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Why 1*G* Was Recorded at TCU129 Site During the 1999 Chi-Chi, Taiwan, Earthquake

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Abstract The strong-motion station TCU129 recorded a peak horizontal acceleration higher than 1*g* during the 1999 Chi-Chi, Taiwan, earthquake. Yet no structural damages occurred in its vicinity. Even some old buildings not far away from the station were not damaged. There did not seem to be very strong ground motion in this area during the Chi-Chi earthquake. To resolve these conflicting phenomena, we performed microtremor surveys in this area and installed additional two strong-motion accelerographs inside station TCU129 to compare the ground-motion records between the original and new accelerographs. We also compared the ground accelerations between station TCU129 and a nearby station TCU076. The results indicate that the high peak acceleration recorded at TCU129 during the 1999 Chi-Chi, Taiwan, earthquake was due to the effects of the concrete recording pier at station TCU129, and not due to the source, path, or site effects of the earthquake. Therefore, the peak acceleration values recorded at station TCU129 should not be used in studies of peak acceleration attenuation. However, the records are still useful, especially the integrated velocity and displacement time histories, for other studies.

Introduction

On 20 September 1999 a magnitude M_w 7.6 earthquake struck the Taichung and Nantou areas in central Taiwan. The earthquake occurred shortly after midnight (21 September 01:47 a.m. local time) when most residents were home sleeping. The official report from the Seismology Center of the Central Weather Bureau (CWB) put its epicenter at 23.85° N, 120.82° E, and its focal depth at 8 km. Since 1991, the CWB installed a very dense free-field strong-motion network in the nine metropolitan areas in Taiwan (Taiwan Strong Motion Instrumentation Program [TSMIP] network) (Kuo *et al.,* 1995; Wen *et al.,* 1995; Liu *et al.,* 1999). Therefore, a lot of high-quality data were recorded during the 1999 Chi-Chi event. Figure 1 shows the TSMIP station distribution in central Taiwan.

The TCU129 station is located in Hsin-Chieh elementary school, which is on the footwall near the Chelungpu fault rupture zone. This strong-motion station recorded a horizontal peak acceleration higher than 1*g* during the 1999 Chi-Chi, Taiwan, earthquake. Figure 2 shown the three-component acceleration waveforms recorded at station TCU129 and the nearby station TCU076 during the Chi-Chi earthquake. Waveforms at station TCU129 show that high peak values occurred in impulsive spikes. After visiting the areas surrounding station TCU129, we found that no structural damage occurred in the area. Even a very old building, which is constructed of adobe blocks and not far away from the station, was undamaged by this destructive earthquake. It does not seem to indicate the occurrence of very strong ground motion in this area during the 1999 Chi-Chi earthquake. If this was the case, why was a horizontal peak acceleration higher than 1*g* recorded at station TCU129 during the Chi-Chi earthquake? The first causes to be considered are source, path, or site effects like other earthquake records (Shakal *et al.,* 1996). In this study, we compared the ground-motion records between TCU129 and the nearby station TCU076 about 3.4 km away. We also made microtremor surveys to check the site effects at station TCU129. Furthermore, two accelerographs were added inside station TCU129 to study the effects of recording pier on the recorded motions. Through these investigations we hope to understand why the station generated a horizontal peak acceleration larger than 1*g* during the 1999 Chi-Chi, Taiwan, earthquake.

Site Conditions at Station TCU129

The strong-motion accelerograph station TCU129 is located in the Hsin-Chieh elementary school at Ming-Chien, Nantou. It is on the footwall of the Chelungpu fault and about 1.9 km away from the fault trace. This station is not a typical TSMIP free-field station. It is a real-time station that

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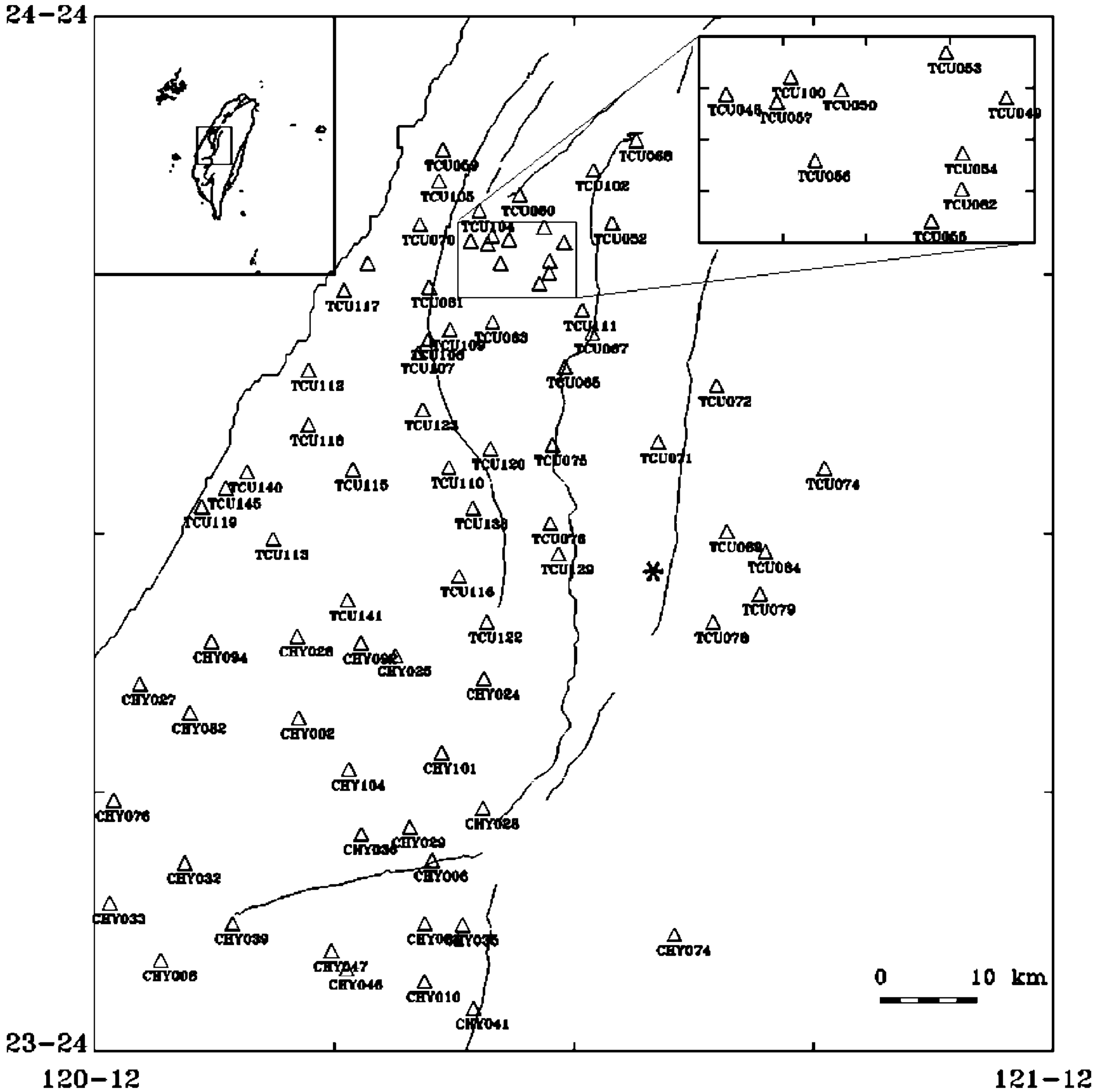

Figure 1. Station distribution of the TSMIP network in central Taiwan. The asterisk (*) shows the location of epicenter.

is connected through a phone line to the CWB headquarters as a station of the Central Weather Bureau Seismic Network (CWBSN) (Shin, 1993). It was originally a telemetered, digital, short-period seismographic station. In May 1997 a telemetered digital accelerograph was placed at every CWBSN short-period seismograph site to form the Taiwan Rapid Earthquake Information Release System (TREIRS) (Wu *et al.,* 1997). In all, the instruments in station TCU129 include (1) an A900 accelerograph of the TSMIP network, (2) an A800 accelerograph of TREIRS, and (3) an S13 velocity type sensor of the CWBSN. So, the station building is much larger than that of a typical TSMIP station. Figure 3 shows the design of both kinds of recording enclosures. A schematic diagram of the station building for station TCU129 is shown in Figure 3b. When compared to the structure of a typical TSMIP free-field station in Figure 3a, the biggest difference is that station TCU129 has a square concrete pier that is more than 3 m deep. The accelerometers are mounted on the pier. The gap between the pier and floor is around 5 cm. Polymer is filled in the gap to prevent knockings between the pier and the floor. A thin gravel layer was laid under the station building. The topography surrounding station TCU129 is shown in Figure 4. The station TCU129 was located near a steep bank. The elevation of the floor of recording room is about 2.5 m higher than the nearby private houses. Considering these conditions, the topography, local soil layer under the recording building, and the large recording pier may all have influenced the ground motion recorded at station TCU129, in addition to the source and path effects.

Analysis of Source and Path Effects

To examine whether the source and path effects can cause the 1*g* ground motion at TCU129 or not, pairs of re-

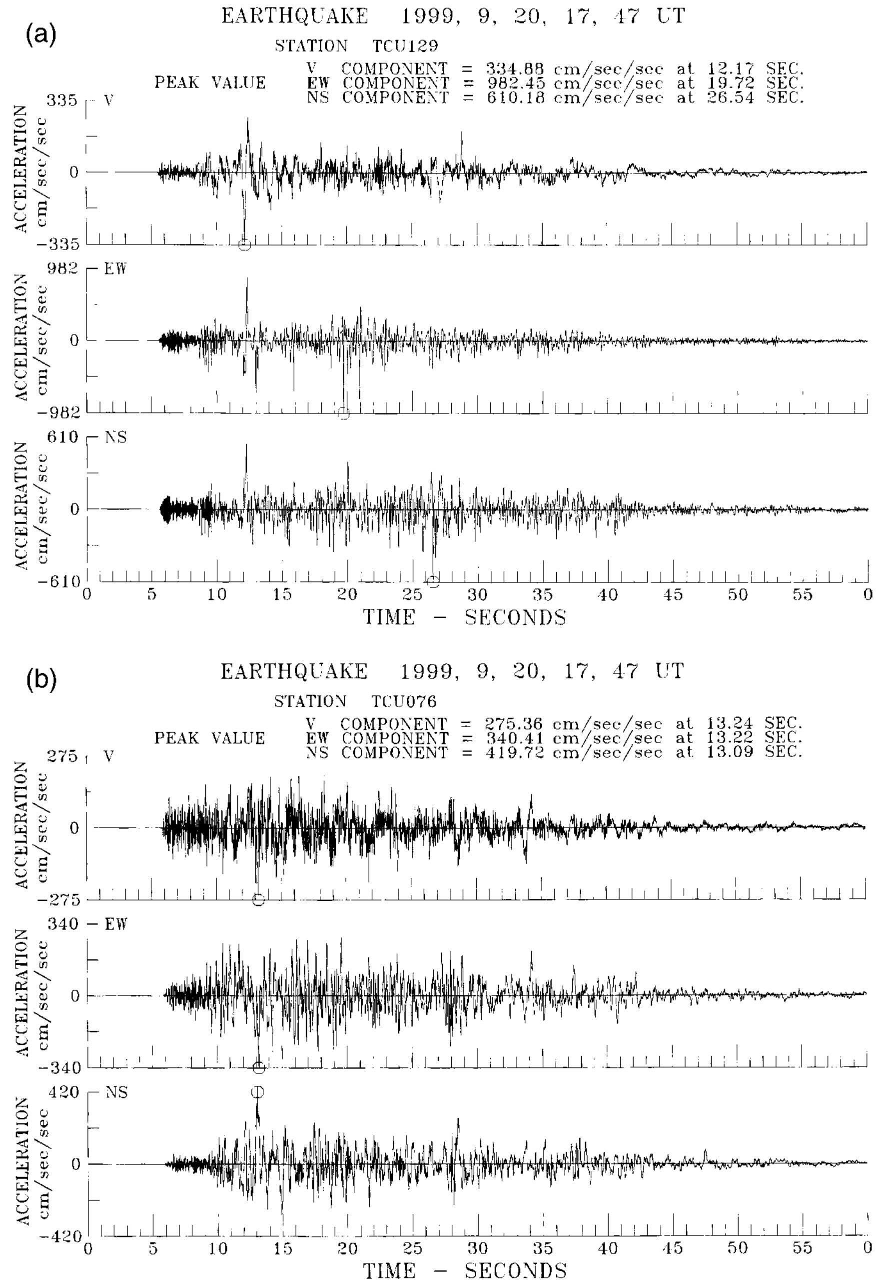

Figure 2. Three-component accelerograms recorded at (a) station TCU129 and (b) the nearby station TCU076, about 3.4 km away, during the 1999 Chi-Chi, Taiwan, earthquake. Peak values: (a) V component = 334.88 cm/sec^2 at 12.17 sec; E–W component = 982.45 cm/sec^2 at 19.72 sec; N–S component = 610.18 cm/sec^2 at 26.54 sec; (b) V component = 275.36 cm/sec^2 at 13.24 sec; E–W component = 340.41 cm/sec^2 at 13.22 sec; N–S component = 419.72 cm/sec^2 at 13.09 sec.

cords at station TCU129 and a nearby station TCU076 (Fig. 1) from the same earthquakes were compared to study the effects of source and path. Only records at epicentral distances larger than 20 km were selected. A total of 11 events were selected, from 1993 to 1998. The event parameters and peak ground acceleration (PGA) values are listed in Tables 1 and 2. The epicenter and station locations are plotted in Figure 5. Correlation between the PGA values recorded at TCU129 and TCU076 is plotted in Figure 6. It clearly shows that stations TCU129 and TCU076 had the same PGA values when the PGA was less than about 15 gal. Above this level the PGA values at TCU129 were larger than that at TCU076 for the horizontal components, especially in the N–S component. Ground motions in the vertical component were not so large, less than 15 gal, and did not show large differences. The 1*g* PGA recorded at station TCU129 was larger than that

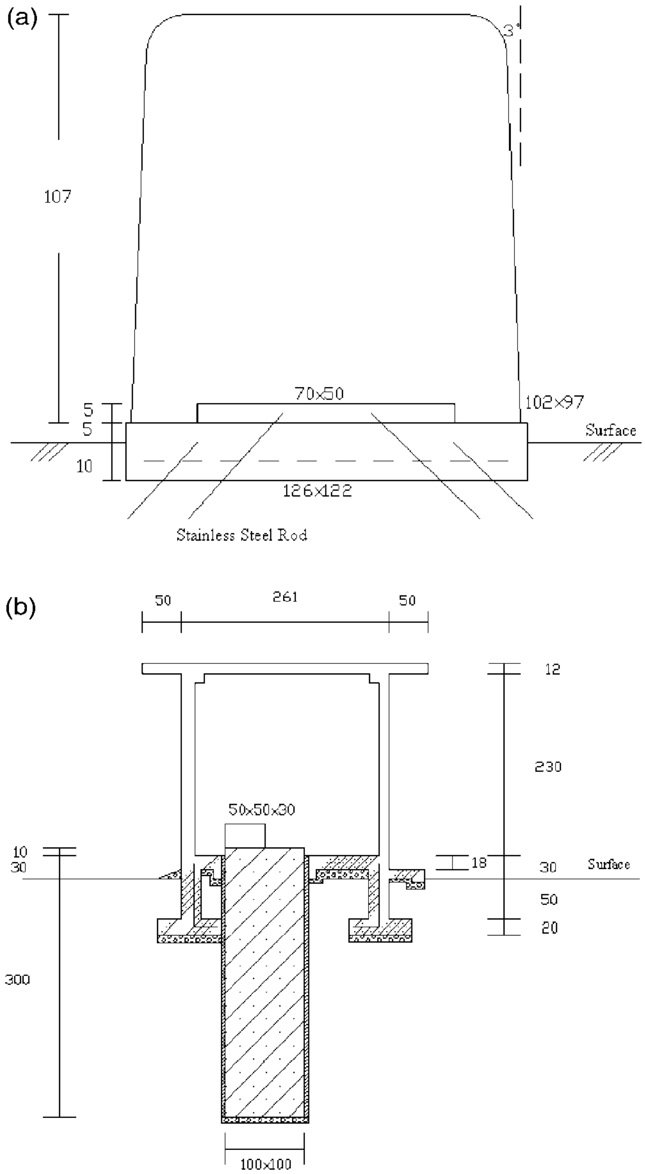

Figure 3. Schematic diagram of (a) the recording enclosure of a typical TSMIP free-field station (units in cm); (b) a typical station structure of the CWBSN network, one of which is TCU129 (units in cm).

Figure 4. Photo shows the topography next to station TCU129.

Table 1
Earthquakes Recorded by Both the TCU129 and TCU076 Stations

Event No.	Date (yyyy/mm/dd)	Time (hr:min:sec)	Lat.	Lon.	Depth (km)	M_L	Δ* (km)
1	1993/12/15	21:49:43.10	23° 12.80′	120° 31.42′	13	5.7	76
2	1994/05/24	04:00:40.49	23° 49.60′	122° 36.20′	4	6.2	196
3	1994/09/16	06:20:15.62	22° 25.58′	118° 28.01′	19	6.4	278
4	1994/10/05	01:13:24.47	23° 09.38′	121° 43.22′	31	5.8	133
5	1995/02/23	05:19:02.78	24° 12.22′	121° 41.22′	22	5.8	108
6	1996/07/29	20:20:53.53	24° 29.33′	122° 20.82′	66	6.1	182
7	1997/05/02	21:30:23.58	24° 11.15′	120° 10.74′	23	4.5	62
8	1997/07/15	11:53:33.39	24° 37.30′	122° 30.95′	87	6.1	203
9	1998/05/01	17:22:32.72	24° 12.20′	120° 09.96′	17	4.4	64
10	1998/05/03	23:30:16.64	22° 13.26′	125° 37.60′	61	7.0	539
11	1998/07/17	04:51:14.96	23° 30.16′	120° 39.75′	3	6.2	42

*Epicentral distances referred to the station TCU129.

at TCU076 (0.43*g*) during the Chi-Chi earthquake. This large difference in PGA probably was not due to source and path effects. Actually, this phenomenon has already been shown in many records before the 1999 Chi-Chi earthquake. Next we examine whether the site effects at TCU129 can cause the observed high PGA value.

Analysis of Site Effects

Since station TCU129 is located near a steep bank, one possible factor that can cause large amplification of ground motion is local site effects. Recently, microtremor measurements were made at station TCU129 and in the nearby areas after the Chi-Chi earthquake in order to understand the site response at TCU129. Figure 7 presents a sketch map that shows the microtremor survey points. The elevations of the survey points TCU129-3 and TCU129-4 are the same.

Table 2
PGA Values Recorded at TCU129 and TCU076 for the Earthquakes Listed in Table 1.

	TCU129 PGA (gal)			TCU076 PGA (gal)		
Event No.	V	E–W	N–S	V	E–W	N–S
1	6.30	11.08	12.17	4.39	8.68	7.80
2	3.20	8.24	5.49	2.41	6.47	4.33
3	5.77	9.38	9.23	3.19	7.74	7.36
4	14.18	37.35	30.69	10.59	19.63	17.34
5	6.18	10.40	14.95	9.61	12.46	13.24
6	2.84	14.52	22.85	5.21	17.05	10.07
7	1.42	9.76	8.11	2.79	6.80	3.54
8	1.71	4.59	6.21	2.85	5.70	6.09
9	1.46	10.07	5.28	1.74	5.66	3.25
10	3.26	4.50	10.21	2.77	6.49	6.27
11	10.39	51.14	50.81	10.85	20.89	18.38

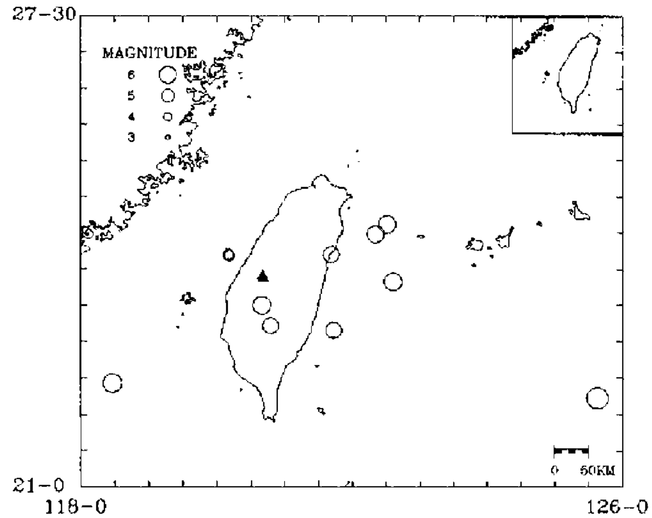

Figure 5. Epicenter distribution of the earthquakes listed in Table 1.

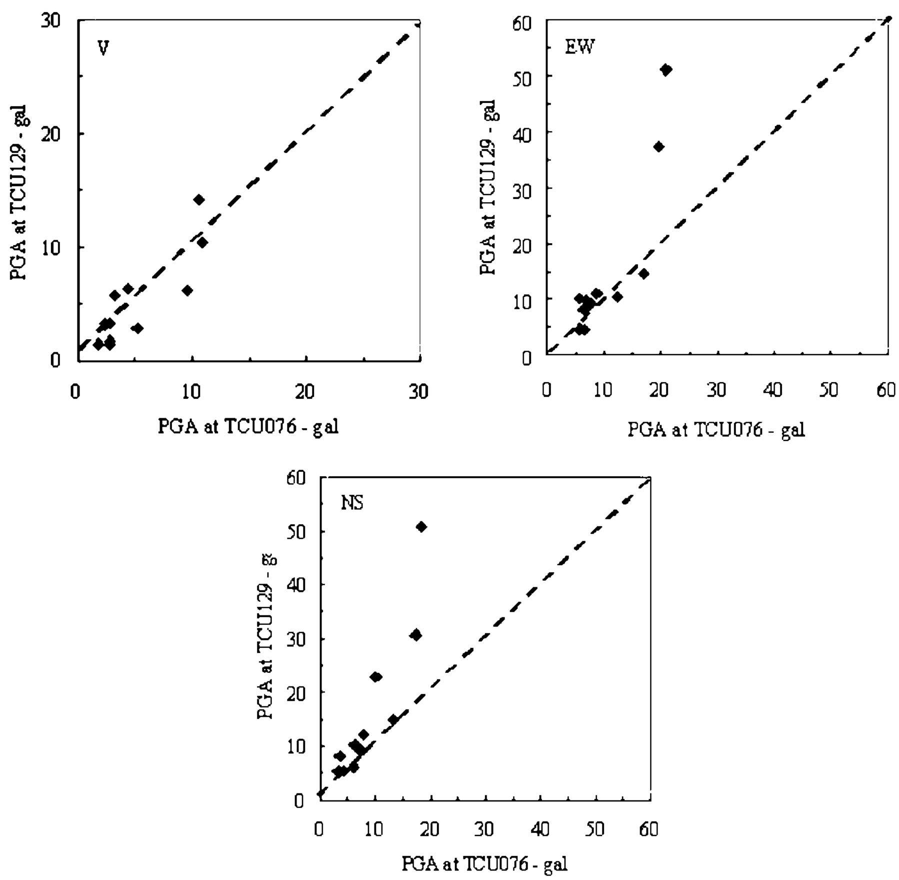

Figure 6. Correlation between the PGA values recorded at stations TCU129 and nearby TCU076.

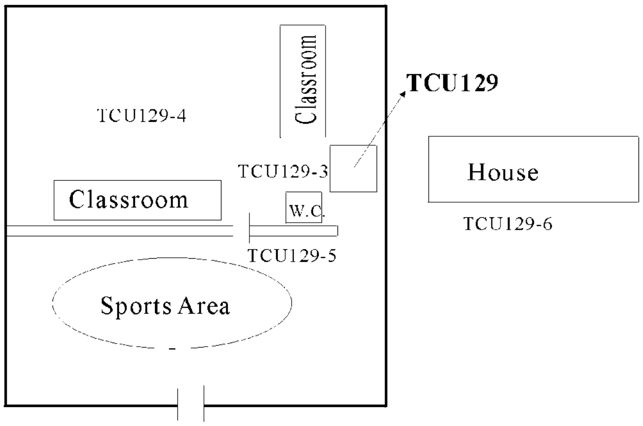

Figure 7. Microtremor survey points near station TCU129.

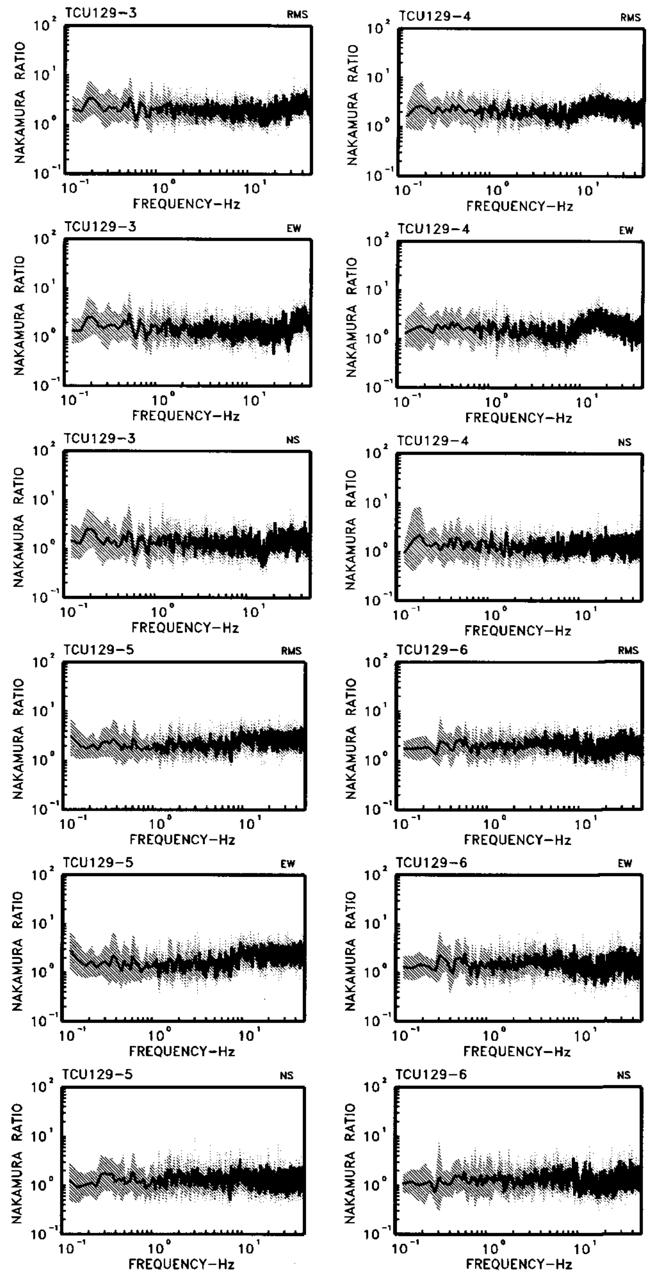

Figure 8. H/V ratios at four microtremor survey points near station TCU129.

TCU129-5 is about 1.5 m lower than points TCU129-3 and TCU129-4, whereas TCU129-6 is about 1 m lower than TCU129-5. Each measurement was recorded for 3 min with a sampling rate of 200 points per sec by using a K2 digital acceleragraph.

Nakamura (1989) proposed an empirical method by which site effects can be determined by simply evaluating the Fourier spectral ratio of the horizontal- versus vertical-component microtremor of motions observed at the same site. Figure 8 shows the horizontal to vertical ratios (H/V) at these microtremor measurement points. We cannot find any strong amplification band from Figure 8. This means that site response at station TCU129 is not strong. To understand site response at station TCU129, the spectral ratios are analyzed between observation points at different elevations. The results are plotted in Figure 9. From the spectral ratios of TCU129-3/TCU129-5, TCU129-3/TCU129-6, and TCU129-5/TCU129-6, we can see that the top 2.5 m soil layer under the TCU129 site only has a small amplification effect at around a 10- to 20-Hz frequency band. Figure 10 shows the spectral ratio of the records from stations TCU129 and TCU076 of the Chi-Chi earthquake. It again does not show any amplification in this high-frequency band. So, the 1*g* peak was not caused by the local site effect of station TCU129. With the influence of source, path, and site effects having been proven improbable, the deep concrete pier in the recording room remains the only factor in suspect that can generate the abnormally high PGA values recorded at station TCU129.

Analysis of Recording Pier Effects

A schematic diagram of the recording building at station TCU129 is shown in Figure 3b. When compared to the structure of a typical TSMIP free-field station, as shown in Figure 3a, the biggest difference is the big concrete pier that is more than 3 m deep, on which the accelerometers are mounted. To check the effects of this concrete pier, we installed two more accelerographs (Kinemetrics K2) inside the TCU129 recording room. The locations are plotted in Figure 11 and designated as TCU129N and TCU129S. At the same time, microtremor surveys were measured at points TCU129-1 (atop the concrete pier) and TCU129-2 (off the concrete pier), as shown in Figure 11.

During the observation period, the accelerographs at TCU129N, TCU129S, and TCU129 recorded eight earthquakes. The source parameters and the PGA values are listed in Tables 3 and 4. Although these three instruments were all

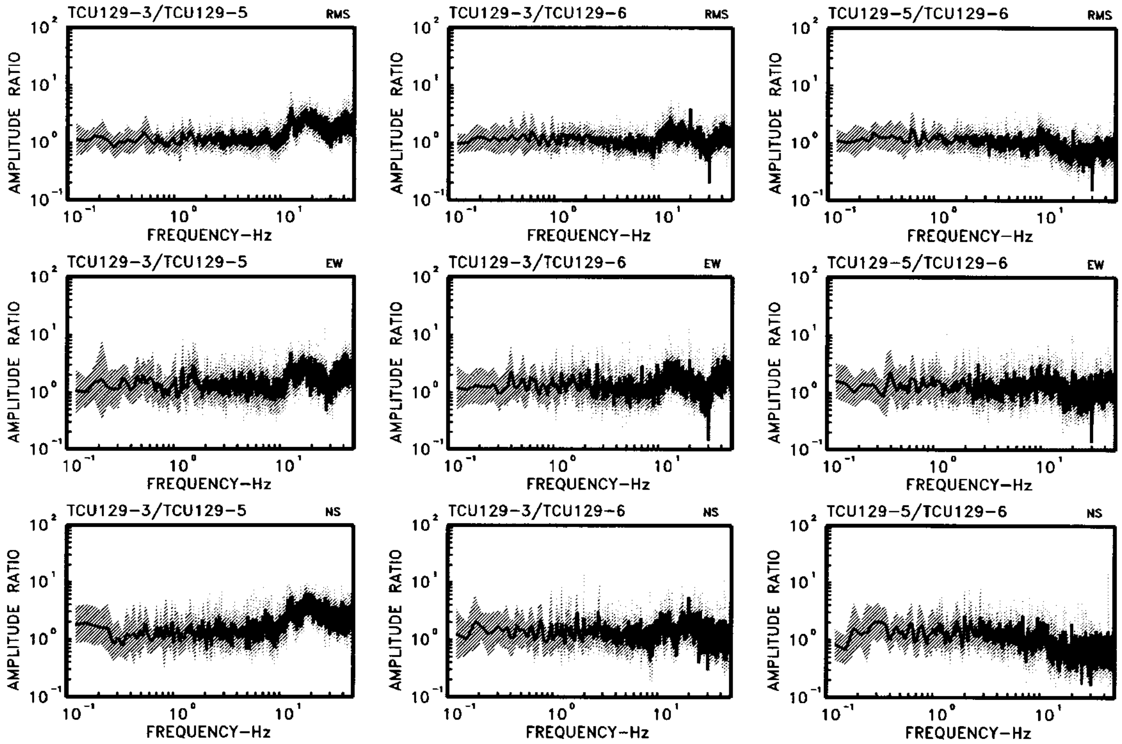

Figure 9. Microtremor spectral ratios of TCU129-3/TCU129-5, TCU129-3/TCU129-6, and TCU129-5/TCU129-6.

in the same recording building of station TCU129, the PGA values are not the same. Figure 12 shows an example of the records at TCU129 and TCU129N for the same earthquake at 21:57 of 19 June 2000. Figure 13 plots the average spectral ratios of TCU129/TCU129N and TCU129/TCU129S. The shaded area shows the band within one standard deviation. It clearly shows that the motions recorded at TCU129 are different from that at TCU129N and TCU129S. The ratios also show that motions recorded at the latter two points are about the same. Note that the observation point of TCU129 is located in between TCU129N and TCU129S. This result clearly shows that the big concrete pier under station TCU129 is responsible for anomalous recorded motions.

The PGA values recorded at TCU129 are different from that at TCU129N and TCU129S (Fig. 14). It shows the horizontal motions at TCU129 (on top of the concrete pier) are larger than that at TCU129N and TCU129S (off the concrete pier). On the contrary, the vertical motions at TCU129 are less than that at TCU129N and TCU129S. Before the Chi-Chi earthquake this phenomenon was not clear. After strong ground shaking during the Chi-Chi earthquake sequence, the gravel layer under the concrete pier may have become loose. Also, strong shaking may have caused large horizontal movements of the concrete pier so that it hit the adjacent concrete floor pad and generated spikelike peaks of high PGA values. As for the vertical component, the big mass of the pier and its soft coupling to the sides tends to reduce the motions.

Figure 15 shows the spectral ratios of microtremor records between TCU129-1, TCU129-2, and TCU129-3. The ratios between TCU129-1/TCU129-2 and TCU129-1/TCU129-3 all show strong amplification at a frequency band of 10–20 Hz, but the ratio of TCU129-2/TCU129-3 does not show this amplification effect. This also proves that the motion on the top of concrete pier is different from the motion off the pier.

Conclusions and Discussion

After the 1999 Chi-Chi, Taiwan, earthquake, the E–W PGA value recorded at station TCU129 was higher than 1*g*. It raised a question why no damage occurred at nearby areas around station TCU129. Even a very old building not far away from the station was undamaged by this destructive earthquake. It seems that this area did not experience very strong ground motion during the Chi-Chi earthquake. A series of analysis were made to resolve these conflicting phenomena. First, we compared the ground-motion records between TCU129 and a nearby station TCU076. As a result, the source and path effects were ruled out as the cause that can generate the high PGA values. From the spectral ratios of microtremor records at TCU129-3, TCU129-5, and TCU129-6 (Fig. 9), we found that site amplification at

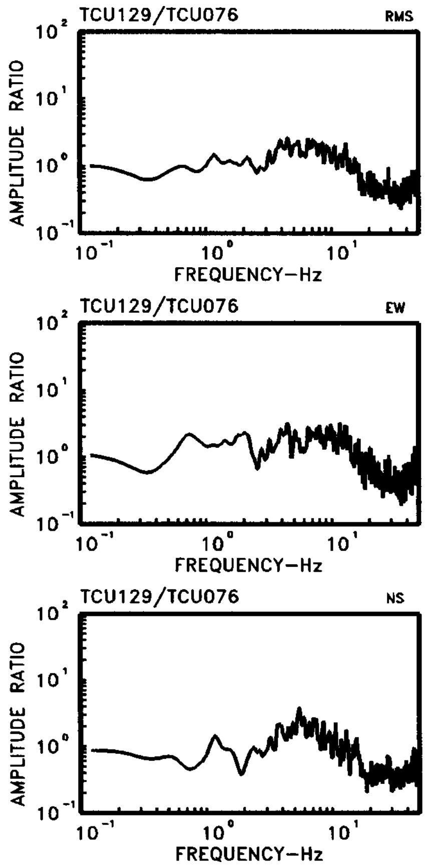

Figure 10. TCU129/TCU076 spectral ratios of the Chi-Chi earthquake.

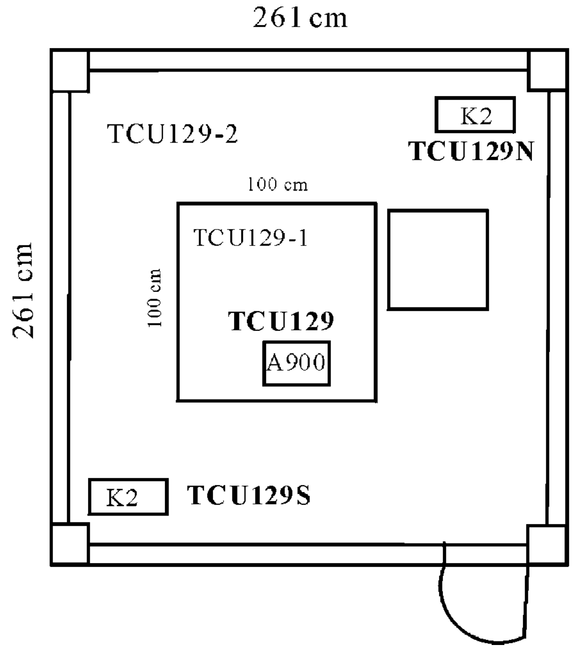

Figure 11. K2 instruments and microtremor survey points inside station TCU129.

Table 3
Earthquakes Recorded by Stations TCU129, TCU129N, and TCU129S

Event No.	Date (yyyy/mm/dd)	Time (hr:min:sec)	Lat.	Lon.	Depth (km)	M_L
1	2000/06/19	21:57:26.62	23.91°	121.09°	23	5.7
2*	2000/06/29	14:20	–	–	–	–
3*	2000/07/03	18:26	–	–	–	–
4	2000/07/11	00:40:55.16	23.82°N	121.10°E	25	4.8
5	2000/07/13	12:35:02.74	23.97°N	120.67°E	8	4.4
6	2000/07/28	21:32:15.07	23.40°N	120.95°E	3	4.6
7	2000/07/31	20:28	–	–	–	–
8	2000/08/02	14:19:42.34	23.85°N	120.70°E	27	4.4

*Local events not reported by CWB.

Table 4
PGA Values Recorded at Individual Stations for the Earthquakes Listed in Table 3

		PGA (gal)		
Event No.	Station Code	V	E–W	N–S
1	TCU129	7.03	41.10	86.73
	TCU129N	11.06	17.32	25.59
	TCU129S	11.30	22.72	26.08
2	TCU129	2.84	11.63	25.79
	TCU129N	7.31	7.38	13.66
	TCU129S	6.48	9.33	14.20
3	TCU129	1.10	6.85	13.67
	TCU129N	2.57	4.69	5.91
	TCU129S	2.28	4.84	6.15
4	TCU129	2.53	14.57	23.75
	TCU129N	3.52	6.98	14.25
	TCU129S	3.35	7.14	14.38
5	TCU129	6.38	18.92	39.78
	TCU129N	12.09	10.43	22.39
	TCU129S	9.73	11.03	23.91
6	TCU129	7.36	25.39	26.28
	TCU129N	7.72	23.50	21.33
	TCU129S	8.13	24.01	21.37
7	TCU129	2.06	15.64	8.68
	TCU129N	4.74	7.65	8.08
	TCU129S	4.13	8.93	8.57
8	TCU129	4.34	12.12	19.62
	TCU129N	11.41	11.90	15.71
	TCU129S	14.66	14.95	16.59

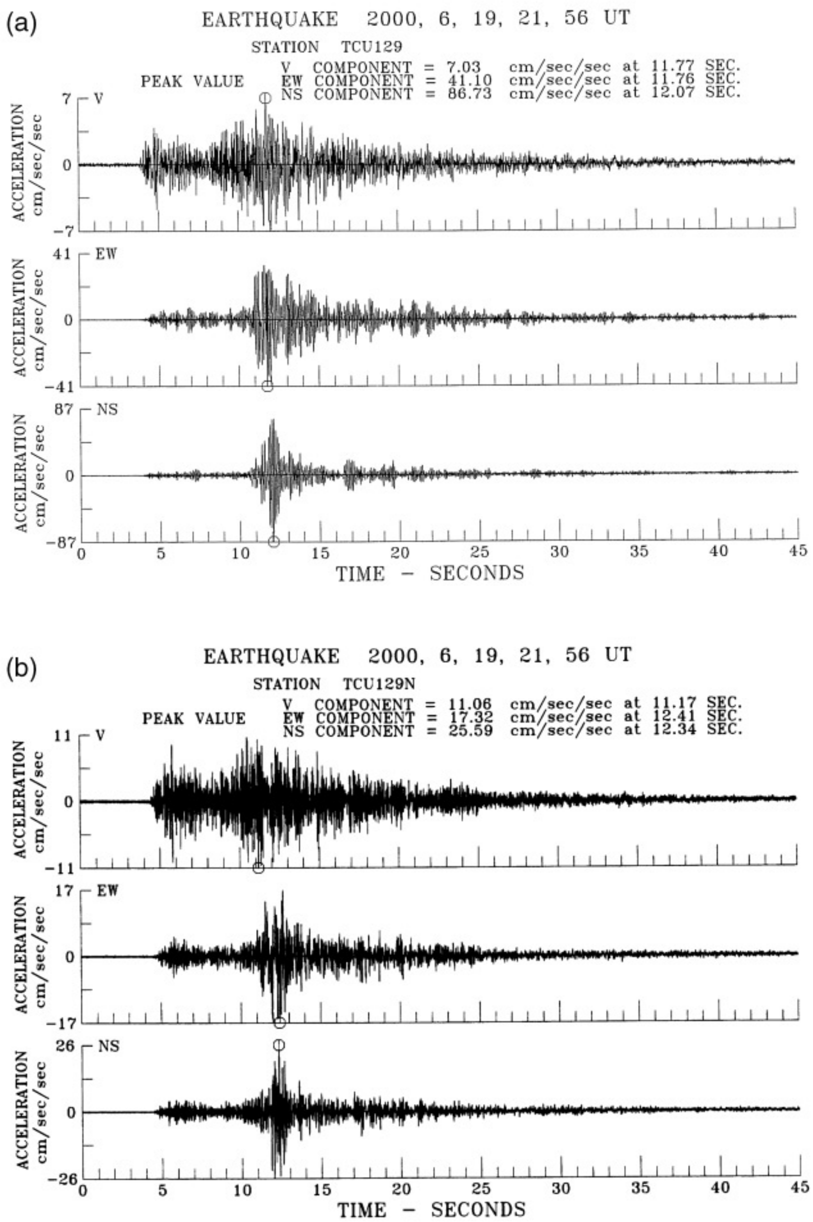

Figure 12. Acceleration waveforms recorded at (a) TCU129 (on the pier) and (b) TCU129N (on the floor) for the earthquake at 21:57 of 19 June 2000. Peak values: (a) V component = 7.03 cm/sec^2 at 11.77 sec; E–W component = 41.10 cm/sec^2 at 11.76 sec; N–S component = 86.73 cm/sec^2 at 12.07 sec; (b) V component = 11.06 cm/sec^2 at 11.17 sec; E–W = 17.32 cm/sec^2 at 12.41 sec; N–S component = 25.59 cm/sec^2 at 12.34 sec.

TCU129 was not strong. It cannot cause a large difference in ground motion between TCU129 and the nearby station TCU076. Third, two additional accelerographs were installed inside station TCU129 to study the effect of the concrete pier in the recording building. We compared the ground motions of the same earthquakes recorded by these accelerographs. The concrete pier on which the instruments are mounted is identified as the cause that has generated the larger than 1*g* peak values at station TCU129 during the 1999 Chi-Chi, Taiwan, earthquake. The gravel layer under the concrete pier may have been shaken loose due to strong earthquake ground motions, or it was not properly constructed. Another cause could be the resonant vibrations of the concrete pier. If it is not tightly bounded with the surrounding ground, the pier can have its own resonant vibrations that will affect the seismic recording (Basili, 1987). Comparisons of microtremor measurements on top of the concrete pier and off the pier also show such amplification effects of the concrete pier at around 10–20 Hz. Integration of the acceleration records of the Chi-Chi earthquake to velocity waveforms will exhibit the motion at a lower frequency band. Figure 16 plots the velocity waveforms of the records shown in Figure 2. From this figure we can find the peak velocities between stations TCU129 and TCU076 are very similar. Therefore, the recorded PGA values should not be used in the studies of the peak acceleration attenuation. However, the records are still useful, especially in the forms of velocity and displacement time histories, for other studies.

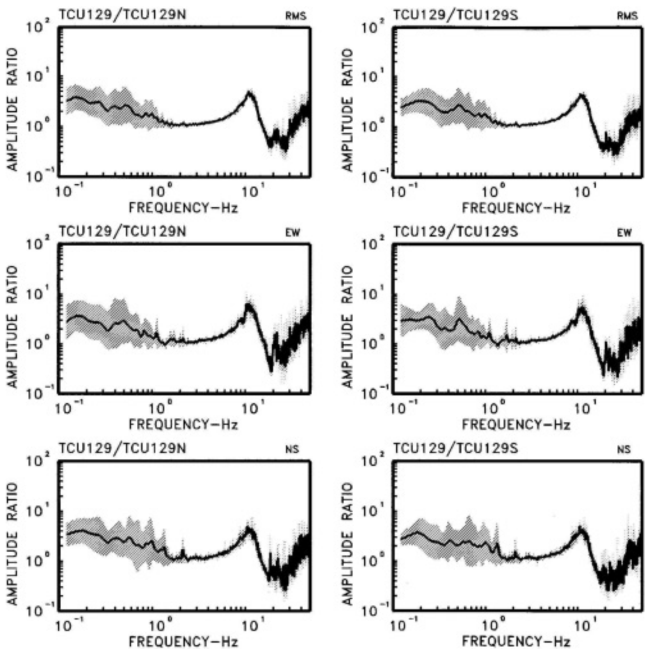

Figure 13. Average spectral ratios of TCU129/TCU129N and TCU129/TCU129S. The shaded areas show the one standard deviation area.

On the basis of this study, the high PGA values recorded at station TCU129 during the Chi-Chi, Taiwan, earthquake should be reduced to about the same level as that at nearby stations in the future strong earthquake. The accelerographs of the TREIRS system correctly mounted on a big concrete pier like station TCU129 should all be moved off the pier and installed on the floor to avoid the vibrational effects of the concrete pier.

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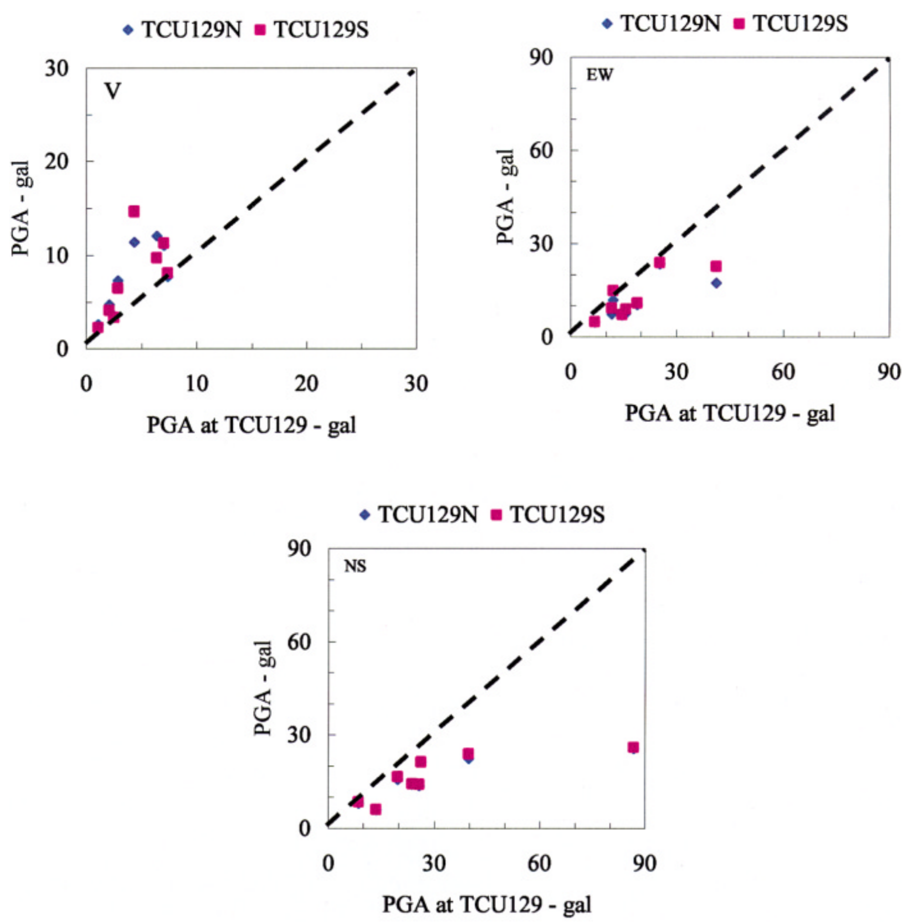

Figure 14. Correlation between PGA values recorded at stations TCU129 (on the pier), TCU129N, and TCU129S (on the floor).

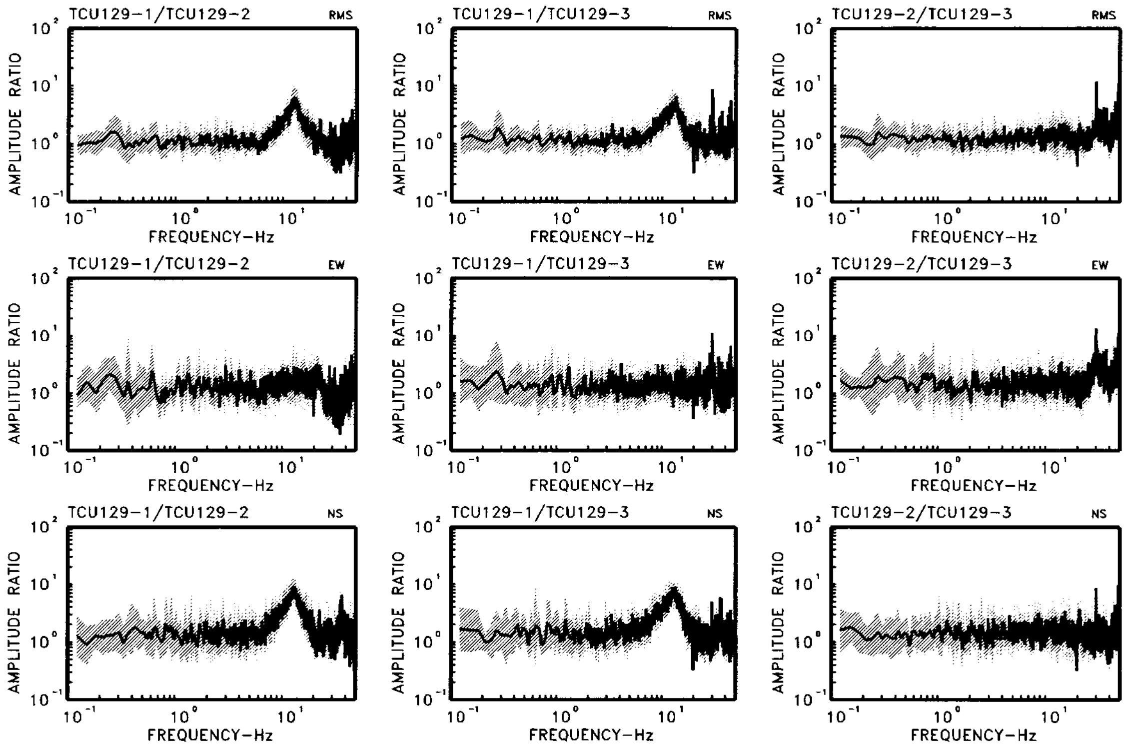

Figure 15. Microtremor spectral ratios of TCU129-1/TCU129-2, TCU129-1/TCU129-3, and TCU129-2/TCU129-3.

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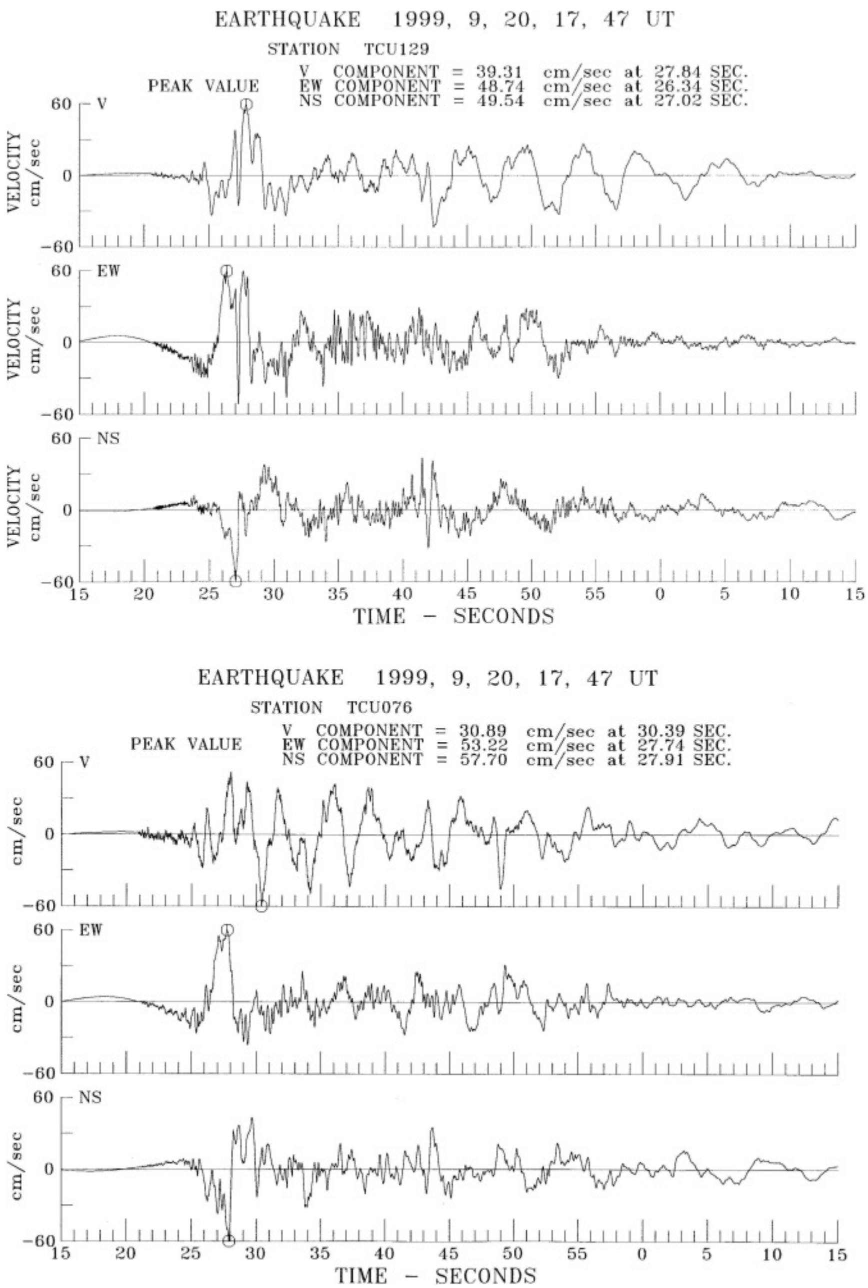

Figure 16. Three-component velocity waveforms at stations TCU129 (upper) and TCU076 (lower) from the 1999 Chi-Chi, Taiwan, earthquake.