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Observations of strong ground motion at hill sites in Mexico City from recent earthquakes

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RESUMEN

Se presentan resultados del estudio de la respuesta sísmica de las estaciones de la Red Acelerométrica de la ciudad de México localizadas en la zona de lomas. Se analizaron siete sismos provenientes de diferentes fuentes sismogénicas, con magnitudes entre 5.9 y 7.3. Existe una sensible dependencia de la respuesta sísmica en las estaciones con respecto a las características del terremoto (magnitud, acimut, distancia epicentral y profundidad). Los sismos provenientes de la costa concentran su mayor energía en frecuencias menores de 1 Hz. Mientras que sismos intraplaca en frecuencias mayores de 1 Hz. El análisis de los acelerogramas en el dominio del tiempo muestra dos tipos significantes de amplificación: Regional (estaciones localizadas al suroeste de la zona de lomas presentan mayores amplificaciones que las localizadas al norte de la ciudad) y local (las estaciones localizadas en la zona suroeste presentan una mayor amplificación respecto a CU). Se realizaron además cocientes espectrales de las estaciones localizadas en la parte central y suroeste respecto a la estación Estanzuela (ES), localizada en la zona norte de la ciudad. La comparación de estos cocientes espectrales muestra que existen amplificaciones relativas hasta de cuatro veces entre algunas de las estaciones localizadas en la zona suroeste de la ciudad en el rango de frecuencias de 1 a 3 Hz. Estos efectos observados se pueden deber a la presencia de material mucho más suave debajo de los flujos de lava donde se localizan las estaciones.

PALABRAS CLAVES: Ciudad de México, zona de lomas, cocientes espectrales, efectos de sitio, amplificación y trayectoria.

ABSTRACT

Results of seismic response of the stations of the Acelerometric Network of Mexico City located in the hill zone are presented. Seven earthquakes from different seismic sources were analyzed, with magnitudes between 5.9 and 7.3. There is a dependence of the seismic response at hill sites on earthquake magnitude, azimuth, epicentral distance and depth. Subduction earthquakes concentrate their energy at low frequencies (<1 Hz), while intraplate earthquakes have frequencies higher than 1 Hz. We find two significant types of amplification: regional, for sites located to the southwest hill zone over sites located to the north of the city, and local. Stations located in the southwest area show higher amplification with respect to the reference station. The spectral ratios of stations located in the central and southwest part of the hill zone show relative amplifications up to four times higher than stations located in the north area of the city for frequencies between 1 and 3 Hz. These local amplifications may be due to the presence of soft material under the lava flows where the stations are located.

KEY WORDS: Mexico City, hill zone, spectral ratio, site effects, amplification and wave path.

INTRODUCTION

Amplification of ground motion during earthquakes in sedimentary alluvial valleys can cause considerable damage, as in the earthquake of Michoacán 1985 in Mexico City. Numerous authors have been working on the task of explaining the behavior of the seismic response of this basin. The observed effects are enormous spectral amplifications and large strong motion duration and spatial variability. However, the seismic response of firm soil in the hill zone of Mexico City has not been much studied.

Singh *et al*. (1988) and Ordaz and Singh (1992) suggest that the hill zone in the Valley of Mexico features important amplification with respect to the attenuation laws. This amplification could reach 10 times for frequencies between 0.2 and 0.7 Hz. Singh *et al*. (1995) conclude that two northern stations of the hill zone (MADI and TEXC), where the motion is less amplified than at other sites, still present a significant amplification. They suggest low S wave velocities and complex structure of the upper layers of volcanic rocks as a possible explanation.

Reinoso and Ordaz (1999) found important differences in the Fourier amplitude spectra in the hill zone between areas in the southwest and the north for the earthquake of September 14, 1995. The spectral amplitude of the stations of the southwest is eight times larger than to the north for all frequencies.

Pérez-Rocha (1998) carried out the scaling of amplitudes of ground motion in the hill zone for several earthquakes using simple theoretical models of the seismic source. He found that the strongest earthquakes for structures in the Valley of Mexico are those from the Guerrero coast. If an earthquake with M = 8.1 originates at this coast, the design spectra specified in the building code may be underestimated for shortperiod structures. This is particularly dangerous for structures located in the hill zone. He concluded that a detailed study of the seismic response of the hill zone is justified.

As for frequencies larger than 1 Hz, Pérez-Rocha (1998) suggested that earthquakes from the Petatlán gap are very energetic for these frequencies. This is very important for the hill zone since structures there are vulnerable to motions with this frequency content. An earthquake originated in this subduction zone caused the collapse of the Ibero-American University in 1979.

García and Suárez (1996) compiled the effects of historical earthquakes felt in Mexico, including Mexico City and its hill zone. The earthquake of 1858 caused extensive damage in the state of Michoacán and in Mexico City. Newspapers of that time describe that in Coyoacán "many houses suffer damages". This town is located at the border between the transition and hill zone. Singh *et al.* (1996) estimate a magnitude of 7.7 for this earthquake and suggest a normal fault origin.

GEOLOGY

The basin of Mexico is located in the central part of the Mexican Volcanic Belt (MVB). Volcanic rocks form the geology of the basin. It is filled by lacustrine sediments, volcanic tuff, sands and gravels. Based on the geotechnical characteristics of its shallow layers, the Valley of Mexico has been divided into three regions: (1) the hill zone, formed by volcanic tuffs and lava flows, (2) the lake bed zone, formed by clays with thickness varying from 10 to 100 m; and (3) the transition zone, composed by alluvial sandy and silty layers, with scattered clay layers (Marsal and Mazari, 1959).

The southwest part of the hill zone is formed by recent Quaternary deposits (lava flows from Xitle volcano) that overlie soft material (Delgado *et al.*, 1999). The north part is composed of hard Pleistocene lava of a few meters in thickness, that overlies volcanic rocks of Oligocene age (Singh *et al.*, 1995).

DATA AND ANALYSIS

We examine the effects of azimuth, magnitude, epicentral distance and depth of earthquakes on the seismic response of the stations located in the hill zone of Mexico City.

Seven earthquakes from different seismic regions were used (Figure 1). Most of the data come from subduction earthquakes with epicentral distances larger than 130 km from

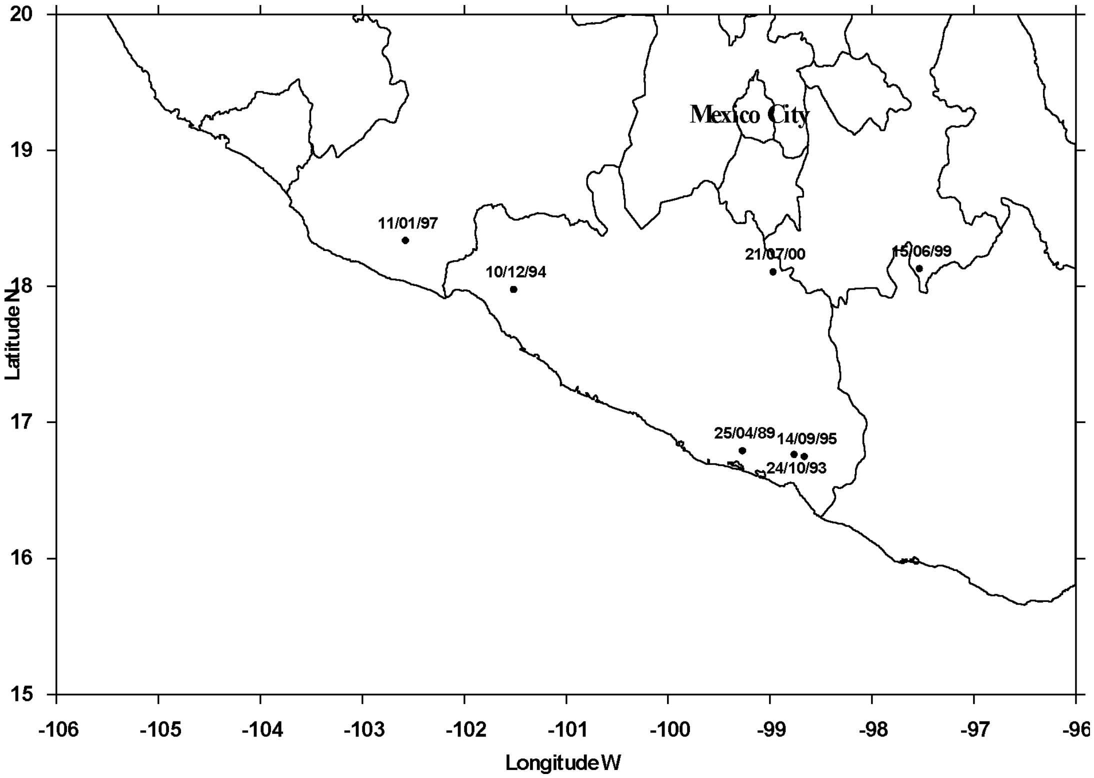

Fig. 1. Location of epicenters and Mexico City.

the accelerometer station at Ciudad Universitaria, UNAM (CU). Table 1 shows the parameters of these earthquakes. We shall discuss events 1, 2 and 7 in particular, due to their combination of relatively near epicentral distance and large magnitude.

After the extensive damage caused by the 1985 Michoacán earthquake in Mexico City, the accelerometer array has grown considerably. It now consists of more than 90 free-field digital accelerometric stations, 18 of them in the hill zone (stations 07, 13, 18, 21, 28, 34, 40, 50, 64, 74, 78, ES, CU, CH, CN, TX, MD and TY). Figure 2 shows the location of these stations.

The earthquake of June 15, 1999, M 7.0, H = 60 km

The epicenter of this earthquake (see Table 1 and Figure 1) was located southwest of Tehuacán, Puebla. It caused severe damage in the state of Puebla and Morelos. In Mexico City, about 200 km from the epicenter, damage was associated only to non-structural elements (Singh *et al.,* 1999). The ground motion observed in Mexico City during this earthquake was much smaller than the predicted one (Shapiro *et al.,* 2000; Singh *et al.,* 1999).

Figure 3 shows the accelerograms from this earthquake recorded at hill zone sites and at station CUER in Cuernavaca, Mor, on firm soil, but outside the valley. We also show the response spectra of absolute acceleration and displacements (with damping ratio of 5%) for the north-south component.

The accelerograms show unusually large amplitudes and high frequency content. Stations 40, 34, 74 and CU are located in the southwest part of the city, very close to each other (~3.0 km). The motion was expected to be very similar, because four sites are on lava flows. However, station CU exhibits a smaller amplitude than sites 40, 34 and 74. Response spectra show similar behavior. Figure 4 shows Fourier amplitude spectra for the horizontal components of motion. The largest spectral amplitude is at stations CUER, 34 and 74. The average spectra for the southwest stations, ASW, and for the north station, AN, are shown.

The northern stations 07, 64 and ES show the smallest amplitude, both in the frequency and time domains. This may be due to a strong change in the geological conditions between the southwest and north parts of the hill zone. The older rocks are north of the city. Attenuation is not an important factor since the distance between the southwest stations and the north stations is small. The epicentral distance for sites CU and ES is 222 and 227 km respectively.

The earthquake of September 14, 1995, M 7.3

Figure 5 shows the accelerograms and the acceleration response spectra and displacement (with damping ratio of 5%) corresponding to the north-south component. In the time domain, the accelerograms differ in amplitude and duration of motion. Figure 6 displays the smoothed Fourier amplitude spectra for all stations, using a one-sixth-octave band filter. Note the important differences of frequency content (Reinoso-Angulo, 1996; Reinoso and Ordaz, 1999).

From Figure 5, two groups of stations follow the same behavior: the southwest station and the north stations (Figure 2). North stations have smaller amplitudes than southwest stations. From Figures 3, 4, 5 and 6, the largest spectral amplitudes are found in the southwest part of the city, while the smallest are observed in the northern part. The maximum spectral amplitude varies for both earthquakes. For the 1995 event the maximum peaks are in the range of 0.2 to 0.7 Hz, typical of subduction earthquakes, while for the 1999 event the maximum peaks are between 1.0 and 3.0 Hz.

Table 1

Earthquakes used in this work

Date dd/mm/yy	Origin	Magnitude	Depth (km)	Latitude (N)	Longitude (W)
(1)15/06/99	Intraplate	7.0	63	18.133	97.539
(2) 14/09/95	Subduction	7.3	21	16.752	98.667
(3) 10/12/94	Intraplate	6.3	53	17.980	101.520
(4) 24/10/93	Subduction	6.6	30	16.767	98.767
(5) 11/01/97	Intraplate	7.3	40	18.340	102.580
(6) 25/04/89	Subduction	6.9	23	16.795	99.275
(7) 21/07/00	Intraplate	5.9	58	18.110	98.974

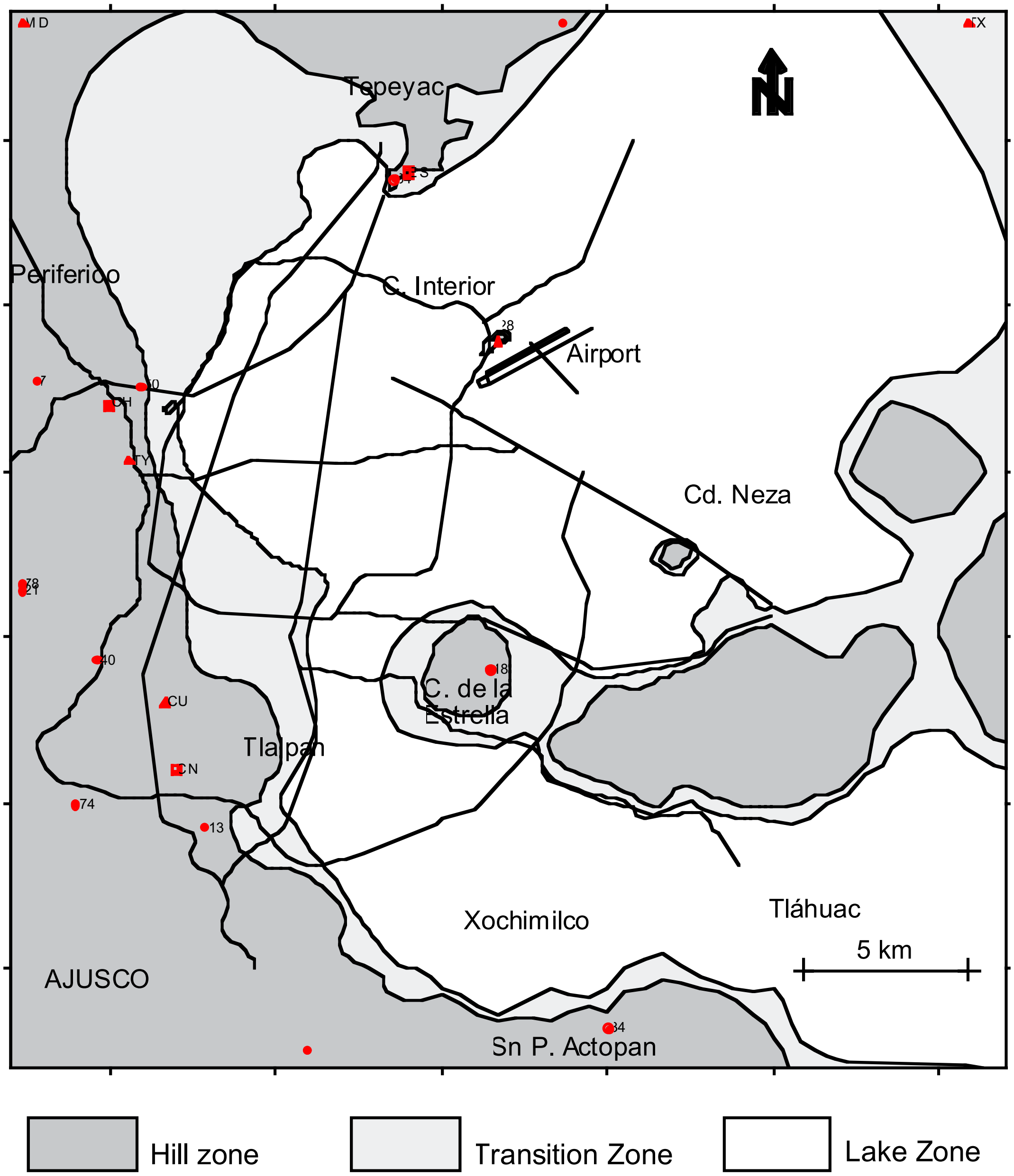

Fig. 2. México City: accelerometric stations, geotechnical zones and reference sites. The accelerometric array consists of more than 90 free-field digital accelerometric stations, 18 in the hill zone (07, 13,18, 21, 28, 34, 40, 50 64, 74, 78, ES, CU, CH, CN, TX, MD and TY)

Figure 7 shows the average Fourier spectra of the north-south component for stations in the southwest and in the north, for both events. Similar to Figures 4 and 6, Figure 7 shows that for each earthquake spectral shapes are very similar, and that strong variations exist in the amplitudes for both groups of stations. The difference is up to 4 times for both earthquakes. Notice the difference between the two types of earthquakes: for the 1999 intraplate earthquake the maximum spectral amplitudes occur at frequencies higher than 1 Hz, while in the 1995 subduction earthquake the maximum amplitude occur at frequencies below 1 Hz.

The earthquake of July 21, 2000, M 5.9

This intraplate earthquake was felt in Mexico City but no damage was reported. Due to the unusual proximity to the city (~ 137 km), acceleration records of very good quality were obtained, and P and S wave arrivals are clearly seen (Figure 8). Figure 9 shows the Fourier amplitude spectra. As expected, the accelerograms contain high energy at high frequencies. Southwest stations show the largest amplitudes with respect to ES station located in the north of the city. This is also observed in the Fourier amplitude spectra shown in Fig-

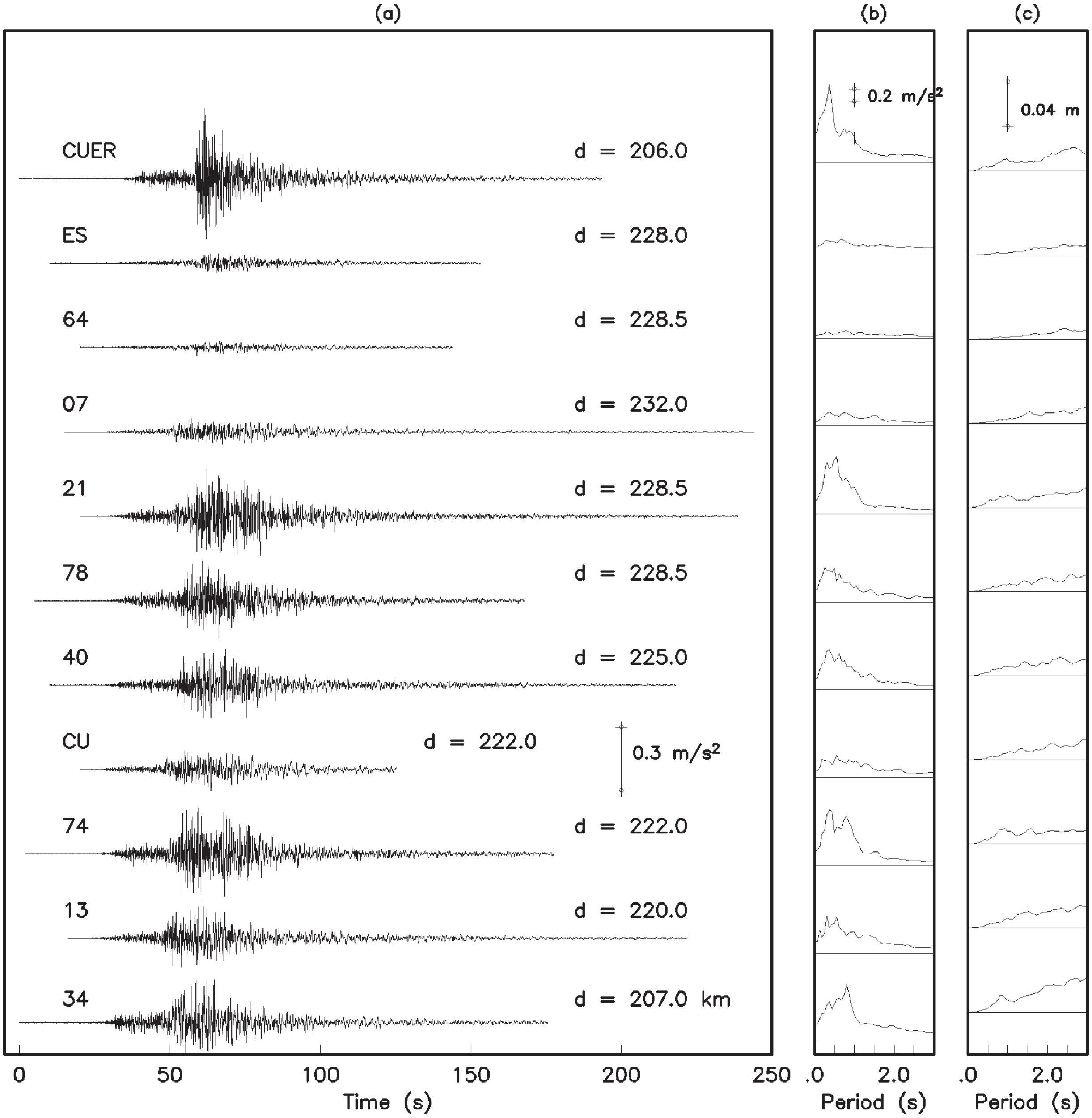

Fig. 3. Strong ground motion at hill-zone sites during the June 15, 1999 earthquake. (a) Accelerograms, (b) response acceleration spectra, (c) response displacement spectra.

ure 9, where the maximum spectral amplitudes are found around 2 Hz. For low frequencies, the amplitude is low. Station CU has smaller amplitudes (in the north-south component) that the other stations located in the southwest: but at low frequencies in the east-west component, the amplitudes with respect to the other stations are large. Figure 9 also shows the average of the Fourier amplitude spectra at the southwest stations. Station ES is located in the north of the city and presents the smallest spectral amplitude. The average spectra for the southwest stations, ASW, and for the north station, AN, are shown.

We compare the effects of path and magnitude of this earthquake (Figure 1) with those of the 1999 event. These earthquakes had similar source mechanics and depth, but they differ in azimuth, magnitude and epicentral distance. The wave path for the 2000 event does not pass through the volcano. We use a theoretical ω^{-2} scaling Pacheco and Singh, 1995; Pérez-Rocha, 1998) for the 2000 event to estimate the Fourier amplitude spectra adjusted to M = 7.0. These spectra were also corrected with distance using a regional spectral attenuation relation for south-central Mexico (Ordaz and Singh, 1992).

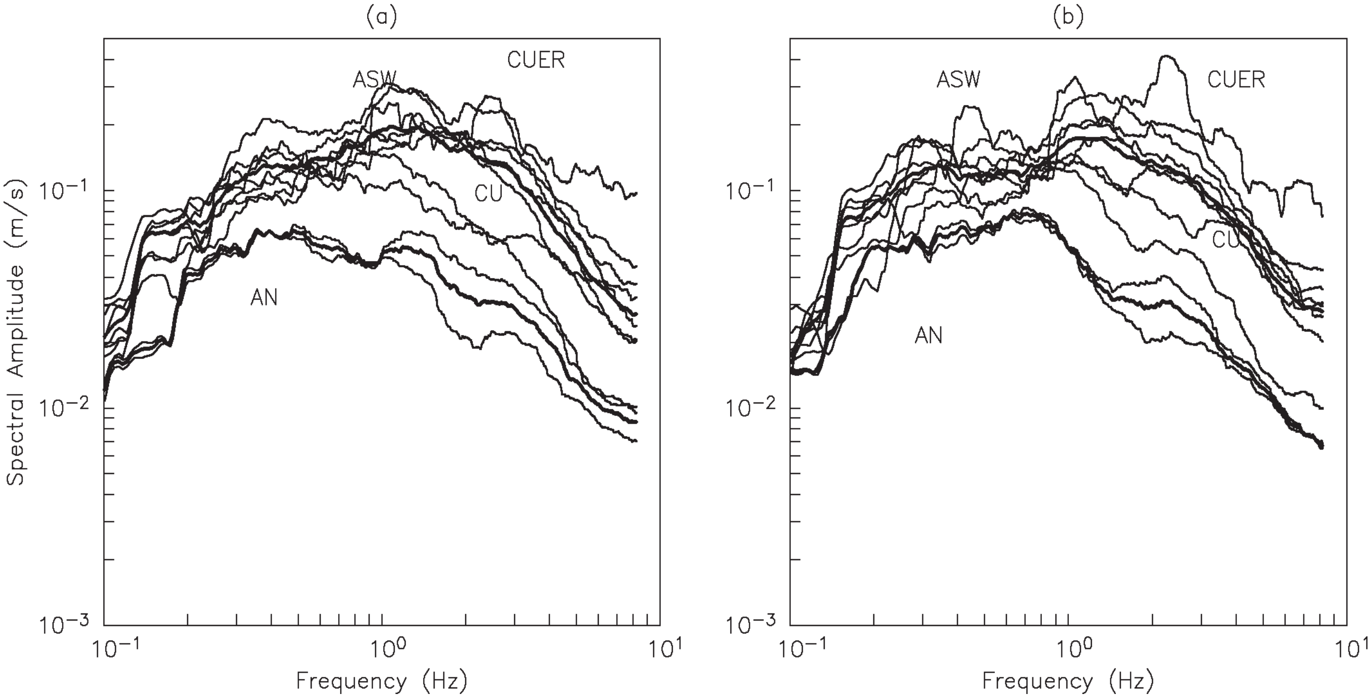

Fig. 4. Fourier amplitude spectra of the June 15, 1999 earthquake. (a) North-south and (b) east-west (ASW, average of southwest stations AN, average of north stations).

Figure 10 shows the Fourier amplitude spectra of the ground motion at CU station of the earthquake of 1999 and the scaled event of 2000. The scaled spectrum has higher spectral amplitudes for the whole range of frequencies. This may be explained by the fact that the July 21 earthquake has a different azimuth and its path to CU does not cross Popocatépetl volcano.

On October 24, 1980 an earthquake of M = 7.0 occurred in the region of Huajuapan de León near the epicenters of events (1) and (7). This event had similar source mechanics and deep of the 1999 earthquake; yet, the 1980 earthquake showed larger spectral amplitudes in the time domain and in the whole range of frequencies (Singh *et al.*, 1999). The differences at site CU for these two earthquakes may be due to the fact that the path for the earthquake of October 24 does not pass through Popocatépetl volcano. Shapiro *et al.* (2000) proposed that the seismic waves that traveled toward Mexico City were strongly attenuated by Popocatépetl volcano.

A similar analysis was carried out for the other earthquakes in Table 1. Similar behaviors are observed between southwestern and northern stations.

Figure 11 shows the average spectra for the southwest stations of all seven earthquakes. The earthquakes of June 15, 1999 and July 21, 2000 show larger amplitudes for frequencies higher than 1 Hz, while the other events present greater amplitudes for low frequencies. The spectra of events (3), (4) and (5) are similar to the coastal events; however, due to their larger epicentral distances and their smaller magnitude, the amplitudes are shorter.

We conclude that (1) there is a dependence of the seismic motion in the hill zone due to azimuth, magnitude, epicentral distances and depth; (2) the stations in the southwest of the hill zone have larger spectral amplitudes than the stations in the north area of the city, and (3) there are important local differences of the seismic motion for the stations in the southwest region even when they are very close to each other.

RELATIVE AMPLIFICATION BETWEEN HILL ZONE SITES

To compute amplification factors we decided to eliminate the effects of azimuth, path, magnitude and depth using the spectral ratio technique. Amplitude ratios were obtained for stations CU and 74 with respect to station Estanzuela (ES), located on the oldest rocks (Singh *et al.*, 1995; Reinoso and Ordaz, 1999). Stations 74 and CU are on lava flows from the Xitle volcano (Delgado *et al.*, 1999); they are only 3.5 km away. The spectral ratios of these two stations were compared with the 1-D response using the Haskell method. The

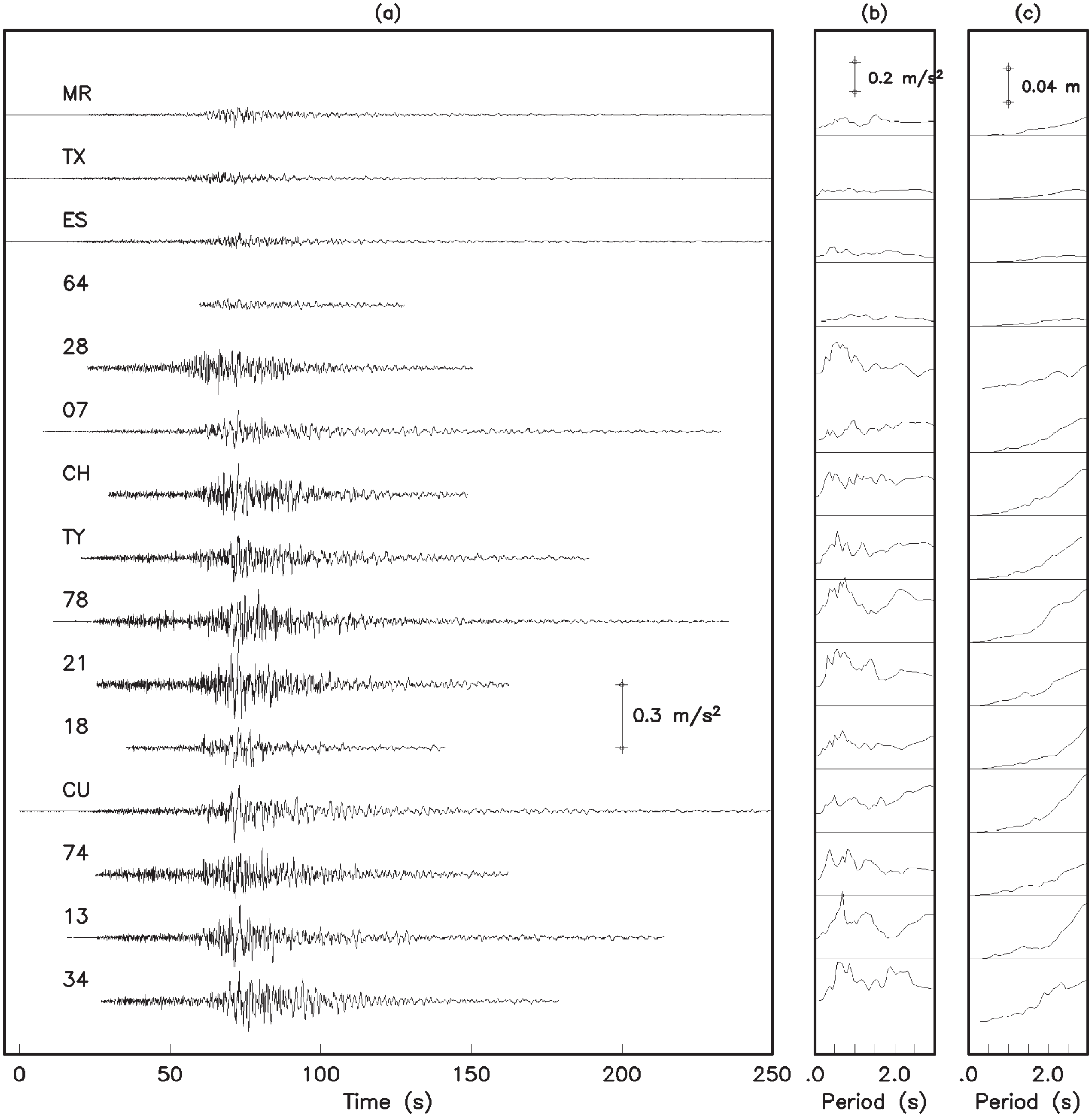

Fig. 5. Strong ground motion at hill-zone sites during the September 14, 1995 earthquake. (a) Accelerometric data, (b) response spectra of acceleration, (c) response spectra of displacement.

geologic model corresponds to site CU (Table 2) after Gutiérrez *et al*. (1994).

Figure 12a shows the Fourier amplitude spectra of the three stations, Figure 12b shows the transfer functions CU/ES, 74/ES and the 1-D response, and Figure 12c shows the accelerograms. It appears that the 1-D model reproduces reasonably well the response of the transfer function of site CU for frequencies between 1 and 4 Hz. The ratio 74/ES shows important differences with the 1-D transfer function; amplitudes are up to 4 times larger. This effect may be due to geological conditions at site 74. Delgado-Granados and Mooser

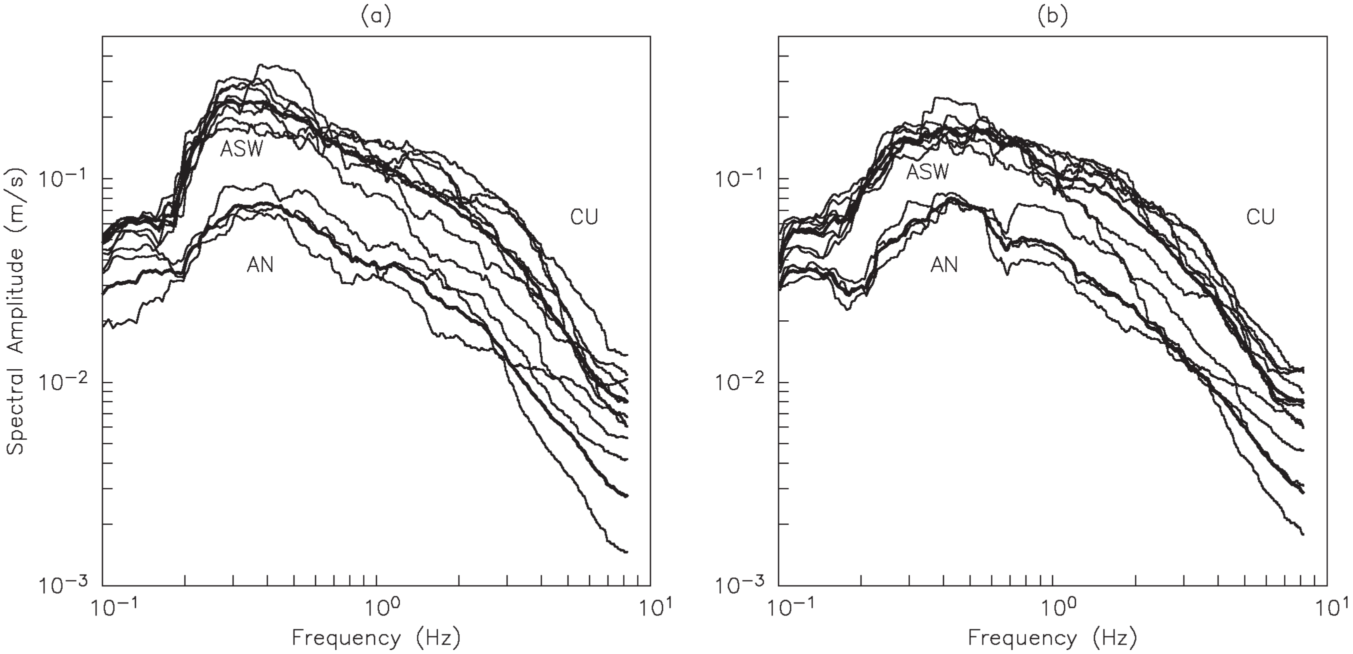

Fig. 6. Fourier amplitude spectra of the September 14, 1995 earthquake. (a) North-south, and (b) east-west (ASW, average of southwest stations, AN, average of north stations).

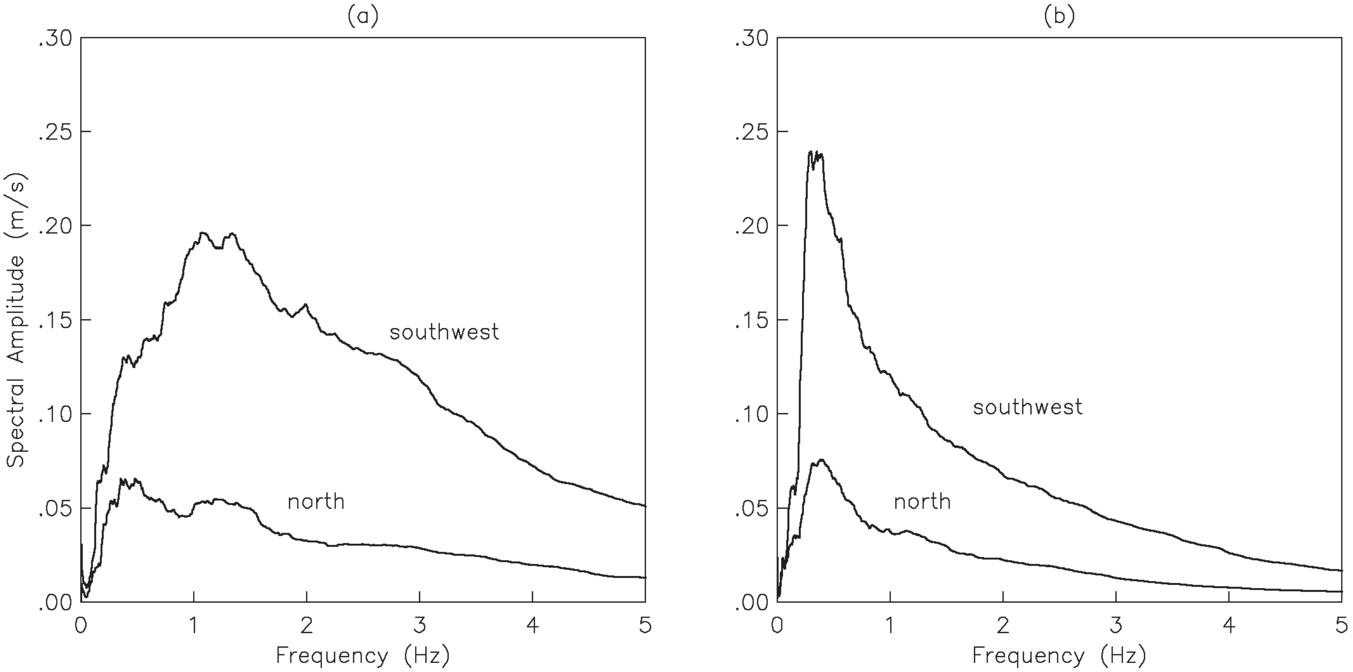

Fig. 7. Average of Fourier amplitude spectra for the north-south component of motion for southwest and north stations. (a) June 15, 1999 and (b) September 14, 1995.

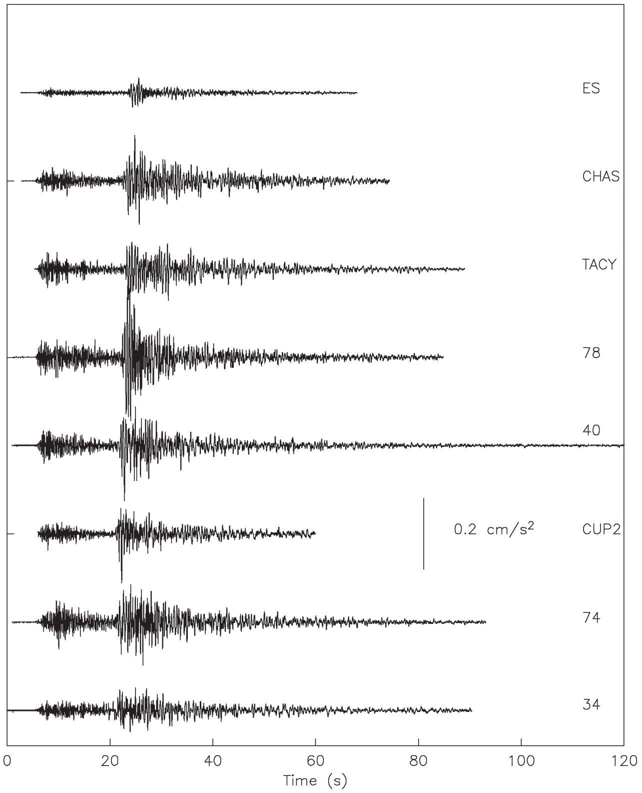

Fig. 8. Strong ground motion at hill-zone sites during the July 21, 2000 earthquake.

(personal communication) believe that the material under the lavas beneath station 74 is much softer. This causes the higher amplifications observed in Figure 12 compared to station CU.

Figure 13, shows the average spectral ratios of all southwest stations with respect to station ES for two earthquakes (1999 and 1995), with magnitudes greater than 7.0. They are plotted against period. From this figure, the transfer functions are not as similar as might be expected. For periods between 1 and 2.5 s, the largest amplitudes are for the coastal earthquakes, while for periods smaller than 0.6 s (Figure 13b), the intraplate earthquake of 1999 has larger amplitudes. Thus the seismic behavior of the structure of the Mexican Volcanic Belt, where Mexico City is located, depends on the type of earthquake, and the input motion will shake the structure differently depending on the azimuth, distances and magnitude of the earthquake.

CONCLUSIONS

1) In the time domain, higher amplitudes are observed in the stations located in the southwest compared to those in the north. In the frequency domain, the average spectral amplitudes are up to 4 times larger.

2) For subduction earthquakes, the higher amplitude is found at frequencies below 1 Hz, while for intraplate earth-

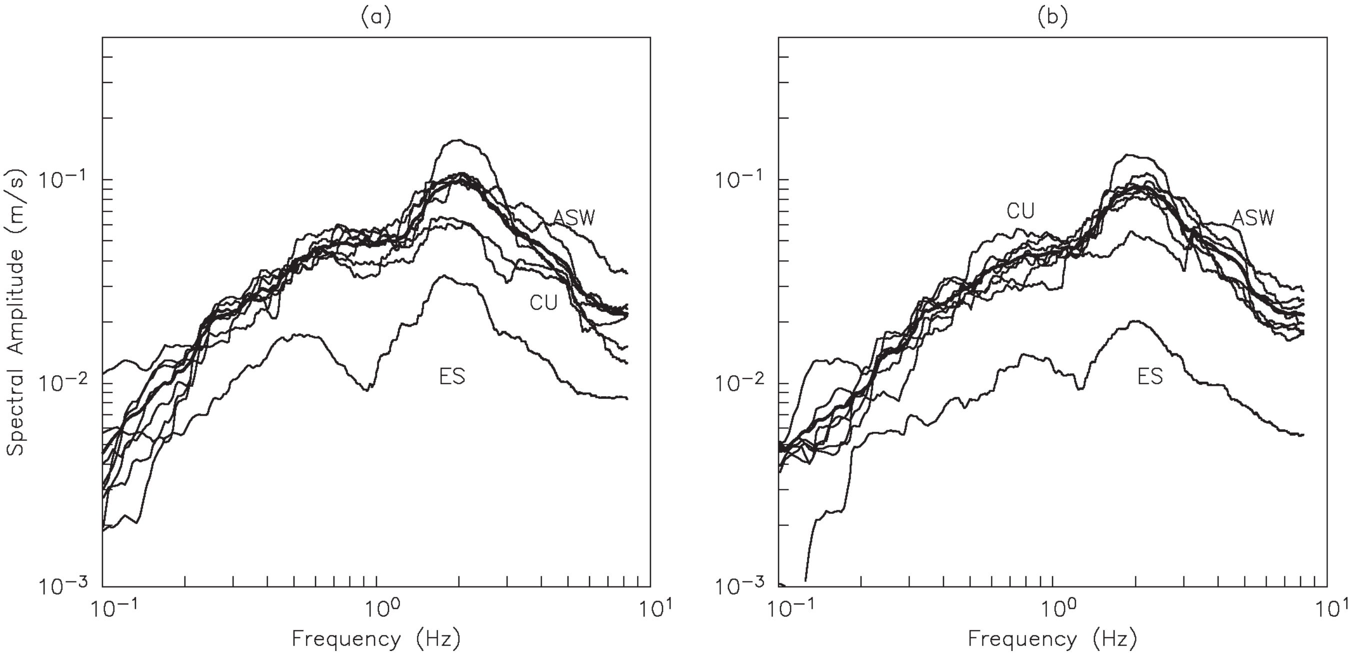

Fig. 9. Fourier amplitude spectra of the July 21, 2000 earthquake. (a) North-south and (b) east-west. The ES station is shown at the bottom of the figure.

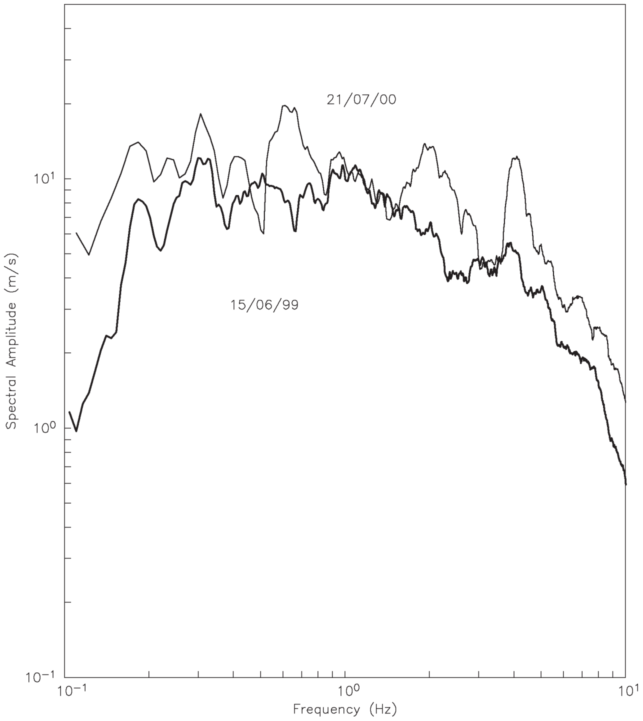

Fig. 10. Fourier amplitude spectra of the June 15, 1999 earthquake and scaled (M = 7) Fourier amplitude spectra of the July 21, 2000 earthquake.

quakes the higher amplitudes correspond to frequencies above 1 Hz.

3) Regional site effects are observed at southwest stations at frequencies over 1 Hz, for stations 34, 40, and 74 with respect to CU.

4) Important differences in the transfer functions at the southwest stations are found. This suggests a dependence of the amplification patterns on the origin and localization of the earthquake.

5) The seismic risk in Mexico City is smaller when the earthquake occurs east of Popocatépetl volcano.

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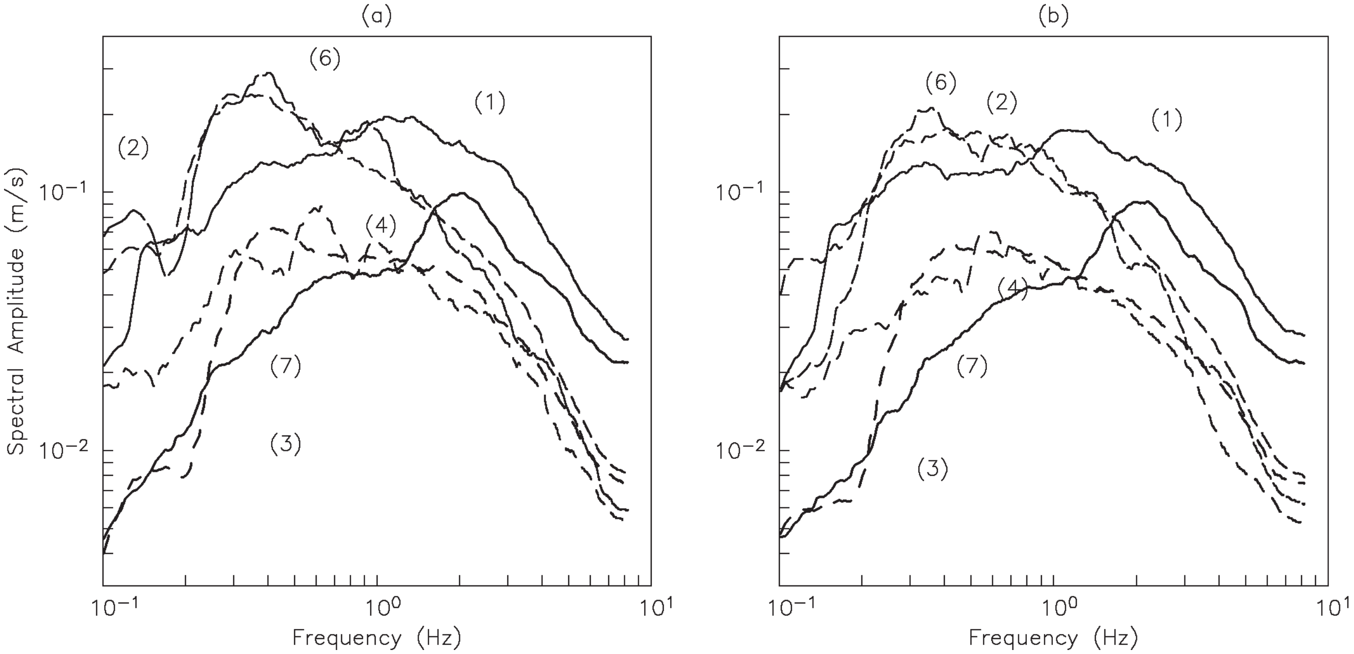

Fig. 11. Average of Fourier amplitude spectra of seven earthquakes for southwest stations. (a) North-south and (b) east-west.

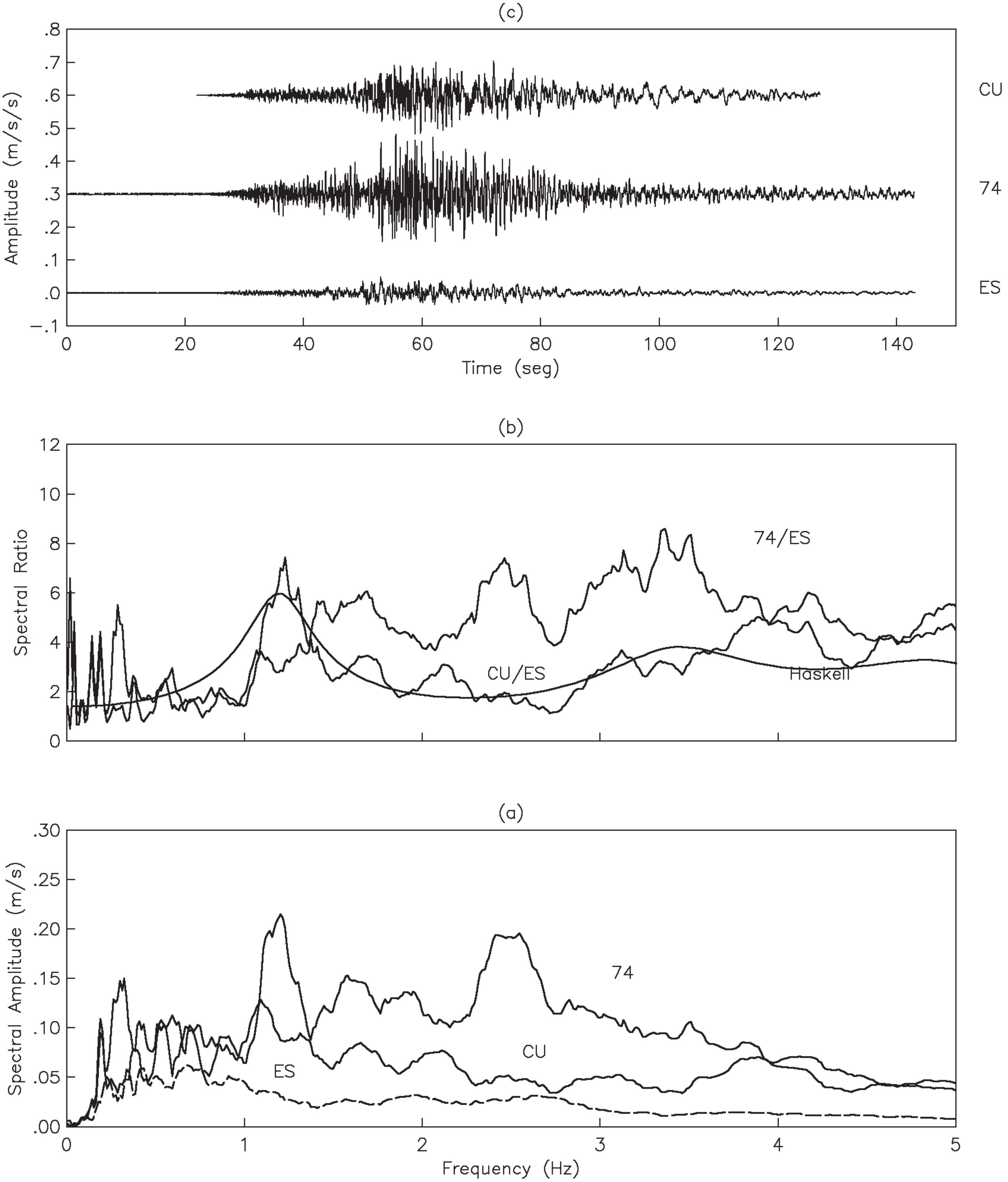

Fig. 12. Strong ground motion at stations 74, CU and ES, of the June 15, 1999 earthquake east-west component. (a) Fourier amplitude spectra, (b) spectral ratios 74/Es, CU/ES, and 1D response, (c) accelerometric data.

Table 2

Site profile used to compute one-dimensional transfer function at site CU

Thickness (m)	Velocity P waves (m/s)	Velocity S waves (m/s)	Density T/m3	QP	QS
80.0	1000.0	430.0	1.9	280	140
50.0	2062.0	875.0	2.0	600	300
∞	3000.0	1500.0	2.5	5000	5000

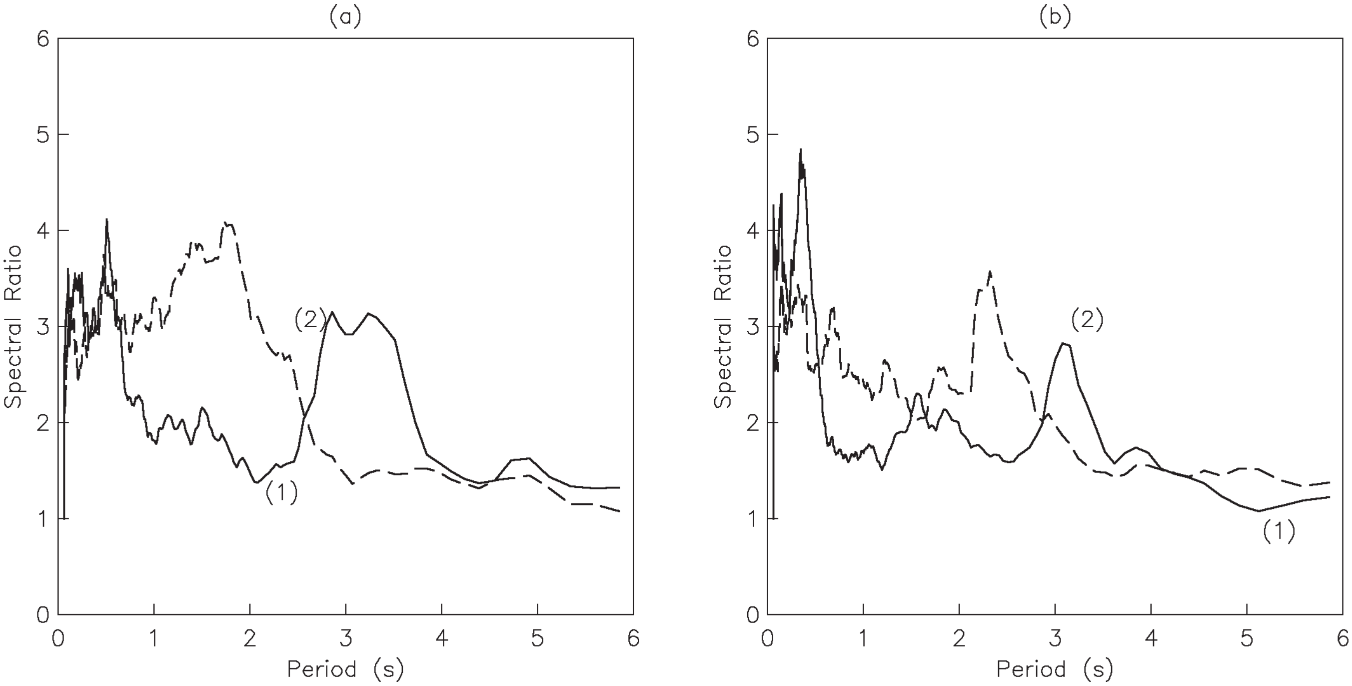

Fig. 13. Spectral ratios of earthquakes with magnitudes ≥ 6.9 (1999 and 1995 events). (a) North-south and (b) east-west.

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