

Identification of Nonlinear Site Response Using the H/V Spectral Ratio Method

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ABSTRACT

The horizontal-to-vertical spectral ratio has become increasingly popular in studies of site effect and determination of the predominant period of a site. In this study, this method is extended to identify nonlinear soil responses. To establish this phenomenon, borehole array records that already showed nonlinear site responses using spectral ratios between surface and borehole station pairs were analyzed. Moreover, in this study, the horizontal-to-vertical spectral ratio method was applied to weak and strong motion records from the same dataset. The results demonstrate that nonlinear site responses can be evaluated using horizontal-to-vertical spectral ratios of surface recordings at a single station.

(Key words: Horizontal-to-vertical spectral ratio, Nonlinear site effect, Borehole array)

1. INTRODUCTION

Nonlinear site effects, such as increases in damping and reduction in shear wave velocity as input strength increases, are commonly observed in the dynamic loading of soils using geotechnical models. In recent years, mounting evidence indicates that nonlinear site effects in strong-motion seismology are more common than previously assumed (Beresnev and Wen 1996). Direct seismological evidence of nonlinear site effects was reported using spectral ratio techniques for two-station pairs, including soil-to-rock and surface-to-borehole station pairs (Wen 1994; Wen et al. 1994).

In recent years, several large earthquakes were recorded by modern digital surface and vertical arrays. Borehole data ensure reliable assessment of the soil transfer function. Obser-

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variations in different parts of the world already provide direct evidence of the significance of nonlinear site effects. Using the spectral ratio method, Wen et al. (1995) demonstrated strong motion records of LSST array in Taiwan. (Wen et al. 1986) represented nonlinear site response; however, the SMART2 array in Taiwan (Chiu et al. 1994) did not register this effect. By comparing spectral ratios from surface- and borehole-station records in Port Island, Japan, Aguirre and Irikura (1997) demonstrated the presence of the nonlinearity effect during the 1995 Hyogo-ken Nanbu earthquake.

Spectral ratio of a two-station pair involves analyzing the near-surface amplification, calculated from data records of soil and rock or surface and borehole instruments. The amplification function is controlled by the wave velocity and damping in the soil layer between the two stations. Amplification function becoming amplitude dependent (difference between weak and strong motions) is an indication of nonlinearity (EPRI 1993; Beresnev and Wen 1996). However, the horizontal-to-vertical (H/V) spectral ratio for a single surface station can be used to identify subsurface structure by the receiver function method (Phinney 1964; Langston 1979; Ammon et al. 1990). When nonlinearity occurs in the soil layer under the station, the H/V ratio should be adjusted according to changes in the site condition. So, we can expect the H/V ratio to indicate difference between weak and strong motions.

Results derived by two-station pair spectral ratio analysis can be applied to evaluate nonlinearity in a specific local area. When a destructive earthquake occurs, a high level of ground motion or liquefaction ground failure often occurs over a large region. In most instances, however, the borehole array is lacking, rendering the two-station pair spectral ratio method inapplicable. In this study, the horizontal-to-vertical (H/V) spectral ratio for a single surface station is introduced to identify nonlinear site response. In order to demonstrate the applicability of the technique, borehole-array data already used to show nonlinear site response are utilized.

2. H/V SPECTRAL RATIO METHOD

Kagami et al. (1982, 1986) proposed that the ratio of the horizontal components of velocity spectra at the sediment site to those at the rock site serve as an indication of microseism ground motion amplification. This proposition assumed a common source and similar paths for sediment and bedrock sites. Nakamura (1989) hypothesized that microtremor site effects can be determined by evaluating the spectral ratio of horizontal versus vertical components of motion observed at the same site. Field and Jacob (1993) and Theodulidis et al. (1996) showed that H/V spectral ratio can be applied to earthquake data records to study site response. Site response estimations analyzed by the H/V spectral ratio and other methods were compared and evaluated by Field and Jacob (1995), Bonilla et al. (1997), Riepl et al. (1998), and Huang and Teng (1999).

In this study, data used by Wen et al. (1995) and Aguirre and Irikura (1997) to demonstrate nonlinear soil response by two-station (surface and borehole) spectral ratio analysis were utilized. The horizontal-to-vertical spectral ratios were calculated from the same earthquake data, and then spectral ratios between strong and weak motion events were compared with the aim of evaluating nonlinear site response during an earthquake.

3. IDENTIFICATION OF NONLINEAR SITE RESPONSE

3.1 Borehole Arrays in Taiwan

As mentioned, the dataset of Wen et al. (1995) was selected for this study. Table 1 gives the LSST array data, including 11 weak motion events with peak ground acceleration (PGA) less than 60 gal and 3 strong motion events with PGA greater than 150 gal; Table 2 presents data for the SMART2 array. For the present study, 8 weak motion events with PGA less than 20 gal and 3 strong motion events with PGA greater than 100 gal were selected. Wen et al. (1995) showed that these three strong motion events recorded by the LSST array had nonlinear soil response, whereas the SMART2 array did not, due to the firm soil site conditions.

Table 1. Selected LSST events. (same data as Wen et al. 1995)

Event	Date	Depth (km)	M_L	Δ (km)	PGA* (gal)
Weak motion					
3	07/11/85	74	5.5	17	27.3
5	29/03/86	10	4.7	8	41.4
6	08/04/86	11	5.4	31	35.4
8	20/05/86	22	6.2	69	35.0
14	30/07/86	2	4.9	5	57.5
20	10/12/86	98	5.8	42	23.8
21	06/01/87	28	6.2	77	31.8
22	04/02/87	70	5.8	16	43.4
23	24/06/87	31	5.7	52	31.7
24	27/06/87	1	5.3	40	23.7
27	18/09/88	63	5.6	68	22.3
Strong motion					
7	20/05/86	16	6.5	66	223.6
12	30/07/86	2	6.2	5	186.7
16	14/11/86	7	7.0	78	167.2
Foreshock to event 12					
9	11/07/86	1	4.5	5	72.8
10	16/07/86	1	4.5	6	70.0

Note: PGA* is peak ground acceleration recorded at the free surface.
 Δ is the epicenter distance.

Table 2. Selected SMART2 events. (same data as Wen et al. 1995)

Event	Date	Depth (km)	M_L	R (km)	PGA* (gal)
Weak motion					
176	21/05/92	16.7	4.5	38.4	15.4
185	30/06/92	28.6	4.5	33.9	17.5
189	23/07/92	12.8	4.5	31.1	15.3
198	09/10/92	15.9	4.1	24.1	16.5
222	04/05/93	1.0	4.0	5.8	17.5
231	24/06/93	65.0	5.2	87.4	12.0
234	25/06/93	4.6	3.9	12.2	17.5
235	26/06/93	6.7	3.6	11.6	17.0
Strong motion					
183	25/06/92	22.7	4.5	24.2	160.2
192	14/08/92	15.7	4.5	26.3	135.9
202	28/12/92	16.2	4.9	32.4	154.4

Note: PGA* is peak ground acceleration recorded at the free surface.
R is the hypocenter distance.

Figure 1a shows the spectral ratio of the surface to 11-m depth borehole station for the LSST array. Wen et al. (1995) obtained the same results. A 10-sec S-wave portion was selected, and the spectral ratio was calculated between surface and borehole stations. Each ratio was then smoothed 5 times using the 3-point average method for weightings of 1/4, 1/2, and 1/4. The three strong motion events showed nonlinear soil response after comparison of the spectral ratios between the surface and borehole stations and that of the weak motion events. The results were in agreement with those of Wen et al. (1995). Figure 1b shows the H/V spectral ratios of the surface station for the same events. Figure 1b also indicates the dominant frequency shift to lower frequency and lower ratio level for the strong motion events in a frequency range from ~2 to 10 Hz, as is exhibited in Fig. 1a.

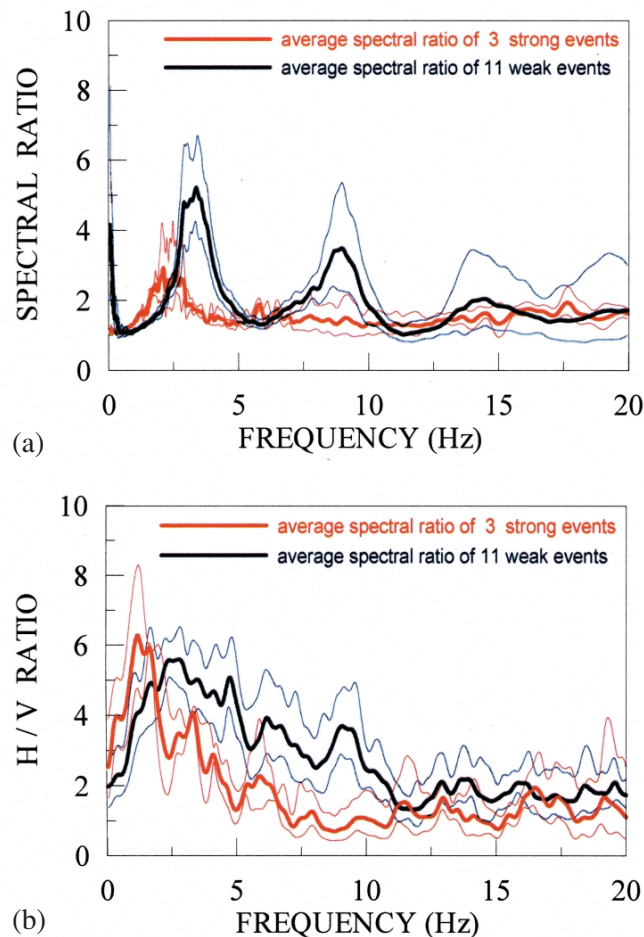


Fig. 1. (a) Strong and weak motion spectral ratios of surface to 11-m deep borehole station for the LSST array. (b) H/V spectral ratio for strong events (red line) and weak events (black line) for the same data used in (a). Thick line is the mean value and thin lines show the one standard deviation range. Red lines for strong motions and blue lines for weak motions.

The comparison for a main- and after-shock pair from the 20 May 1986 earthquake sequence and for the foreshock-mainshock-aftershock sequence on 30 July 1986 are shown in Figs. 2 and 3, respectively. Again, the H/V spectral ratios indicate dominant frequency shift and lower ratio level for mainshock ratios (Figs. 2b, 3b), which is comparable to the spectral ratio results for data from surface to an 11-m depth (Figs. 2a, 3a).

The surface to 200-m borehole depth spectral ratio for the SMART2 array was calculated by the same procedure. This array was situated in the Hualien gravel layer area; the results

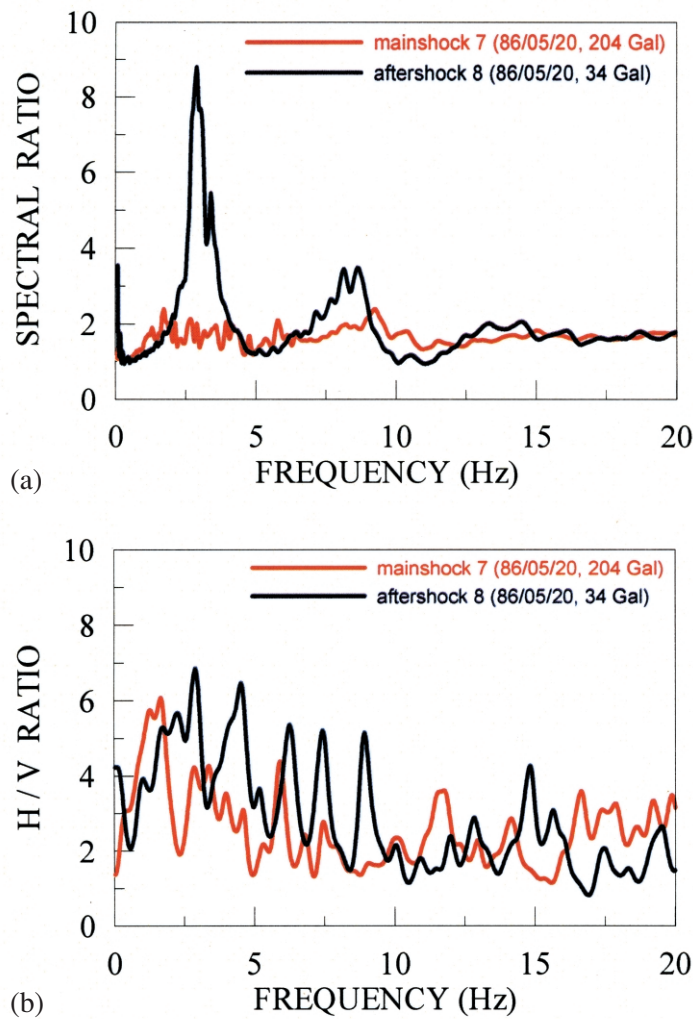


Fig. 2. (a) Spectral ratios of surface to 11-m deep borehole station for a mainshock and aftershock pair of 20 May 1986 earthquake recorded by the LSST array. (b) H/V spectral ratios for mainshock and aftershock (black line) for the same events in Fig. 2a. Red and blue lines are the ratios of the mainshock and aftershock, respectively.

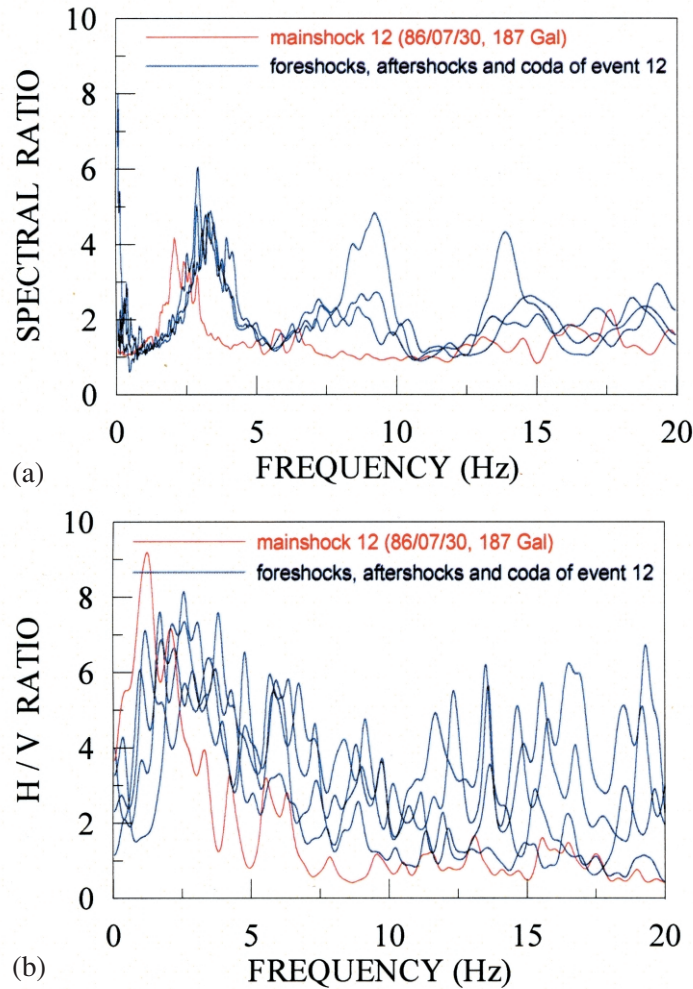


Fig. 3. Spectral ratios for foreshock, mainshock, aftershock sequence of 30 July 1986 earthquake recorded by the LSST array. Mainshock shows in red line and weak motions in blue lines. (a) Spectral ratios of surface to 11-m deep borehole station; (b) H/V spectral ratios of the surface station.

indicate that the strong motion events did not have nonlinear effects in this firm soil site (Fig. 4a) because the error bars overlap. Figure 4b shows the same characteristics for the H/V spectral ratio from the same dataset.

These comparisons confirm that nonlinear soil responses occurring in the LSST array can be identified using the H/V spectral ratio method. For the SMART2 array, both methods show linear response.

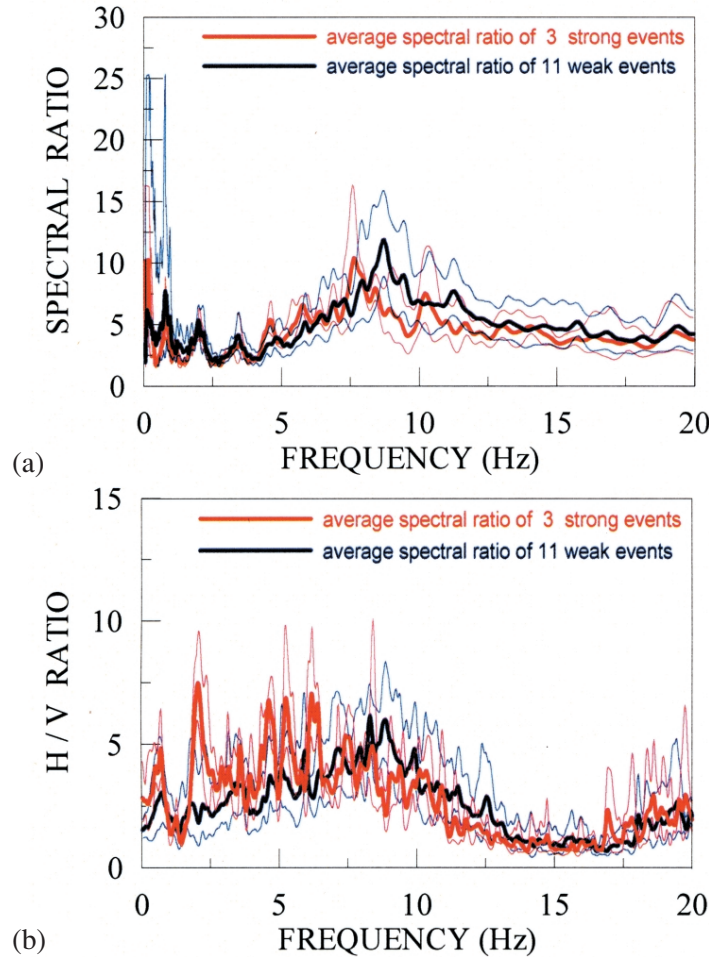


Fig. 4. (a) Strong and weak motion spectral ratios of surface to 200-m deep borehole station for the SMART2 array. Shaded areas show one standard deviation range. (b) H/V spectral ratio for strong events (red line) and weak events (blue line) for the same data used in (a). Thick line is the mean value and thin lines show the one standard deviation range.

3.2 Port Island Array in Japan

During the 1995 Hyogo-ken Nanbu earthquake, a large portion of Port Island was subject to liquefaction damage. Aguirre and Irikura (1997) compared the spectral ratios between the records at surface and borehole stations in Port Island and found a large variation in the spectral ratios during strong ground motions and the liquefied state. The nonlinearity effect occurred during the 1995 Hyogo-ken Nanbu earthquake. In the following, the horizontal-to-vertical spectral ratio method is applied to the data records from the surface station of the

borehole array in Port Island to evaluate nonlinear site response.

Table 3 lists a portion of the data used by Aguirre and Irikura (1997). The waveform of ground motion recorded at the free surface during the 1995 Hyogo-ken Nanbu earthquake is shown in Fig. 5, which also plots the time windows (MpI, MpII, A - H) used by Aguirre and Irikura (1997). A time window of 10.24 sec (other windows MpI, B, and F are 5.12 sec) was selected to calculate the spectral ratio by the same smoothing method. The spectral ratio between the surface (PR4) and 16-m depth (PR3) for the 5 small events before the mainshock was calculated to serve as the referent weak motion ratio. The results indicate that strong nonlinear soil responses occurred in the strong ground motion window (MPI) and liquefied state windows (after MPII windows) (Fig. 6a). The 0858 aftershock shows not-so-strong nonlinear effect compared to the results for the mainshock. Aguirre and Irikura (1997) reported the same results. The H/V ratios for the time windows in Fig. 5 were calculated and compared to the average H/V ratio of the weak motions. Figure 6b plots the H/V ratios of the mainshock record for various time windows (red line) and compares this with the average H/V ratio for the weak motions of the 5 small events (black line). The area in yellow shows a one standard deviation range for the weak motion ratios. The H/V ratios in different time windows are clearly lower than the referent weak motion ratio in the larger frequency band. Nonlinear soil response occurred in the mainshock record of the 1995 Hyogo-ken Nanbu earthquake during the strong ground motions and the liquefied state. The H/V ratio of the 0858 aftershock in Fig. 6a shows similar results for the spectral ratio of surface to borehole station pair. The results in Fig. 6b are comparable with the results for the spectral ratios between the surface and borehole records of Fig. 6a and those of Aguirre and Irikura (1997). Although the peak ground acceleration of the 0858 aftershock was less than 50 gal (Table 3), the spectral ratio of the 0858 aftershock ~24 hrs later was nonlinear and still not back to about the same ratio as that of the reference motions. This was due to liquefaction in the Port Island area. Site conditions had already changed, as explained by Aguirre and Irikura (1997).

Table 3. Selected events recorded by the downhole array in Port Island, Japan.

Date	Time	Depth (km)	M _L	Δ (km)	PGA* (gal)
28/06/94	13:08:53.02	16.0	4.6	65.4	5.66
28/07/94	10:01:52.04	11.5	4.1	40.3	7.92
24/10/94	11:51:10.72	15.1	4.3	45.6	11.56
09/11/94	20:26:56.41	10.4	4.1	32.6	5.58
10/11/94	00:38:17.72	11.1	3.9	32.1	6.98
17/01/95	05:46:46.74	16.0	6.9	17.7	555.00
17/01/95	08:58:16.14	18.8	4.7	15.1	43.75

Note: PGA* is peak ground acceleration recorded at the free surface.

This analysis shows that the H/V ratio method can be successfully applied to the data records of the Port Island borehole array to study nonlinear soil response during the 1995 Hyogo-ken Nanbu earthquake. The results are comparable with those obtained by spectral ratio analysis using the surface-borehole station pair (Aguirre and Irikura 1997).

4. CONCLUSIONS AND DISCUSSIONS

In recent years, nonlinear site effects were shown to be more common than previously assumed for strong-motion seismology. Direct seismological evidence of nonlinear site effects were observed using spectral ratio techniques. In recent years, several large earthquakes have been recorded by modern digital surface and vertical arrays. Borehole data ensure reliable assessment of soil transfer function. Observations in different parts of the world already provide direct evidence of the significance of nonlinear site effects. But, the borehole array is not available in most areas, and the results analyzed from borehole array data are applicable only to site response in that area. In this study, the horizontal-to-vertical spectral ratio (H/V spectral ratio) method was introduced to identify nonlinear site response. The data from LSST and Port Island's borehole arrays, already shown to have nonlinear site responses by previous spectral ratio analyses between surface and borehole station pairs, are here used to show the applicability of H/V technique for nonlinear site response identification.

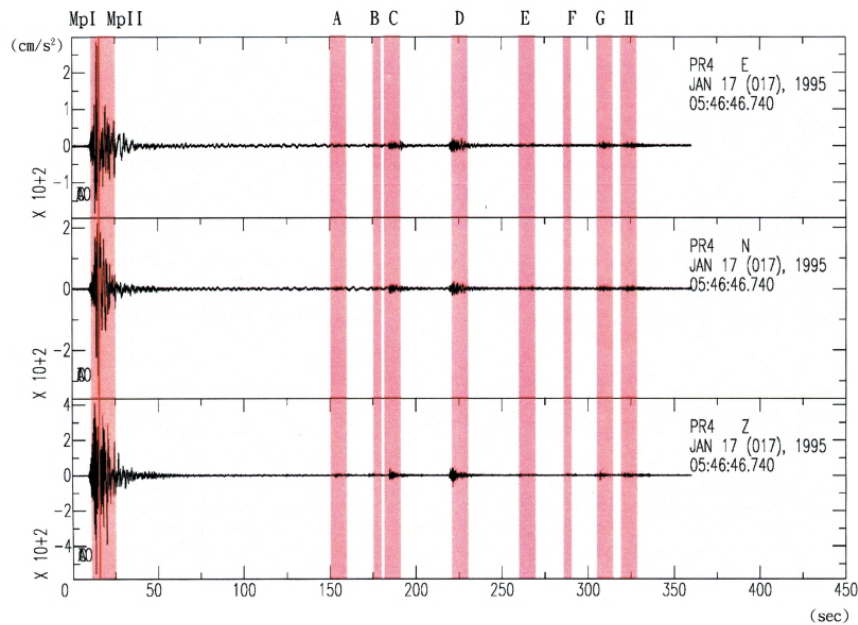
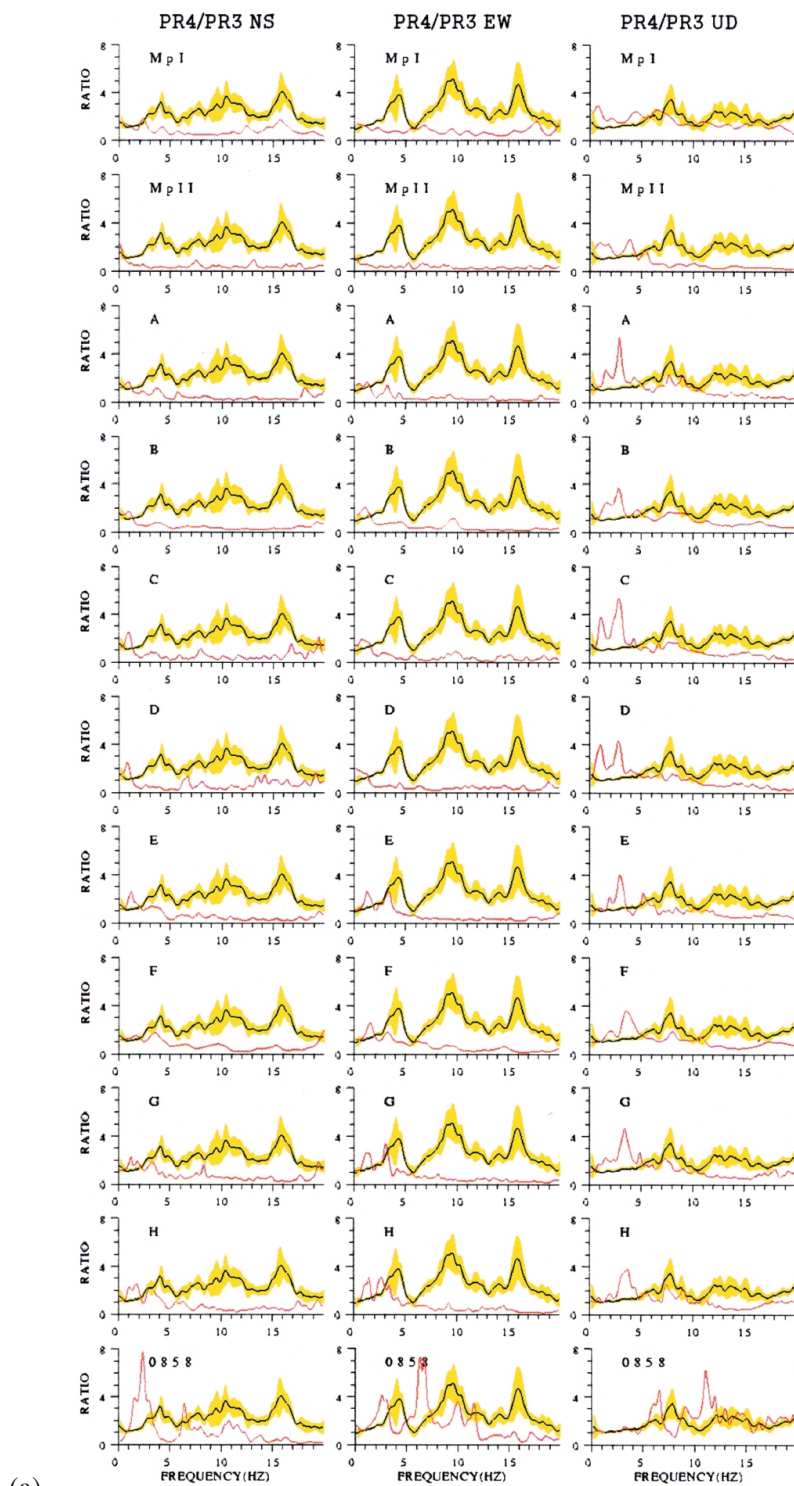


Fig. 5. The waveform recorded at free surface in Port Island, Japan during the 1995 Hyogo-ken Nanbu earthquake. Windows MpI, MpII, and A to H are the same as those used by Aguirre and Irikura (1997).



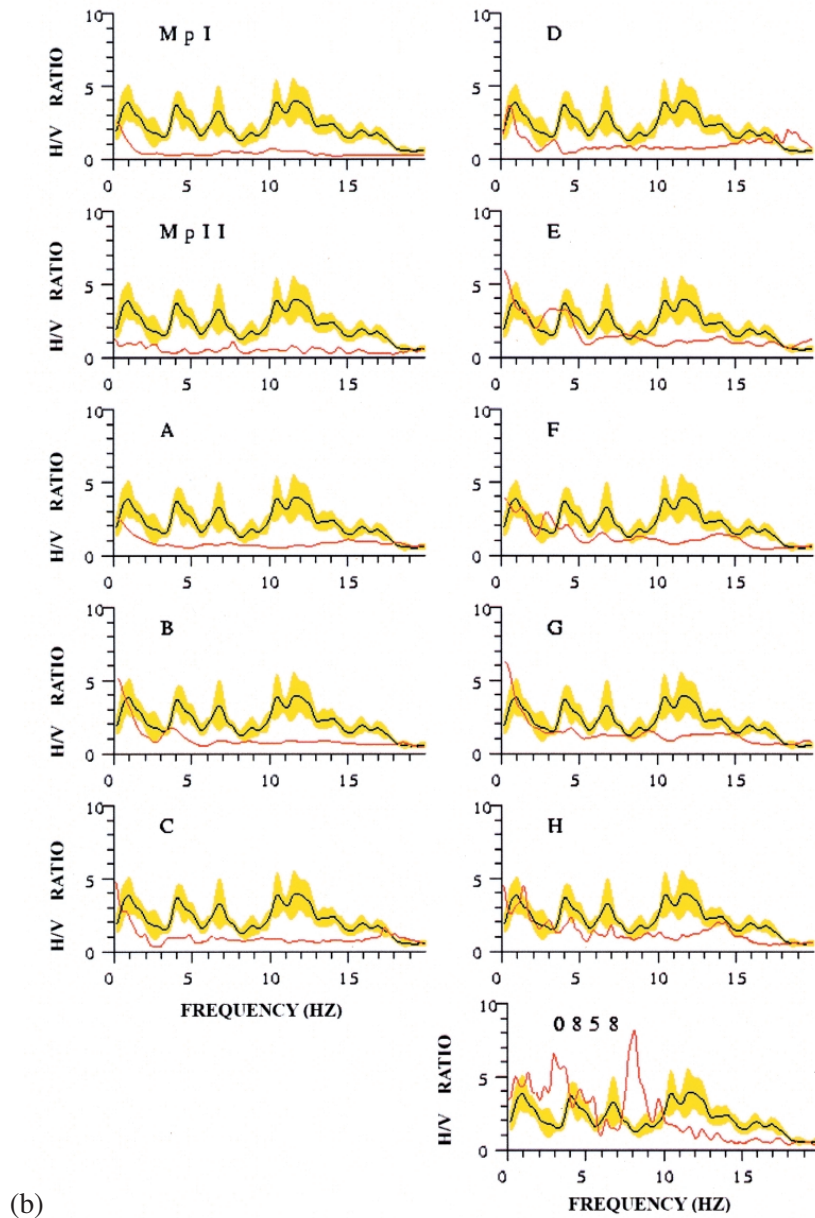


Fig. 6. Spectral ratios in the different time windows calculated from the mainshock and one aftershock of the 1995 Hyogo-ken Nanbu earthquake (red line). Time windows are the same as those in Fig. 5. Black line is the mean ratio of the weak motions before the Kobe mainshock and yellow area shows the one standard deviation area; (a) The results of surface to a 16-m deep borehole station pair are given and are the same as those of Aguirre and Irikura (1997). (b) The results of H/V ratios from the surface station.

Many studies indicate shear-wave nonlinearity calculated from horizontal records of surface to downhole seismometers, between weak and strong motions (Beresnev and Wen 1996). Beresnev et al. (2002) analyzed the data from KiK-net borehole arrays in Japan (<http://www.kik.bosai.go.jp>) and found nonlinearity in P waves observed at acceleration levels exceeding roughly 0.1 g. This is similar to observations for S waves. The spectral ratios of the vertical component in Fig. 6a also indicate that nonlinearity occurred in vertical motions, as observed by Beresnev et al. (2002).

As most data show that peak ground acceleration in vertical component usually is less than in horizontal component, we expect that nonlinear soil response in horizontal component is stronger than that in vertical component. PGA data recorded during the 1995 Hyogo-ken Nanbu earthquake in Port Island's borehole array show that the horizontal PGA at the depth of 16 m and ground surface were less than that recorded at the vertical component (Fig. 7). This result indicates that the H/V spectral ratio method can be applied to identify the nonlinear soil response.

This study demonstrates that the H/V technique can be used to identify nonlinearity of site response after a strong event. For the many areas that lack borehole arrays to check spectral ratios between surface-borehole station pairs, the horizontal-to-vertical technique can be used to study site response characteristics during strong earthquakes.

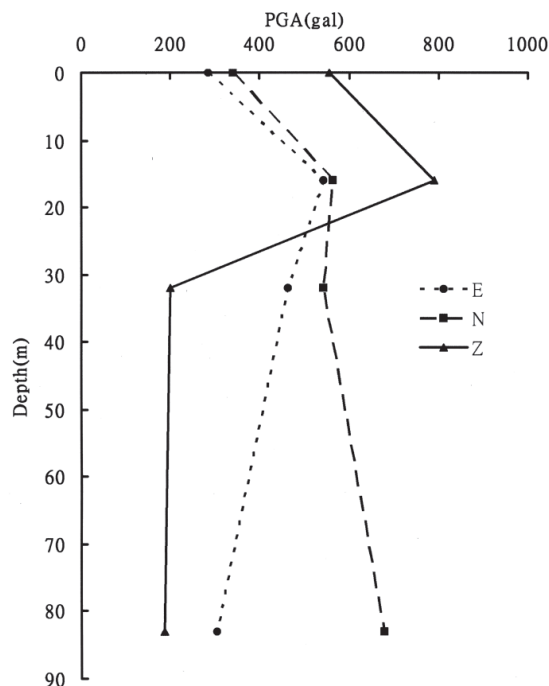


Fig. 7. Peak ground accelerations recorded in the three components of the borehole array in the Port Island during the 1995 Hyogo-ken Nanbu earthquake.

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