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NONLINEAR RESPONSE OF SURFACE LAYERS AT KIK-NET STATIONS IN JAPAN

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SUMMARY

Since accelerometers are installed on the ground surface and in the borehole at KiK-net stations in Japan, we can directly investigate nonlinear behavior of surface layers during actual earthquakes through the analysis of strong motion records at these stations. We analyze spectral ratio between accelerograms recorded on the ground surface and in the borehole during a large ($M_w = 6.6$) and a small ($M_w = 4.0$) earthquakes occurred in Tottori Prefecture, Japan.

Clear difference can be seen between spectral ratios for the large and the small earthquakes at KiK-net stations with the epicentral distance less than 50 km. One dimensional nonlinear response analysis of surface layers is carried out at two closest stations, SMNH01 and TTRH02. A gravel layer with the thickness of about 10 m lies on a weathered rock layer at these stations. Accelerograms expected on the ground surface are synthesized from observed borehole records. Comparing observed and synthetic accelerograms, strain dependency of the shear modulus ratio and the damping ratio for the gravel layers and the weathered rock layers are evaluated by trial and error method. The maximum shear strain during the large event is estimated to have been more than 1% in the gravel layer at TTRH02 where the acceleration more than 1g was observed on the ground surface.

The nonlinear characteristics of surface layers seems to be one of the causes of saturation of maximum acceleration near the epicenter of large earthquakes. Also, attention should be paid on the nonlinear behavior of surface layers when we aim at deducing earthquake source characteristics from near-field strong motion records.

INTRODUCTION

It is widely known that soil layers show nonlinear behavior under the condition of large strain. Dynamic characteristics of various soils have been tested mainly in the laboratory. It has been seldom examined whether the test result in the laboratory may explain the behavior of surface layers during actual earthquakes, because observed ground motion is affected not only by the characteristics of the surface layers at the station but also by the characteristics of earthquake source and wave propagation path.

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Table 1. Earthquakes Analyzed.

Event No.	Date	Latitude (N)	Longitude (E)	Depth (km)	Moment Magnitude
1	2000 07 17	35.372	133.422	17	4.0
2	2000 10 06	35.275	133.350	11	6.6

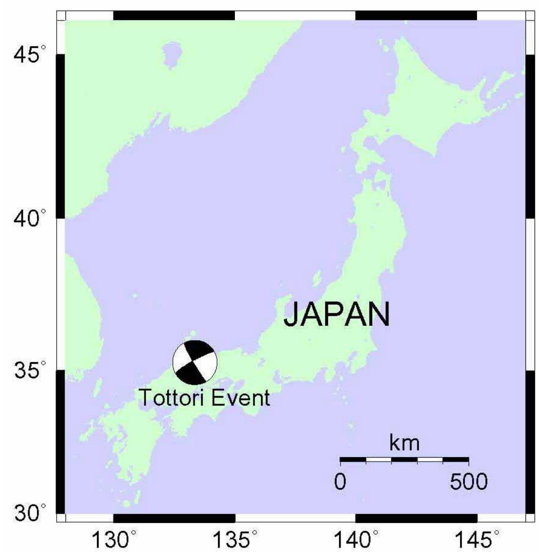

Fig. 1. Epicenter of Event 2 and its focal mechanism.

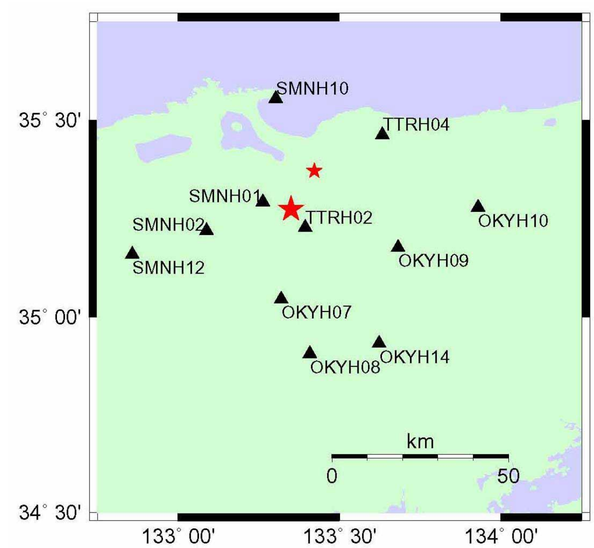

Fig. 2. Epicenters of the events (red stars) and KiK-net stations (black triangles).

A strong motion seismograph network, KiK-net, has been installed by National Institute of Earth Science and Disaster Prevention, Japan (NIED), since 2000. Each KiK-net station has accelerometers on the ground surface and in the borehole. Underground structure has been explored at the stations. Simultaneous analysis of surface and borehole records is a very powerful tool for investigating nonlinear characteristics of surface layers (e.g., Satoh et al. [1]). Effect of the characteristics of earthquake source and wave propagation path can be removed by taking spectral ratio of the record observed on the ground surface to that in the borehole. The spectral ratio provides us with information of the surface layers between the two accelerometers.

The purpose of this study is to examine the observational fact of nonlinear behavior of surface layers during actual earthquakes. Then we investigate whether nonlinear characteristics obtained through laboratory test may explain the observational fact.

DATA

We analyze accelerograms during two earthquakes occurred in Tottori Prefecture, Japan, in 2000. The hypocenter coordinates and the moment magnitudes of the events are listed in Table 1. Fig. 1 shows the location of the epicenter of the larger event (Event 2) and its focal mechanism. The focal mechanism of the smaller event (Event 1) is very similar to that of Event 2. The large and small red stars in Fig. 2 show the epicenters of Event 2 and Event 1. There are 11 KiK-net stations within 50 km from the epicenter of Event 2 as shown in Fig. 2.

Table 2. Maximum acceleration for Event 1.

Station	Epicentral Distance (km)	Maximum Acceleration (gal)	Sensor Depth (m)
SMNH01	17	39	0
		8	101
SMNH12	56	32	0
		2	101
TTRH02	16	56	0
		9	100
TTRH04	21	40	0
		11	207

Table 3. Maximum acceleration for Event 2.

Station	Epicentral Distance (km)	Maximum Acceleration (gal)	Sensor Depth (m)
SMNH01	7	707	0
		194	101
SMNH12	46	247	0
		41	101
TTRH02	6	1066	0
		484	100
TTRH04	33	195	0
		72	207

We analyze transverse component accelerograms, which almost consist of S-waves, at four stations (SMNH01, SMNH12, TTRH02, and TTRH04). The maximum values of acceleration recorded on the ground surface and in the borehole are listed in Tables 2 and 3. The acceleration more than 1g was observed on the ground surface at TTRH02 during Event 2.

OBSERVED SPECTRAL RATIO

Spectral ratio between transverse component accelerograms observed on the ground surface and in the borehole at each of the stations is calculated. The solid curves in Fig. 3 show spectral ratios for the large event (Event 2) and the dotted curves for the small event (Event 1).

It can be clearly seen that peaks of the spectral ratios for Event 2 shift toward lower frequency range relative to those for Event 1. Also the amplitude of the spectral ratios for Event 2 is smaller than that for Event 1 in the high frequency range. These phenomena can be seen more clearly in the spectral ratios at stations, SMNH01 and TTRH02, where the accelerations during Event 2 are much larger than those at the other stations. Therefore, it is concluded that the spectral ratios show an apparent evidence of the nonlinear behavior of the surface layers between the accelerometers on the ground surface and in the borehole.

Layer parameters are given by NIED for SMNH01 and by Higashi and Abe [2] for TTRH02 as shown in Tables 4 and 5. The gravel layers and the weathered rock layers marked by asterisks in the tables seem to have nonlinear characteristics.

ONE DIMENSIONAL NONLINEAR SITE RESPONSE ANALYSIS

One dimensional nonlinear site response analysis is carried out to investigate nonlinear characteristics of the surface layers at SMNH01 and TTRH02. Acceleration on the ground surface is synthesized from observed borehole record with one dimensional nonlinear site response analysis software developed by Kumazaki [3]. Strain dependent shear modulus ratio, G_0 / G, and damping ratio, h, of the layers are assumed as shown in Fig.4 based on the laboratory test result for gravel by Imazu and Fukutake [4] and the estimation result for gravel layers during the 1995 Hyogo earthquake by Satoh [1].

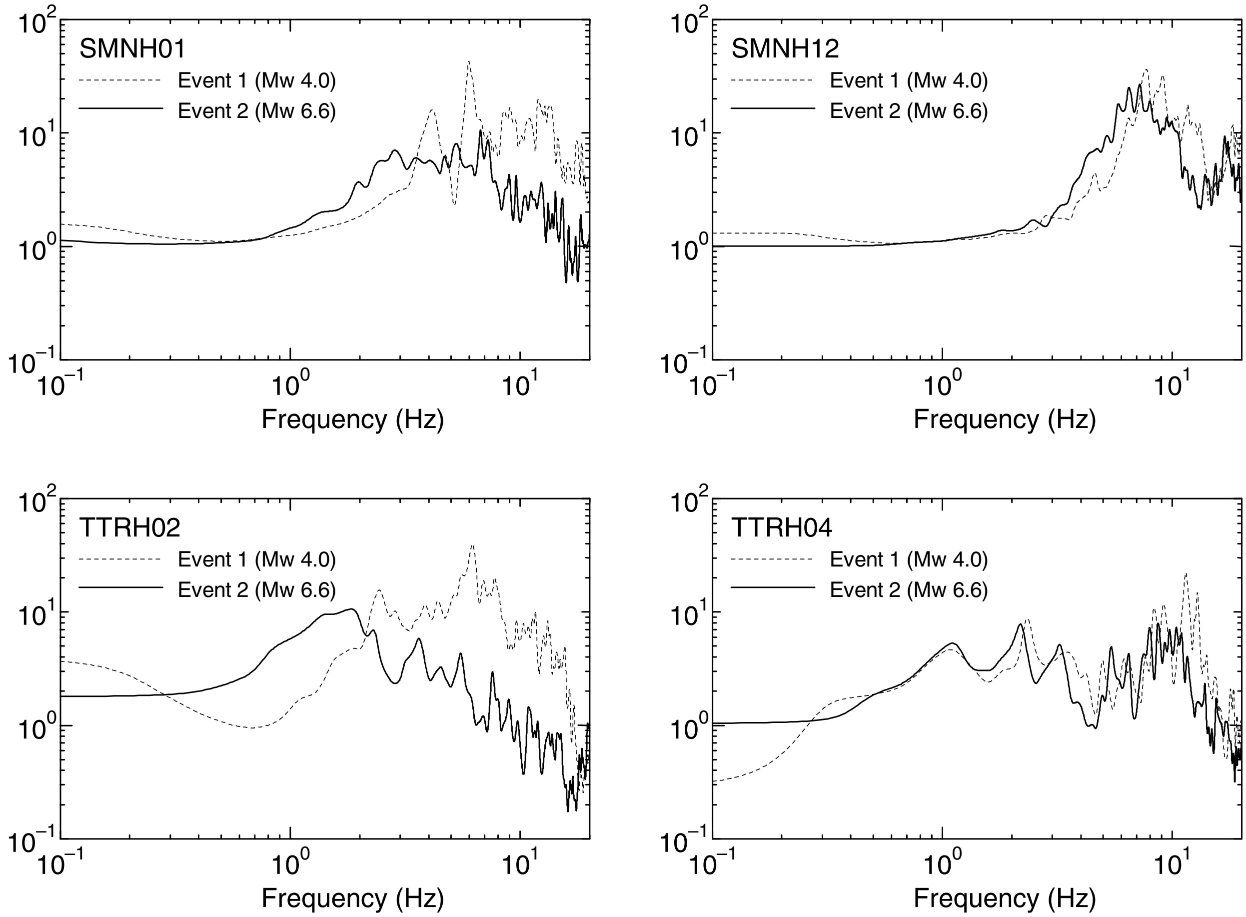

Fig. 3. Observed spectral ratios.

Table 4. Layer parameters at SMNH01.

Soil Type	Thickness (m)	Density (g/cm³)	S-wave Velocity (m/s)
Gravel*	13.5	1.8	290
Rock*	8.5	2.2	550
Rock	20.0	2.4	1200
Rock	12.0	2.4	1900
Rock	47.0	2.6	2800

Table 5. Layer parameters at TTRH02.

Soil Type	Thickness (m)	Density (g/cm³)	S-wave Velocity (m/s)
Gravel*	4.0	1.8	127
Gravel*	6.4	1.8	211
Rock*	9.6	2.0	382
Rock*	22.0	2.2	551
Rock	42.0	2.4	943
Rock	16.0	2.6	2487

One of the pairs of the curves marked from '1' to '5' in Fig. 4 is applied to the gravel layers. The same or another pair is applied to the weathered rock layers. Synthetic spectral ratios and synthetic accelerograms are compared to the observations and the most plausible nonlinear characteristics for the gravel layers and the weathered rock layers are chosen by trial and error method.

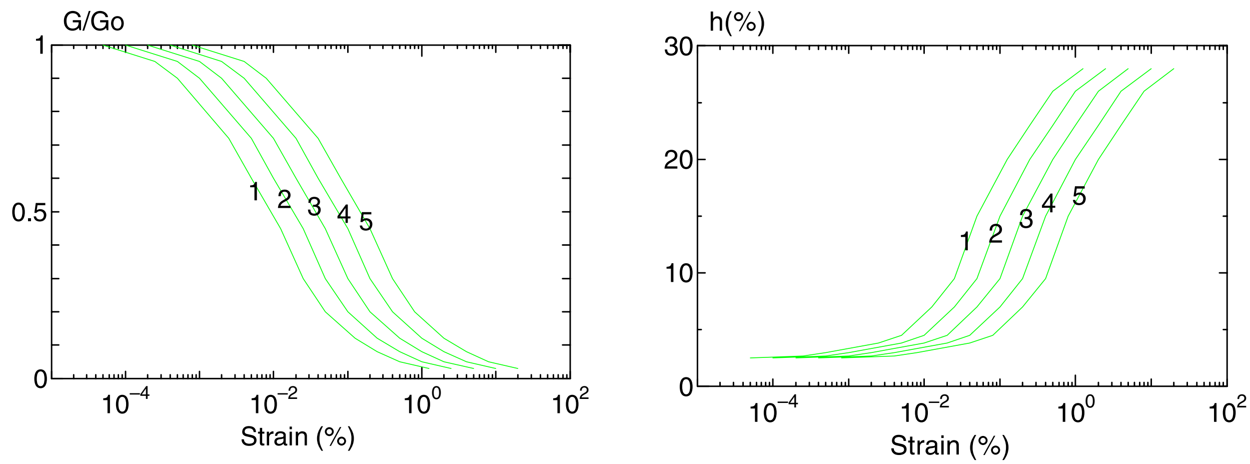

Fig. 4. Strain dependence of rigidity and damping ratio.

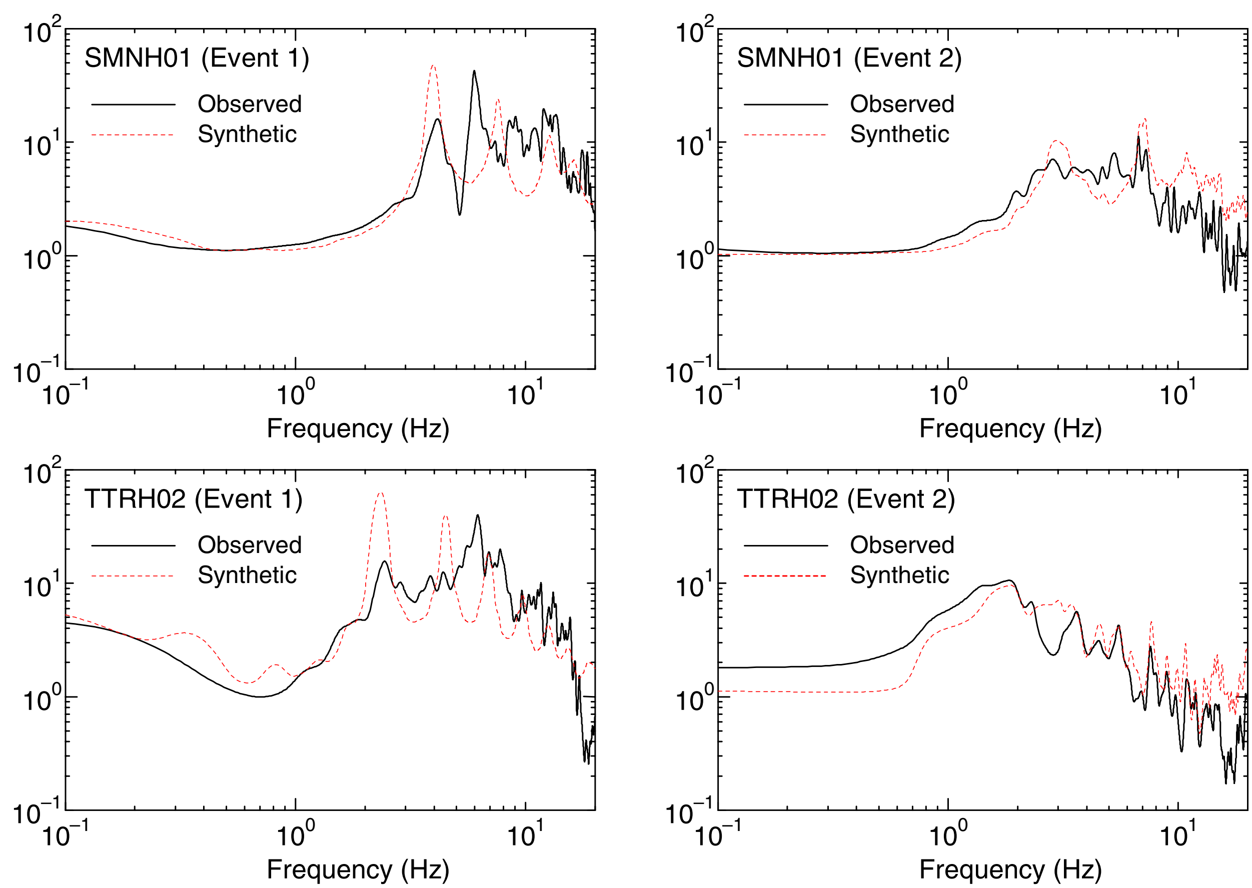

Fig. 5. Observed and synthetic spectral ratios.

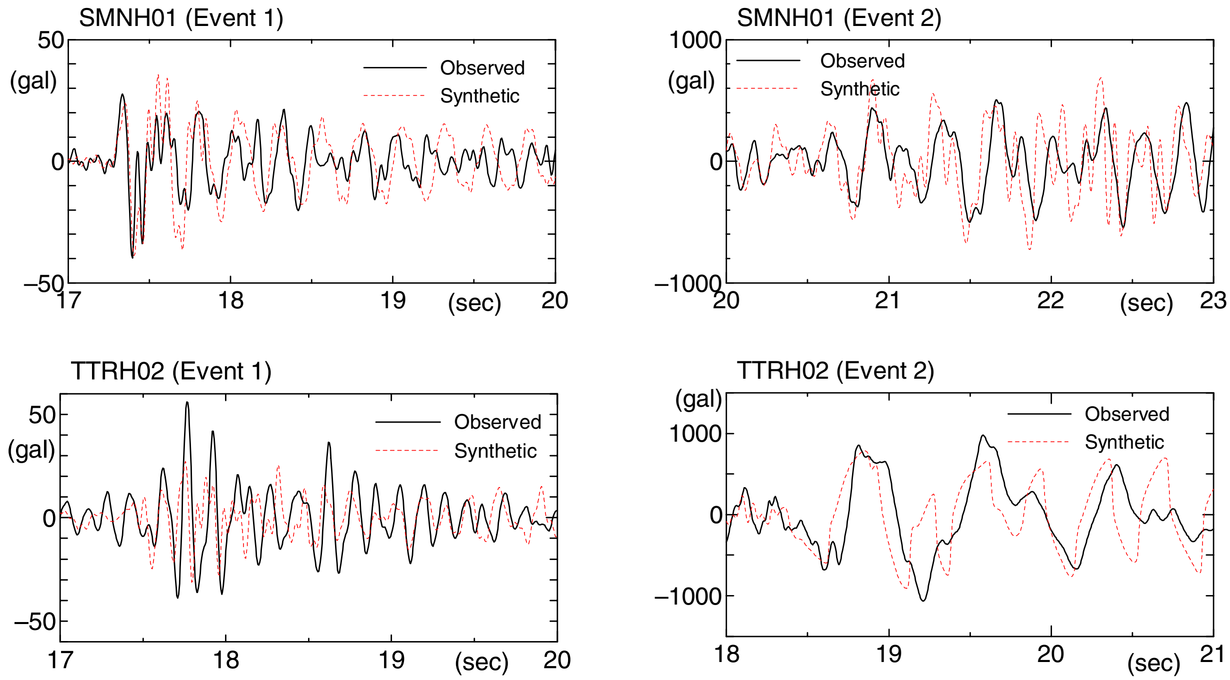

Fig. 6. Observed and synthetic acccelerograms on the ground surface.

Observed and the best fit synthetic spectral ratios are shown in Fig. 5. Observed and synthetic accelerograms for 3 seconds from the S-wave arrival are shown in Fig. 6. The adopted nonlinear characteristics are those marked by '4' in Fig. 4 for the gravel layers and also '4' for the weathered rock layers. The maximum strain is estimated to have been more than 1% in the gravel layer at TTRH02 during Event 2.

Satoh et al. [1] found that gravel layers show nonlinear behavior under the condition of relatively small shear strain ('1' or '2' in Fig. 4) during the 1995 Hyogo earthquake. However, the present result suggests that the gravel layers at the KiK-net stations show nonlinear behavior under the condition of relatively large shear strain ('4' in Fig. 4). If we use the nonlinear characteristics marked by '1' or '2' for the gravel layers in this study, the amplitude of synthetic accelerograms becomes far too small.

DISCUSSION

It has been clearly seen that surface layers behaved nonlinearly at stations whose epicentral distances are less than 50 km during the 2000 Tottori earthquake ($M_w = 6.6$). The saturation of maximum acceleration near the epicenter of large earthquakes is generally observed (e.g., Fukushima and Tanaka [5]) and it is sometimes attributed to the inadequateness of the measurement of the distance from the source of energy radiation (Ohno et al. [6]). However the present result suggests that one of the causes of the saturation of maximum acceleration in the near-field is the nonlinear behavior of surface layers.

Empirical Green's function method (EGF method) to synthesize strong ground motion for future large earthquakes uses observed records from small earthquakes (e.g., Irikura [7]). EGF method is now widely used for the prediction of strong ground motion for future large earthquakes. When we use EGF method, the nonlinear behavior of surface layers should be taken into account for better prediction of strong ground motion for future large earthquakes.

Recently, near-field strong ground motion records are often analyzed to deduce the characteristics of earthquake source (e.g, Izutani and Kanamori [8], Olsen et al. [9]). If the nonlinear effect of the surface layers is not removed properly before investigating source characteristics, the nature of earthquake source might be misunderstood.

CONCLUSIONS

1. Nonlinear behavior of surface layers is clearly seen in the near-field strong motion records during the 2000 Tottori earthquake ($M_w = 6.6$).
2. The maximum shear strain is more than 1% in the gravel layer at TTRH02 where the maximum acceleration on the ground surface exceeded 1g.
3. The strain dependency of shear modulus ratio and damping ratio obtained by the laboratory test adequately explain the nonlinear behavior of the gravel layers during actual earthquakes.
4. One of the causes of the saturation of the maximum acceleration near the epicenter of large earthquakes seems to be the nonlinear behavior of surface layers.
5. Attention should be paid on the nonlinear behavior of surface layers when we aim at deducing earthquake source characteristics from near-field strong motion records.

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