Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement

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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

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.

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

Figure 1 shows locations of stations and earthquakes used in the present study. Strong motions by the 2000 Western Tottori Earthquake (Mw6.7, 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 (Mw8.3, 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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from 7 km to 149 km for stations TTRH02 and SMNH01, and from 17 km to 504 km for station IBUH03.

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

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. 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.

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

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.

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

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.

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.
The 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 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.

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.

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.

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.

There are no clear seasonal variations in these spectral ratios. From a comparison of the spectral ratio trace...
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 $4.7 \times 10^{-3}$ at TTRH02, $1.4 \times 10^{-3}$ at SMNH01, and $3.0 \times 10^{-3}$ 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.

[17] Acknowledgments. We are grateful to Shin Aoi for helpful suggestions and useful information about the borehole sites. We thank NIED for providing us with the strong motion records of KIK-net. Mare Yamamoto gave us many constructive suggestions. We thank reviewers Gregory C. Beroza and Edoardo Del Pezzo for their helpful comments. All figures were produced by GMT.

References


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1. Land surface evaporation increased during the second half of the 20th century

Evaporation from pans has been decreasing over many areas of the world for the past half century, but the significance of this trend is under debate. Though some speculate that decreases in pan evaporation result from well-documented "global dimming," where less solar irradiance reaches the ground, others hypothesize a complementary relationship between pan evaporation and actual evaporation. For example, in arid climates, terrestrial evaporation is low. However, water in pans left out in this environment can evaporate huge amounts of water. By contrast, water in pans left out in a more humid environment due to increased precipitation will tend to lose less water because of the ambient humidity. Wilfried Brutsaert shows through a mathematical model how lower pan evaporation rates actually indicate higher terrestrial evaporation, in spite of global dimming. Thus, while global dimming had an effect, it was not strong enough to cause a negative trend in evaporation where pan evaporation had been observed to decrease. Based on this, he suggests that the hydrologic cycle is accelerating in those areas.

Title: Indications of increasing land surface evaporation during the second half of the 20th century

Author: Wilfried Brutsaert: School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, U.S.A.


2. Symmetry and stability of the geomagnetic field

The average rate of Earth's geomagnetic reversals has varied enormously, from five reversals per million years during the last 10 to 20 million years to as low as 0.05 reversals every million years between 125 and 84 million years ago. Coe and Glatzmaier analyzed computer simulations of the geodynamo, the process by which magnetic field is produced by the Earth's convecting core. They found that geodynamos that produced highly equatorially symmetric fields were much less stable than those that produced highly asymmetric fields, consistent with earlier studies based on the paleomagnetism recorded by volcanic rocks. Further, a simulation with a solid inner core much smaller than today's produced a very asymmetric field, suggesting that reversals were much less common in the distant geologic past than in the more recent past. Though not definitive, because of the paucity of suitable continuous sections, the authors' review of paleomagnetic results from ancient rocks offers independent support for this conjecture.

Title: Symmetry and stability of the geomagnetic field

Authors:

R. S. Coe and G. A. Glatzmaier: Department of Earth and Planetary Sciences and Institute of Geophysics and Planetary Physics, University of California, Santa Cruz, California, U.S.A.


3. Quantifying lava flows at Arenal volcano, Costa Rica

Arenal, a small stratovolcano in Costa Rica, is currently experiencing activity characterized by continuous lava extrusion, frequent pyroclastic flows, and small ash emissions from its active vents. In 1998 and 2005, NASA's Laser Vegetation Imaging Sensor (LVIS), an airborne laser altimeter system, collected three-dimensional topographic images of the volcano. By recording the shape of reflected laser pulses, LVIS provides views of the vertical structure of Earth's surface, including both ground and canopy-top topographies. Hofton et al. compared data from 1998 with data from 2005 in order to relate changes in ground topography to recent disturbances by lava and pyroclastic flows. By mapping the flows deposited between these years, they found that the active crater grew by about four meters [10 feet] each year. They also estimate that materials extruded by the volcano during this time period reached about 20 million cubic meters700 million cubic feet]. The authors expect that similarly precise elevation change data will be essential to evaluating future hazards and risks at Arenal and other volcanoes.
4. Detailed analyses of the October 2005 Pakistan earthquake

On 8 October 2005, a large earthquake (Magnitude 7.6) shook northern Pakistan, causing more than 80,000 deaths. This earthquake primarily involved thrust motion on a northeast-dipping fault, according to rapid estimates made available a few hours after shaking ceased. Within a few days, Pathier et al. provided a more precise fault location based on synthetic aperture radar data collected from the European Space Agency's Environmental Satellite (ENVISAT). In this paper, the authors present a more extensive analysis of surface deformation, including detailed three-dimensional surface displacement maps of the entire epicentral area and slip distribution inversions to model the earthquake mechanisms. In agreement with other studies, they found that slip occurred shallowly, that the upthrusted segments exhibited some transverse motion, and that the location of rupture initiation or arrest occurred at intersecting faults or other geomorphic features, implying structural control of the slip distribution. The authors expect that similar remote sensing analyses soon after disasters will be critical to directing post-disaster scientific investigations and to relief efforts, because such data can be used to help estimate damage.

Title: Displacement field and slip distribution of the 2005 Kashmir earthquake from SAR imagery

Authors: E. Pathier, T. J. Wright, R. Walker, and B. E. Parsons: Centre for the Observation and Modelling of Earthquakes and Tectonics (COMET), Department of Earth Sciences, University of Oxford, Oxford, United Kingdom;
E. J. Fielding and S. Hensley: Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U.S.A.


5. Surface temperatures in China will increase despite a decrease in insolation

During the latter half of the 20th century, China experienced an increase in surface temperature, despite a decrease in insolation, which is the incoming solar radiation that reaches the surface. Rangwala et al. used observational data and global climate model simulations to examine trends in several climate variables, including surface insolation, surface air temperature, cloud cover, surface vapor and air pressure, and evaporation. Based on the model, the downward trend in insolation is expected to continue as more sulfate pollutants and other manmade aerosols, which scatter incoming solar radiation, are released by industries. However, surface temperatures are nonetheless modeled to increase. The authors suggest that both past and future warming are linked with an increase in downward longwave radiation, which is the radiation directed towards the surface that is emitted by the atmosphere itself. This increase in longwave radiation occurs partly in response to water vapor feedbacks triggered by the increase in manmade greenhouse gases that warm the surface.

Title: Analysis of global climate model experiments to elucidate past and future changes in surface insolation and warming in China

Authors: Imtiaz Rangwala: Department of Environmental Sciences, Rutgers University, New Brunswick, New Jersey, U.S.A.;
Jim Miller: Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey, U.S.A.;
Ming Xu: Department of Ecology, Evolution and Natural Resources, Rutgers University, New Brunswick, New Jersey, U.S.A.

6. Ground frequency recovery after strong earthquakes

Because earthquake shock sometimes decreases the frequency at which the ground vibrates, especially at soft soil sites, the strength of strong ground motion during an earthquake is an important characteristic that can affect the degree to which geological structures and buildings collapse. Although most research focuses on the reduction in peak frequency of site response caused by strong ground motion, Sawazaki, et al. sought instead to document peak frequency recovery following large earthquakes. By analyzing coda waves, which are seismic wave trains generated by energy scattering due to soil and crustal heterogeneities, the authors estimated peak frequency recovery using data from seismometers vertically separated in boreholes at two sites following Japan's 2000 Western Tottori Earthquake, and at a site following the 2003 Tokachi-Oki Earthquake. They find that the peak frequency at relatively solid sites after the Western Tottori Earthquake took a few years to recover to the value before the earthquake, but that the weak site after the Tokachi-Oki earthquake recovered within an hour.

Title: Temporal change in site response caused by earthquake strong motion as revealed from coda spectral ratio measurement

Authors: Kaoru Sawazaki, Haruo Sat, Hisashi Nakahara, and Takeshi Nishimura: Department of Geophysics, Graduate School of Sciences, Tohoku University, Sendai, Japan.


7. Seasonal variations in seismic velocities at Merapi Volcano, Indonesia

Imaging techniques using seismic wave travel times are helpful in determining spatial structure, with applications ranging from medicine to hydrocarbon exploration. However, in cases such as volcano monitoring, temporal changes in seismic wave velocities at the subsurface are also of interest. Sens-Schönfelder and Wegler proposed a technique named Passive Image Interferometry to continuously monitor such changes. In this technique, seismic noise from two permanent seismic stations on the volcano are used to retrieve impulse responses (Green's functions) between the two stations. Using a case study of Indonesia's highly active Merapi volcano, the authors showed that by correlating seismic noise received by two stations, scattered waves from impulse responses could be retrieved. With this information, they inferred seismic velocity variations at Merapi. By tabulating these variations each day, the authors discovered a strong seasonal pattern, which they modeled to result from groundwater-level changes caused by the interplay of precipitation and drainage. This suggests that hydrological factors, rather than internal stress changes, greatly influence the shallow seismic velocity structure of the volcano during periods of volcanic quiescence.

Title: Passive image interferometry and seasonal variations of seismic velocities at Merapi Volcano, Indonesia

Authors: C. Sens-Shönfelder and U. Wegler: Department of Geophysics and Geology, University of Leipzig, Leipzig, Germany.


8. A new technique for measuring turbulence dissipation rates in the ocean

Vertical exchange driven by turbulent mixing is important in determining momentum flux, heat flux, and material transport pathways in the ocean. A recent development in the measurement by Doppler acoustics of the rate of production of turbulent kinetic energy has improved understanding of vertical exchange processes, but is limited in spatial scales and requires an accurately vertical sensor platform. To overcome these limitations, Wiles et al. developed a new technique for measuring turbulent kinetic energy dissipation in the ocean by adapting methods from radar meteorology used to measure turbulence in the atmosphere. Using a standard acoustic Doppler current profiler, a type of sonar that records water current velocities over a range of depths, the authors related spatial correlations in velocity to turbulent kinetic energy dissipation rates. They then compared their estimates with estimates collected using more widely-used, but labor intensive, methods, and found good agreement. Advantages to their technique include its ability to provide long-term continuous time series of dissipation profiles, and that it can be used from a moving platform.

Title: A novel technique for measuring the rate of turbulent dissipation in the marine environment

Authors: Philip J. Wiles, Tom P. Rippeth, and John H. Simpson: School of Ocean Sciences, University of Wales Bangor, Menai Bridge, Anglesley, United Kingdom; Peter J. Hendricks: Naval Undersea Warfare Center, Newport, Rhode Island, U.S.A.

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