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著者	Sawazaki Kaoru, Sato Haruo, Nakahara Hisashi, Nishimura Takeshi
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Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement

Kaoru Sawazaki,[1] Haruo Sato,[1] Hisashi Nakahara,[1] and Takeshi Nishimura[1]

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[1] The spectral ratios of coda waves of local earthquakes have been often used as measures of relative amplification factors of different sites. Applying this method to coda waves registered by seismometers installed on the surface and at the bottom of a borehole, we succeeded in stably measuring the temporal change in site response associated with the occurrence of a large earthquake strong motion. A remarkable drop of coda spectral ratio and a shift of the peak frequency were observed during strong shake at two sites by the 2000 Western Tottori Earthquake and at a site by the 2003 Tokachi-Oki Earthquake in Japan. The reduction of the peak frequency reached 30–70% at all the sites. After that, the peak frequency logarithmically recovered to the value before the strong motions for a few years at two sites, whereas the other one quickly recovered in a few tens of minutes. **Citation:** Sawazaki, K., H. Sato, H. Nakahara, and T. Nishimura (2006), Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement, *Geophys. Res. Lett.*, *33*, L21303, doi:10.1029/2006GL027938.

1. Introduction

[2] Strong earthquake shock sometimes decreases shear modulus and increases attenuation coefficient of the ground especially at relatively young and soft soil sites, and sand sites containing large amount of underground water [e.g., *Beresnev and Wen*, 1996]. Since understanding of such changes in site responses are important for the quantitative prediction of strong motion, site response behaviors under strong motions have been examined at many fields. For example, using site factors estimated from coda waves of microearthquakes, *Chin and Aki* [1991] synthesized strong motions of the 1989 Loma Prieta Earthquake. They found overestimation in the peak accelerations of the syntheses compared to the observed ones at sediment sites near the mainshock epicenter. Analyzing spectral ratios of surface and borehole records for strong and weak motions in Taiwan, *Wen et al.* [1994] found decrease in the peak frequency and the amplitude of spectral ratio by the strong motions.

[3] Although many researches have reported the reduction of shear modulus caused by strong motion, there have been few studies that discuss the recovery process. *Pavlenko and Irikura* [2002] reported a recovery of shear modulus lasting a few minutes just after the strong motion of the 1995 Kobe Earthquake at sites around Osaka Bay at a depth of shallower than a few tens of meters. Their observation is limited to short-term.

[4] The main objective of the present study is to provide an observational evidence of the temporal change in site response factor which followed a remarkable drop caused by a large earthquake shock. Contrary to the previous studies in which the properties of direct S-waves are examined, we analyze coda waves. Spectra of coda waves of a local earthquake are independent of epicentral distances and the focal mechanism after about twice the S-wave travel time, since coda waves are mostly composed of S-waves scattered by randomly distributed heterogeneities [*Rautian and Khalturin*, 1978]. This property enables us to estimate relative site amplification factors between spatially separated stations on different geological conditions by calculating the spectral ratio of their coda waves [e.g., *Phillips and Aki*, 1986]. This method is also applicable to seismograms recorded by seismometers vertically separated in a borehole. It enables us to extract more stable site response factors compared to a conventional method which uses direct S-waves. Applying this method to data registered by seismometers on the ground surface and at the bottom of a borehole of KiK-net, Japan (see KiK-net website: http://www.kik.bosai.go.jp/kik/index_en.shtml), we show the change in the spectral ratio caused by a large earthquake shock, especially the drop of the peak frequency and the recovery process that continued for a long time.

2. Data and Site Information

[5] Figure 1 shows locations of stations and earthquakes used in the present study. Strong motions by the 2000 Western Tottori Earthquake (M_W6.7, 06/10/2000) are recorded at stations TTRH02 and SMNH01 of KiK-net, Japan, with a sampling frequency of 200 Hz. A strong motion by the 2003 Tokachi-Oki Earthquake (M_W8.3, 25/09/2003) is recorded at station IBUH03 of KiK-net. There are several reports indicating the change in site amplification just after these strong motions [*Yamazoe et al.*, 2004; *Yamanaka et al.*, 2004]. Hereafter, we refer to earthquakes occurred before and after the mainshock as foreshocks and aftershocks, respectively, even though they are not correct in the strict sense of the words. We analyze seismic records of 3 foreshocks, the mainshock, and 115 aftershocks for the station TTRH02, and 2 foreshocks, the mainshock, and 117 aftershocks for SMNH01. We also analyzed 43 foreshocks, the mainshock, and 94 aftershocks for IBUH03. The magnitudes of the foreshocks and aftershocks relative to the 2000 Western Tottori Earthquake are ranging from 2.7 to 6.4, and those relative to the 2003 Tokachi-Oki Earthquake are from 3.6 to 7.2. Their hypocentral distances are distributed

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[1] Department of Geophysics, Graduate School of Science, Tohoku University, Sendai, Japan.

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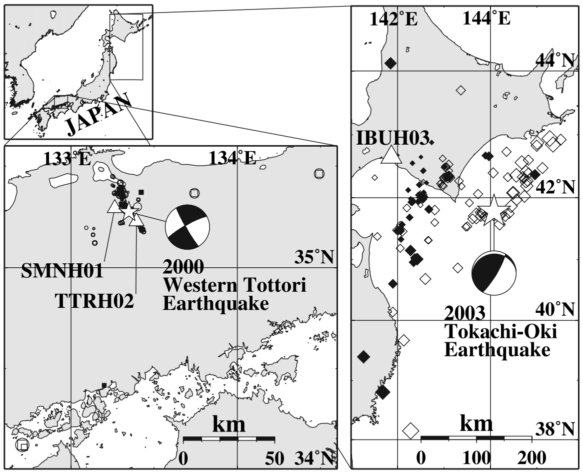


Figure 1. Locations of three KiK-net stations (triangles) and epicenters of the 2000 Western Tottori Earthquake and the 2003 Tokachi-Oki Earthquake (stars with focal spheres), foreshocks (solid symbols), and aftershocks (open symbols) used in this study. Circles, squares, and diamonds correspond to epicenters of microearthquakes recorded by TTRH02, SMNH01, and IBUH03 stations, respectively.

from 7 km to 149 km for stations TTRH02 and SMNH01, and from 17 km to 504 km for station IBUH03.

[6] Figure 2 shows PS well-logging data at the three stations with geologic age. The acceleration seismometers are installed on the ground surface and at the bottom of a borehole, of which the depth is 100 m at TTRH02 and SMNH01, and 150 m at IBUH03. Lithology of TTRH02 is mostly weathered granite and andesite (S. Aoi, personal communication, 2006) in Paleogene or Cretaceous periods, except Quaternary sandy gravel from the surface to 11 m depth. Lithology of SMNH01 is Neogene solid basalt, except Quaternary sandy gravel from the surface to 13.5 m depth. Lithology of IBUH03 is Quaternary sandy gravel from the surface to 18 m depth, Quaternary silicate lapilli from 18 m to 28 m depth, and Quaternary or Neogene conglomerate, sandstone, and mudstone from 28 m to 150 m depth.

3. Spectral Ratio Measurement

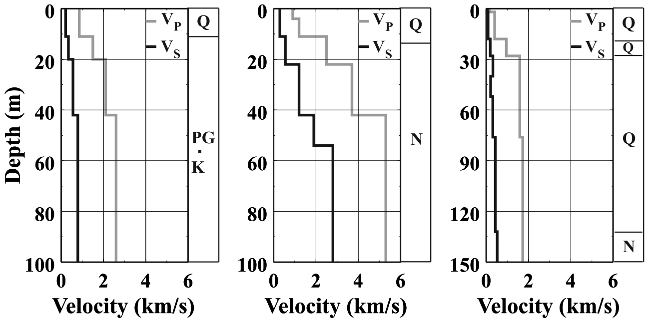
[7] We measure the acceleration spectral ratio of seismic waves recorded on the ground surface to that at the bottom of a borehole at each station. A time window of 10s length is selected in S-coda of foreshocks and aftershocks, where the window starts from twice the S-wave travel time after the origin time of each event. In case the S-wave travel time is shorter than 10s, the time window starts from 10s after the S-wave onset to avoid the effect of source time function. We do not use the data if the signal to noise ratio of the mean power of the trace decreases less than four. Only for the mainshock trace, we analyze the whole data including both direct S-wave and coda wave by shifting the time window of 10s length from the S-wave onset to the end of the trace by 10s time interval. Power spectrum of each acceleration trace is calculated by using FFT after being applied a 5% cosine taper, and smoothed by applying the Hanning window 5 times. Using the square root of the sum of two horizontal-component power spectra, we calculate the ratio of the surface spectrum to the downhole spectrum.

[8] Figure 3 shows a comparison of the spectral ratio of direct S-waves and that of coda waves for 15 aftershocks at the TTRH02 station. The time windows for direct S-waves and coda waves start from 0s and 10s after the S-wave onset, respectively. The aftershocks are selected from those occurred 2 years after the 2000 Western Tottori Earthquake and their hypocenters are widely distributed around the station. Spectral ratios calculated from coda waves approximately agree with those from direct S-waves. However, the ratios from coda waves show a smaller scatter than those from direct S-waves at higher frequencies, which is probably because incident angles and back azimuths of wavelets constituting coda waves are randomly distributed for all the aftershocks. This stability enables us to evaluate the site response from coda wave analyses. Therefore, we use the coda spectral ratio as the site response in the following.

4. Temporal Change in Site Response

[9] Figure 4 shows temporal change of coda spectral ratio at each station. The right bin of each upper panel shows the running spectral ratio in color scale, where the abscissa is lapse time after the S-wave onset of the mainshock. The ratios of foreshocks are shown in the left bin, where the abscissa is precede time before the mainshock in linear scale. Shifting of frequency peaks with time increasing is clearly shown in the upper panel. The lower panel shows logarithmical-average coda spectral ratios for different periods. The largest peaks of the spectral ratio for each period at stations TTRH02 and IBUH03 are marked by a solid circle. For station SMNH01, the highest and the second highest peaks are marked by a solid circle and square, respectively, for each period. The maximum accelerations of coda used for all the spectral analyses were less than 30 gal except the mainshock time window. That is, the coda spectral ratio estimated here represents the site response of small amplitude S-waves.

[10] At station TTRH02, which experienced the largest maximum horizontal acceleration, 1109 gal, on the ground surface among three stations, the peak frequency dropped from 7.4 Hz for the foreshocks to 2.0 Hz for 0–10s after the S-wave onset of the mainshock. The reduction rate of the



(a) (b) (c)

Figure 2. PS well-logging data at (a) TTRH02, (b) SMNH01, and (c) IBUH03 with geologic age (see KiK-net website: http://www.kik.bosai.go.jp/kik/index_en.shtml). The symbols, Q, N, PG, and K, indicate Quaternary, Neogene, Paleogene, and Cretaceous period, respectively.

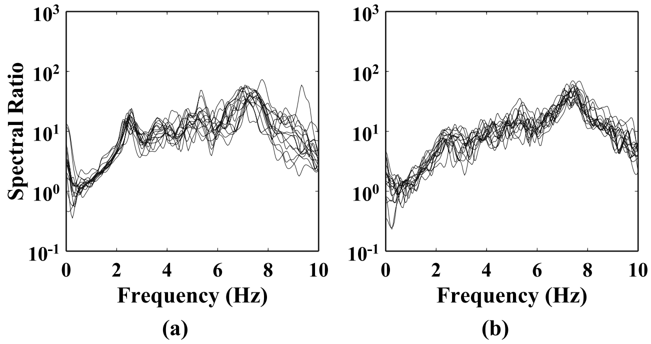


Figure 3. Spectral ratio traces of (a) direct S-waves (0–10s time window after the S-wave onset) and (b) coda waves (10–20s time window after the S-wave onset) of 15 microearthquakes which occurred 2 years after the 2000 Western Tottori Earthquake, recorded at TTRH02 station.

peak frequency is about 70%. The spectral ratio at the peak frequency also decreased from 70 to 10 at the same time. The peak frequency gradually recovered from 2 Hz to 4–5 Hz on coda of the mainshock trace. The peak frequency further recovered to 5–6 Hz when 2.5 days after the mainshock, but it is still smaller than that for the foreshocks. The peak frequency continued to recover for a few years, and is approaching to the value for the foreshocks. The peak frequency looks to recover according to the logarithm of lapse time. Contrary, the lowest peak recognized at 2–3 Hz does not show such time dependence.

[11] At station SMNH01, the highest frequency peak dropped from 9.0 Hz to 6.5 Hz. The reduction rate of the peak frequency is about 30%, which is not as remarkable as that at TTRH02 even though the maximum acceleration was as large as 844 gal. However, gradual recovery of the peak frequency is recognized for a few years after the mainshock. The second highest frequency peak also increased with time approaching that of the foreshocks.

[12] The maximum acceleration at station IBUH03 was 377 gal, which is much lower than other two stations. Nevertheless, the peak frequency was reduced from 1.2 Hz to 0.6 Hz (50% reduction). Since the source duration of the 2003 Tokachi-Oki Earthquake was long and large acceleration appeared 10–20s after the S-wave onset, reduction of the peak frequency was most remarkable in this time window. In contrast to the other two stations, the peak frequency at IBUH03 rapidly recovered to the value for the foreshocks by 20 minutes, and did not show clear temporal change after that.

[13] There are no clear seasonal variations in these spectral ratios. From a comparison of the spectral ratio trace

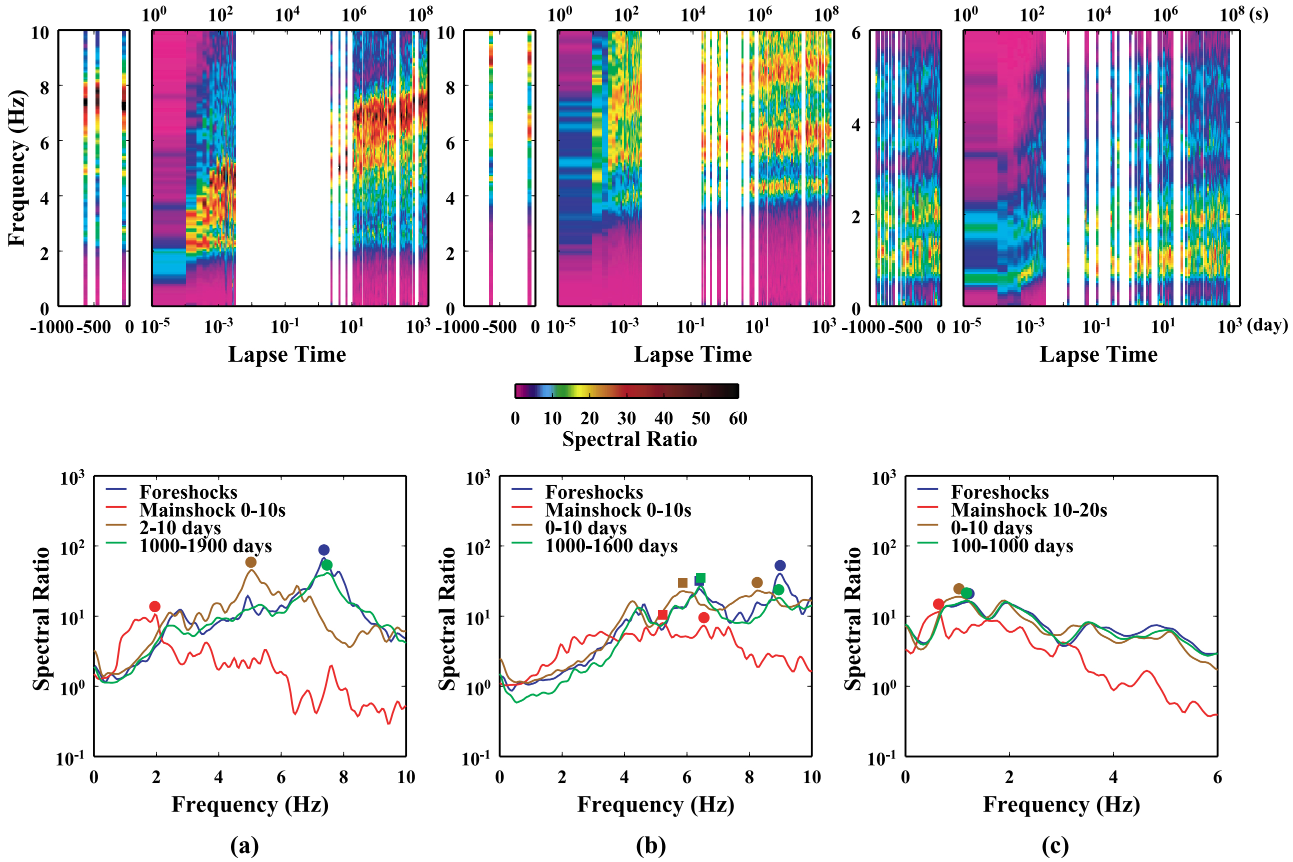


Figure 4. Temporal changes of coda spectral ratio at (a) TTRH02 and (b) SMNH01 for the 2000 Western Tottori Earthquake and that at (c) IBUH03 for the 2003 Tokachi-Oki Earthquake. The right bin of each upper panel shows the running spectral ratio by color code for the mainshock and aftershocks. The left bin shows that for the foreshocks. Values shown on the top and bottom of the abscissa indicate lapse times measured from the S-wave onset of the mainshock in second and in day, respectively. White color represents no data. Each lower panel shows logarithmically averaged coda spectral ratios for the foreshocks (blue), direct S-wave on the mainshock (red), and the aftershocks on different periods (brown and green).

of TTRH02 with a precipitation record near the station, we could not find any correlation between them.

5. Discussion and Summary

[14] There were reports on the change in site amplification factor depending on wave amplitude when the maximum acceleration exceeds 100–300 gal [e.g., *Chin and Aki*, 1991] or when shear strain exceeds about 10^{-4} for soils [*Ishihara*, 1996]. Assuming the S-wave velocity to be 300 m/s, we estimate the maximum shear strain to be 4.7×10^{-3} at TTRH02, 1.4×10^{-3} at SMNH01, and 3.0×10^{-3} at IBUH03. Both of the maximum accelerations and the shear strains at the three sites exceed the criteria mentioned by previous studies. Station TTRH02 which showed the largest peak frequency reduction among three stations is located 10 to 20 meters distance from a lake and the borehole is drilled in weathered granite. Existence of large amount of underground water may explain the significant change in site response at TTRH02.

[15] Recovery of site response is recognized for a few years after the mainshock at solid rock site, SMNH01, and at weathered rock site, TTRH02. However, no such long-term recovery is found at sandy gravel site, IBUH03. We note that there are experimental studies using granular solid samples for the recovery according to the logarithm of lapse time as found in these two cases [e.g., *TenCate et al.*, 2000]. *Pavlenko and Irikura* [2002] showed short-term recovery lasting a few minutes after a strong motion at water-saturated alluvium sites, which is similar to our result at IBUH03. Recently, there have been reports on long-term recovery in the crust after a rapid drop in velocity associated with earthquake occurrence. Applying a cross-spectral analysis to coda wave records of repeated artificial explosions before and after a M 6.1 earthquake in northeastern Honshu, Japan, *Nishimura et al.* [2005] revealed a clear velocity drop by about 1% in a volumetric region near around the focal region. From the successive artificial explosion experiments, they also reported a gradual recovery of seismic velocity with time constant of several years. *Rubinstein and Beroza* [2004] detected delays of S-wave travel time of repeating earthquakes at sites that had been shaken by strong motions of the 1989 Loma Prieta Earthquake. They showed that the delay times logarithmically recovered over a few months. Applying similar analyses to borehole data, *Rubinstein and Beroza* [2005] concluded that the structure shallower than a few hundreds meters depth beneath seismic stations is responsible for the S-wave delays. *Peng and Ben-Zion* [2006] also reported delays of S-wave travel time for the 1999 Izmit and Düzce Earthquakes in Turkey. Long-term recovery of seismic velocity at the shallow part of the crust is similar to our results at stations TTRH02 and SMNH01.

[16] The coda spectral ratio method offers a stable estimate of site response factors. Applying this method to seismograms registered by a pair of seismometers installed on the ground surface and at the bottom of a borehole, we succeeded in detecting the temporal change in site response for over several years after the strong motion shock. The recovery differs with stations: a soft sandy gravel site shows a quick recovery just after the strong motion, solid and weathered rock sites show a recovery which takes a few years according to the logarithm of lapse time. So far it is not clear what parameter controls the recovery time. To confirm the physical process of the recovery, it is necessary to clarify the depth dependence of temporal changes of shear modulus by a comparison of theoretical spectral ratio of coda waves to observed one. Vertical array of seismometers with pore-pressure measurement will also be useful for this purpose.

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H. Nakahara, T. Nishimura, H. Sato, and K. Sawazaki, Department of Geophysics, Graduate School of Science, Tohoku University, Aramaki-aza-Aoba, Aoba-ku, Sendai 980-8578, Japan. (sawa@zisin.geophys.tohoku.ac.jp)