incidence into seismic basement at angle of 30deg is assumed.

3. DEGREE OF NONLINEAR SITE RESPONSE

From results of dynamic soil test, it is known that the nonlinearity of soil response depends on strain level and soil parameters. Thus, the strong/reference which indicates nonlinear site response is expected to be related to the strength of ground motion or surface soil parameters. To investigate the relation quantitatively, we define the index of degree of nonlinearity of site response (DNL). It is a summation of differences between surface/borehole or S-H/V for strong motion and their reference, as follows.

$$\mathrm{DNL} = \sum \left| \log\left(\frac{R_{strong}}{R_{ref}} \right) \right| \cdot \Delta f \tag{2.2}$$

R_{strong} means spectral ratio for strong motion and R_{ref} means the reference. In this analysis, the frequency range of this summation is 0.5-20Hz. So, more than the half of the DNL value depends on high frequency components above 10Hz. The DNL can be derived from either surface/borehole or S-H/V.

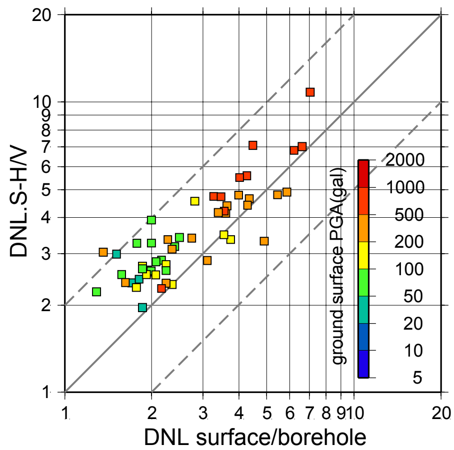

Figure 4 Comparison of DNL for surface/borehole with that for S-H/V. They are calculated using data recorded at KiK-net during the 2003 off-Miyagi Earthquake. PGA is derived from horizontal component at ground surface.

First, we compare DNL calculated from surface/borehole with that from S-H/V using data recorded at KiK-net vertical array. The comparison is shown in Fig.4. It is shown clearly that DNLs calculated using different spectral ratios, surface/borehole and S-H/V, are almost equivalent. This means that the changes of these spectral ratios are almost equivalent. So, the DNL from S-H/V can be used as an index of nonlinear site response instead of surface/borehole. Since the S-H/V is derived from surface records, it is available for K-NET. It is also seen that the DNLs for S-H/V are bigger than these for surface/borehole, especially for smaller DNL. It could be due to that the S-H/V spectra are a bit unstable than surface/borehole.

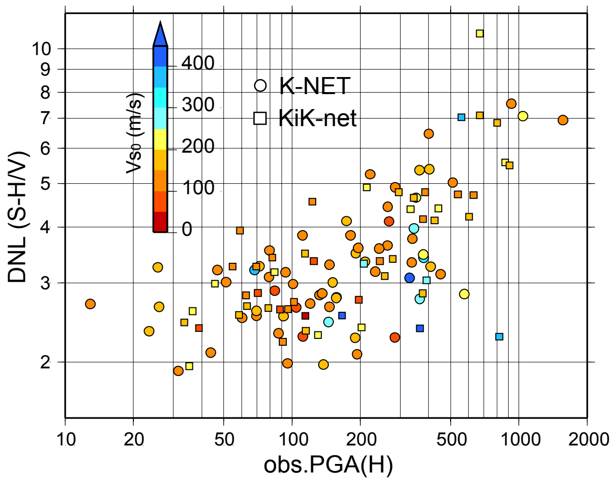

Figure 5 Relation between DNL and observed horizontal PGA at ground surface. *Vs0* means shear wave velocity at surface layer of each site.

Then, we look up the relation between DNL for S-H/V and strength of ground motion or surface soil parameters. In addition to the KiK-net data, the K-NET data from the 2003 off-Miyagi Earthquake are also used. The result is shown in Fig.5. The DNLs for weak motions less than 100gal are around 2 or 3. This value would be due to the fluctuation of S-H/V. Some of DNLs for PGA over 100gal rises over 3, and the DNL values increase as the PGA increase. It can be seen that there is positive correlation between DNL and PGA even though they are scattered. At some sites the DNL is less than 3 even with high PGA. At such sites, the surface soil is expected to be stiffer than the other sites. Actually, there is a trend that the site which has high PGA and low DNL shows higher value of top soil $Vs(Vs_0)$.

4. STRONG MOTION PREDICTION AND NONLINEAR SITE RESPONSE

By means of DNL, we investigate the effect of nonlinear site response on the results of strong motion prediction. The source modeling of the 2003 off-Miyagi Earthquake using empirical Green's function (EGF) method have been performed by Asano *et al.* (2004). According to their study, the synthesized strong motions calculated using their source model differed from observed ones especially in PGA. They suggested one of the causes of the difference was nonlinear site response.

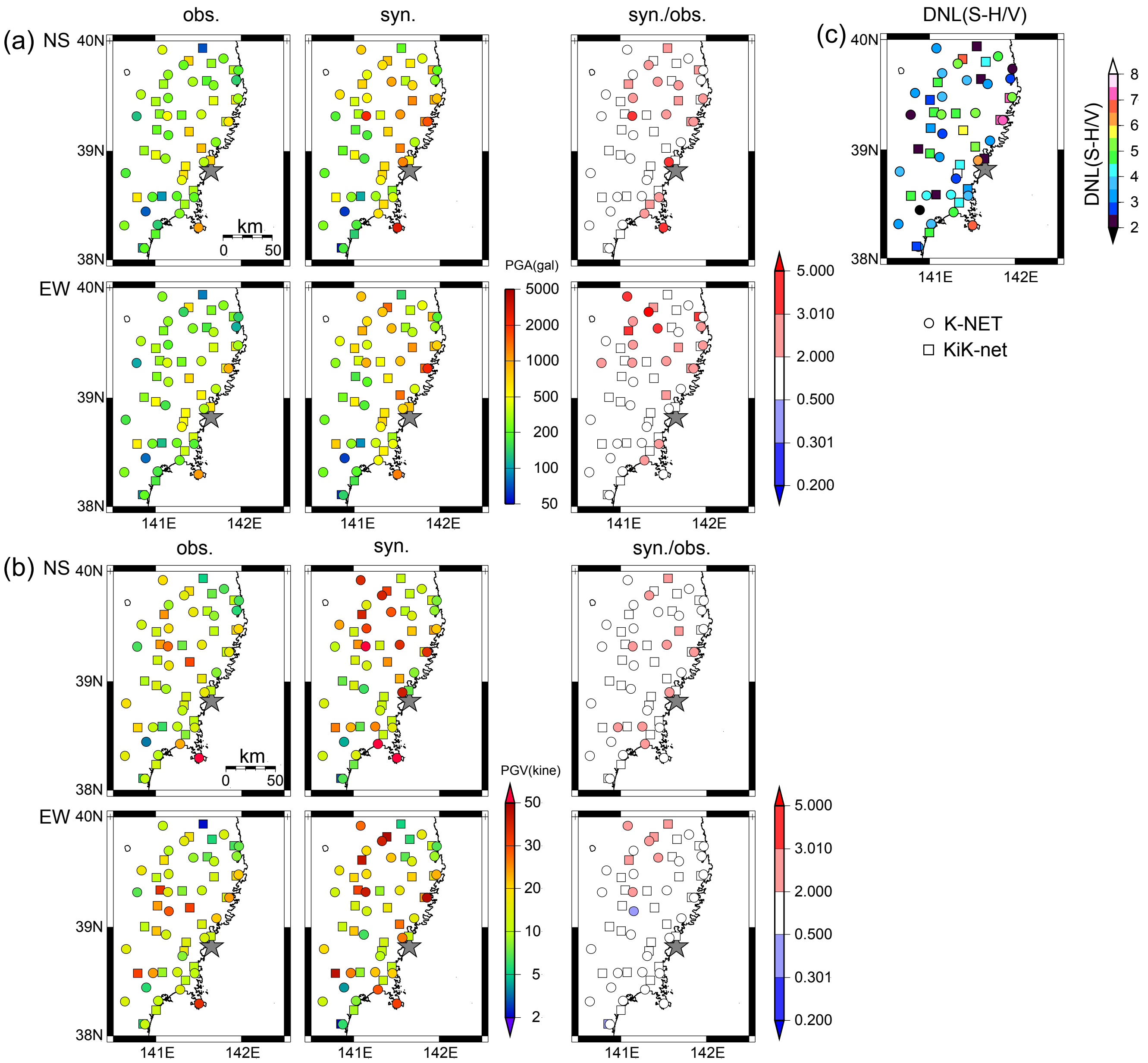

Figure 6 Comparison between observed peak values and synthesized ones by EGF. The data recorded at ground surface during the 2003 off-Miyagi Earthquake are used. DNL distribution from S-H/V is also shown. The gray stars mean epicenter. (a) PGA comparison, (b) PGV comparison, (c) DNL distribution.

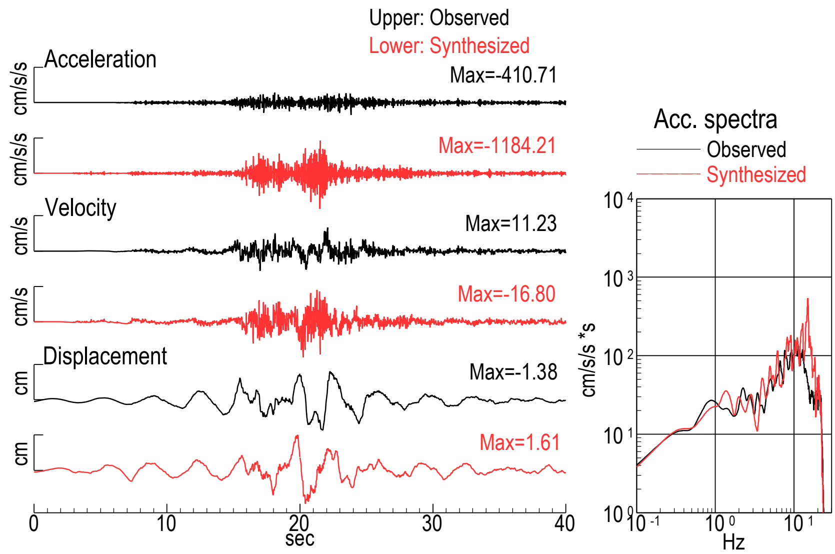

Figure 7 An example of synthesized data by EGF for the NS component on ground surface at KiK-net IWTH23.

We also synthesize strong motion by EGF using source model of Asano *et al.* (2004). The results are shown in Fig.6. Similar to their results, the predicted PGV values are not so different from the observed ones. However the predicted PGAs are much larger than the observed ones. An example of comparison of predicted waveform and its Fourier amplitude spectrum with the observed ones is shown in Fig.7. The data at KiK-net IWTH23 are used; these are also used in Fig.2. It is obvious that only the predicted PGA value is much larger than the observed one. The spectral ratios in Fig.2 indicate that the high frequency component of observed data is strongly reduced by nonlinear site response. Corresponding to that, the DNL for S-H/V from observed data also shows a high value of 7.03. From these results, it can be supposed that the overestimation of PGA is due to the reduction of high frequencies in observed data.

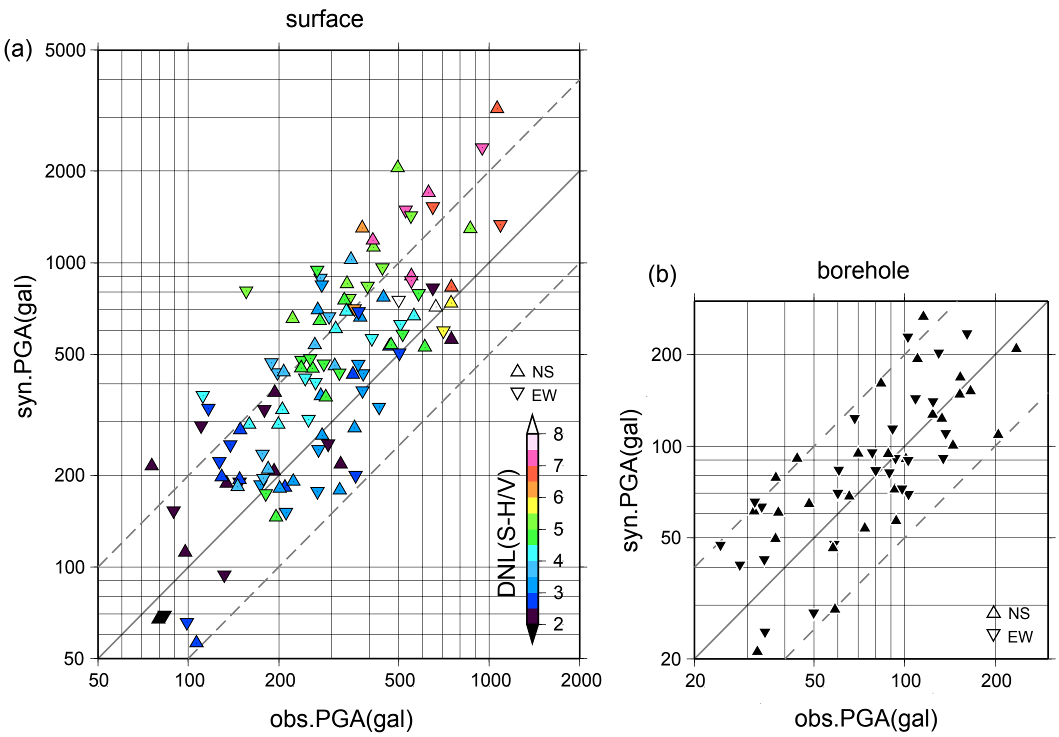

Figure 8 Comparison between predicted PGA by EGF and observed one for the 2003 off-Miyagi Earthquake. The DNLs are derived from S-H/V. (a) Comparison for ground surface data, (b) Comparison for borehole data.

Finally, we compare the difference between predicted PGA and observed one as a function of the DNL for S-H/V. The results are shown in Fig.8. For the borehole data (Fig.8 (b)), differences of predicted and observed PGAs are limited between 2 and 1/2. Compared to these results, the overestimations of PGA at surface are obvious. The PGA tends to be overestimated considerably as the PGA values become higher. At many of these overestimated sites, the DNLs show high value. The group of DNL greater than 5 indicates overestimation of PGA by a factor of about 2. On the other hand, the PGA difference of the site whose DNL is smaller than 3 is almost between 2 and 1/2 even with high PGA. This means that the high frequency component of observed data has been reduced by nonlinear site response compared to the result of linear prediction.

5. CONCLUSION

We investigated strong motion data recorded during the 2003 off-Miyagi Earthquake and confirmed the equivalence of the change of surface/borehole and the change of S-H/V. The strong/reference from S-H/V was very similar to that from surface/borehole. This was also supported by theoretical simulation using model structure and 1D wave propagation theory. To look up the relation between the nonlinearity of site response and strength of ground motion or soil parameter, we proposed quantitative index of degree of nonlinear site response (DNL). The DNL of S-H/V derived from KiK-net and K-NET data showed positive correlation with observed horizontal PGA on ground surface and top soil *Vs*.

We synthesized waveforms of the off-Miyagi earthquake by means of the EGF method. The predicted PGAs for horizontal components at ground surface were overestimated frequently at the site with high PGA, even though the borehole data were synthesized properly. The DNLs from S-H/V at overestimated sites indicated significant high value. It means that the high frequency component of observed data was strongly reduced by nonlinear site response, and the predicted value supposing linear response resulted in considerable overestimation. The predicted PGA at sites with DNL grater than 5 tended to be an overestimation by a factor of about 2.

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