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SITE EFFECT EVALUATION USING SPECTRAL RATIOS WITH ONLY ONE STATION

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ABSTRACT

The spectral ratio technique is a common useful way to estimate empirical transfer function to evaluate site effects in regions of moderate to high seismicity. The purpose of this paper is to show that it is possible to estimate empirical transfer function using spectral ratios between horizontal and vertical components of motion without a reference station. The technique, originally proposed by Nakamura to analyze Rayleigh waves in the microtremor records, is presented briefly and it is discussed why it may be applicable to study the intense *S*-wave part in earthquake records. Results are presented for three different cities in Mexico: Oaxaca, Oax., Acapulco, Gro., and Mexico City. These cities are very different by their geological and tectonic contexts and also by the very different epicentral distances to the main seismogenic zones affecting each city. Each time we compare the results of Nakamura's technique with standard spectral ratios. In all three cases the results are very encouraging. We conclude that, if site effects are caused by simple geology, a first estimate of dominant period and local amplification level can be obtained using records of only one station.

INTRODUCTION

The evaluation of site effects due to local geology or topography has become a standard requirement in microzonation studies or site evaluation for important facilities. One of the more popular techniques to estimate site effects in regions of moderate to high seismicity is to use spectral ratios of earthquake records. This method consists of recording several earthquakes in an array of stations. One of these stations serves as reference and must be located on component rock, away from the source of site effects. Usually, the intense *S*-wave part of the record is used to estimate spectral ratios relative to the reference station, whose records are assumed to be representative of the incident-free field to the topographic or geological irregularity we are assessing. In doing this, we implicitly accept that site effects can be characterized by a 1-D, vertical incidence model. Since the pioneering work by Borcherdt (1970), the calculation of empirical transfer functions, or spectral ratio technique has proven to be very useful to evaluate local site effects in a wide variety of environments (e.g., Borcherdt and Gibbs, 1976; Tucker and King, 1984; Jarpe *et al.*, 1988; Singh *et al.*, 1988a; Chávez-García *et al.*, 1990).

The spectral ratio method however has important limitations to estimate site effects. Some of them have been pointed out by Safak (1991). Others arise from the procedures of operation in the field, where we normally use autonomous, digital recording seismographs. Such stations usually trigger the storage device to record events based on an evaluation of the STA/LTA ratio. Suppose we have installed a reference station on hard rock and we want to evaluate ground motion amplification on soft soil sediments. The background noise level being different in both stations, not all of the events recorded by the soft soil site station will be recorded by the reference station. This situation imposes long periods of observation in order to record several earthquakes in both stations. Another problem is that, in certain cases, it may be very difficult to find a convenient place for the reference station.

In this paper we present an alternative to the evaluation of empirical transfer functions that does not require a reference station. This alternative, originally proposed by Nakamura (1989) to interpret microtremor measurements, rests on the hypothesis that the vertical component of ground motion contains more information on the source of ground motion than does the horizontal components. A suggestion by Singh (1992, personal comm.) led us to try the technique by Nakamura using the S-wave part of earthquake records. In this paper we present empirical results that substantiate the applicability of Nakamura's technique to earthquake records. We have evaluated site effects applying this technique to earthquake records in three cities in Mexico: Oaxaca, Oax., Acapulco, Gro., and Mexico City. These cities are very different by their geological and tectonic contexts and also by the very different epicentral distances to the main seismogenic zones affecting each city. Each time we compare the results of Nakamura's technique with standard spectral ratios. In all three cases the results are very encouraging and suggest that, if site effects are caused by relatively simple geology, the same hypothesis needed by the standard spectral ratios technique, it is possible to estimate dominant period and local amplification level using records of only one station.

THE TECHNIQUE

The technique we apply to earthquake records was originally used by Nakamura (1989) to interpret microtremor measurements. We will describe it following Finn (1991). The hypothesis of departure is that microtremor energy consists mainly of Rayleigh waves, and that site effect amplification is due to the presence at the surface of a soft soil layer overlying a half-space. In these conditions we will have four components of ground motion involved: horizontal and vertical motion components in the half-space, and horizontal and vertical motion components at the surface. According to Nakamura, it is possible to estimate the amplitude effect of the source, A_S, by the ratio

$$A_S = \frac{V_S}{V_B} \tag{1}$$

where V_S = amplitude spectrum of the vertical component of motion at the surface and V_B = amplitude spectrum of the vertical component of motion at the half-space. Nakamura then proceeds to define an estimate of site effect of interest in earthquake engineering, S_E, as the ratio

$$S_E = \frac{H_S}{H_B} \tag{2}$$

where H_S = amplitude spectrum of the horizontal component of motion at the surface and H_B = amplitude spectrum of the horizontal component of motion at the base of the soil layer. Now, to compensate S_E by the effect of the source, we compute a modified site effect function, S_M, as

$$S_M = \frac{S_E}{A_S} \tag{3}$$

which is equivalent to

$$S_M = \frac{\left(\dfrac{H_S}{V_S}\right)}{\left(\dfrac{H_B}{V_B}\right)}. \tag{4}$$

And finally, if we accept that the ratio H_B/V_B is equal to unity, the site effect function, corrected by the source term, may be written as

$$S_M = \frac{H_S}{V_S}. \tag{5}$$

The assumption that H_B/V_B is equal to unity (within a factor of 2, the usual uncertainty when using spectral ratios, e.g., Tucker and King, 1984; Tucker *et al.*, 1984) was verified by Nakamura experimentally, using microtremor measurements at depth in a borehole. The technique by Nakamura has been successfully applied by Ohmachi *et al.* (1991) to interpret microtremor measurements in the San Francisco area, and by Lermo (1992) was applied this method to analyze microtremor records in four different cities in Mexico and obtained very good agreement with results from standard spectral ratios using velocity earthquake records.

However, it is difficult to explain why a technique conceived to analyze Rayleigh waves in microtremor records should work for the intense, S-wave part of seismograms. In order to understand why this may be, we will follow two lines of argument. Let us take in the first place the case of Mexico City, a very relevant case in any study of site effects. Here, ground motion amplification due to a thin, extremely soft clay layer attained a factor of 50 at some frequencies during the great Michoacán earthquakes of 1985 (Singh *et al.*, 1988a). However, despite such large site effects, the vertical component of displacement had the same character and similar amplitudes notwithstanding the type of soil at the station, clay layer, or lava flows (Campillo *et al.*, 1989). Moreover, recent studies with the accelerometric network of Mexico City have confirmed this invariance of vertical component of ground motion for other, smaller events such as the 25 April, 1989, $M_S = 6.9$ (Chávez-García, 1991). It appears then that the vertical component is not subjected to the very important site effects suffered by the horizontal components and may thus be used to measure ground motion incident to the very local site conditions.

Another line of argument is based on very simple numerical modeling. Let us suppose that site effects are due to a single layer over a half-space, and that excitation is given by harmonic plane S waves. In order to have nonzero vertical motion, we must admit incidence other than vertical of SV waves. The parameters of this model include, then, the incidence angle and the mechanical properties of the layer relative to the half-space. The thickness of the layer contributes only as a scale factor for the frequency axis. In this kind of modeling it is usual practice to evaluate surface ground motion relative to the amplitude of the incident wave. However, if we want to conform to the hypothesis of the spectral ratio method we should define site effect amplification as the ratio

$$\frac{u_S}{u_{HS}} \tag{6}$$

where u_S = horizontal displacement at the surface, and u_{HS} = horizontal displacement at the interface sediments-substratum. For the hypothesis we have made concerning the excitation, the difference is a factor $\cos\gamma$, where γ = incidence angle, measured with respect to the vertical. It is obvious that differences will be significant only at large incidence angles. Consider now the vertical component. If Nakamura's technique can be applied in these conditions, the ratio

$$\frac{w_S}{u_{HS}} \tag{7}$$

where w_S = vertical displacement at the surface, should be unity. For the sake of illustration let us consider the 1-D stratigraphic model for SCT station at Mexico City given by Seed *et al.* (1988) and shown in Table 1. We have added reasonable values of damping for P and S waves. Figure 1 shows the transfer functions obtained using Haskell's method (Aki and Richards, 1980) for four different incident angles. Amplification is measured relative to the horizontal component of incident ground motion, u_{HS}. The horizontal component (Fig. 1a) shows the classical 1-D response of a soft layer over a half-space with a resonant peak at a frequency slightly over 0.5 Hz. The amplitude of this resonant peak varies in amplitude by a factor larger than 2 as a function of incident angle. This variation must contribute significantly to the dispersion observed in experimental spectral ratios. In regard to the vertical component (Fig. 1b), we also have important variations (over an order of magnitude) in amplitude, which is not surprising as in this simple model vertical motion for vertical incidence should be zero. What is interesting to note on Figure 1 is that variations of vertical amplification as a function of frequency for a given incidence angle are small, almost always smaller than a factor 2 and certainly much smaller than those of the horizontal component, that attain a factor larger than 20.

We have used the transfer functions of Figure 1 to compute Nakamura's ratio (equation 5). Figure 2 shows this ratio with dotted line, compared to the

TABLE 1

MECHANICAL PROPERTIES AT SCT SITE AT MEXICO CITY

Layer	Thickness	ρ [g/cm^3]	α [m/s]	β [m/s]	ξ_P	ξ_S
1	4.0	1.2	800	70	0.01	0.02
2	27.0	1.2	800	75	0.01	0.02
3	7.0	1.2	800	110	0.01	0.02
Half-space		2.0	1500	900	0.005	0.01

ρ = density; α = P-wave velocity; β = S-wave velocity; ξ_P = damping of P waves; ξ_S = damping of S waves.

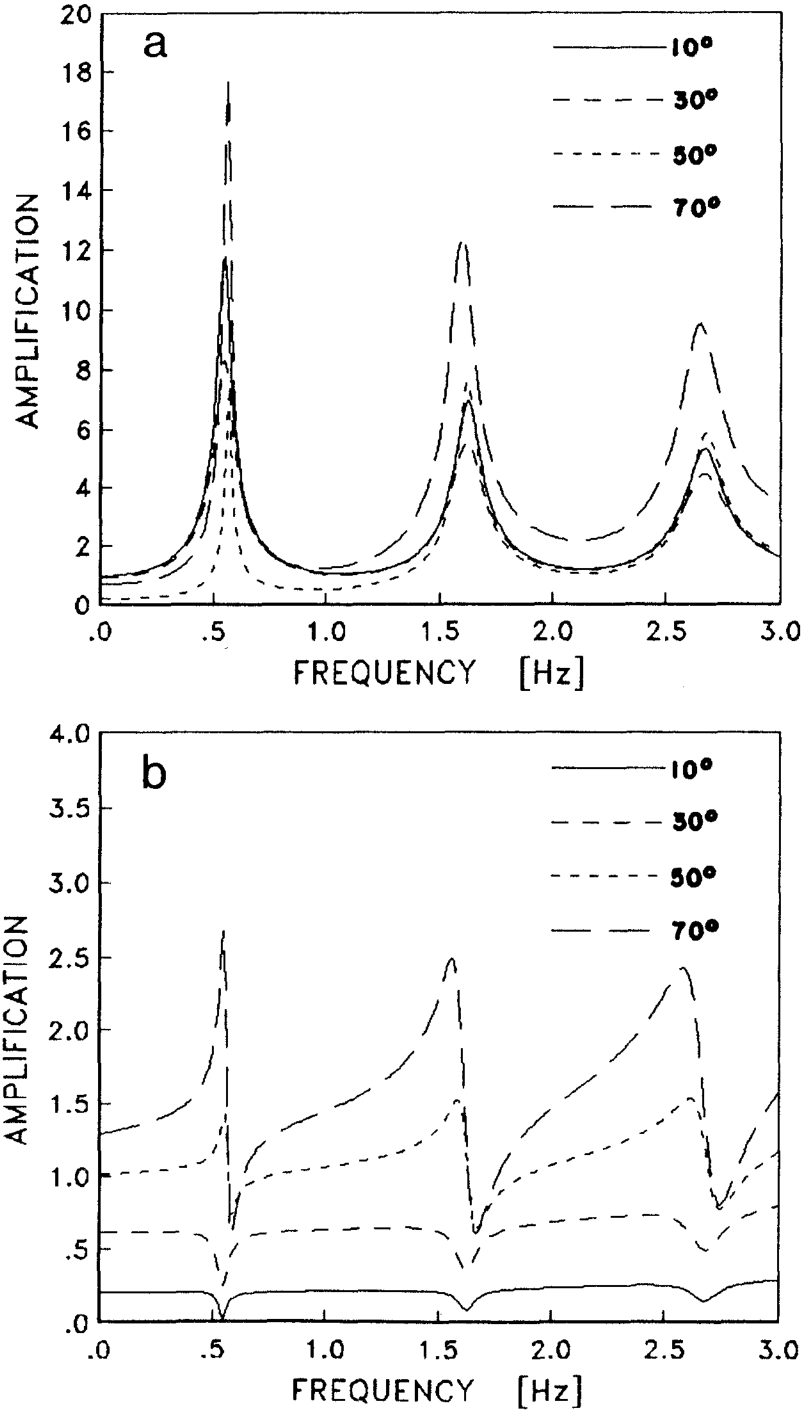


FIG. 1. Transfer functions of horizontal (a) and vertical (b) motion relative to the horizontal amplitude of incident motion for the plane layer model of Table 1. Excitation is given by plane *SV* waves with four different incidence angles relative to the vertical.

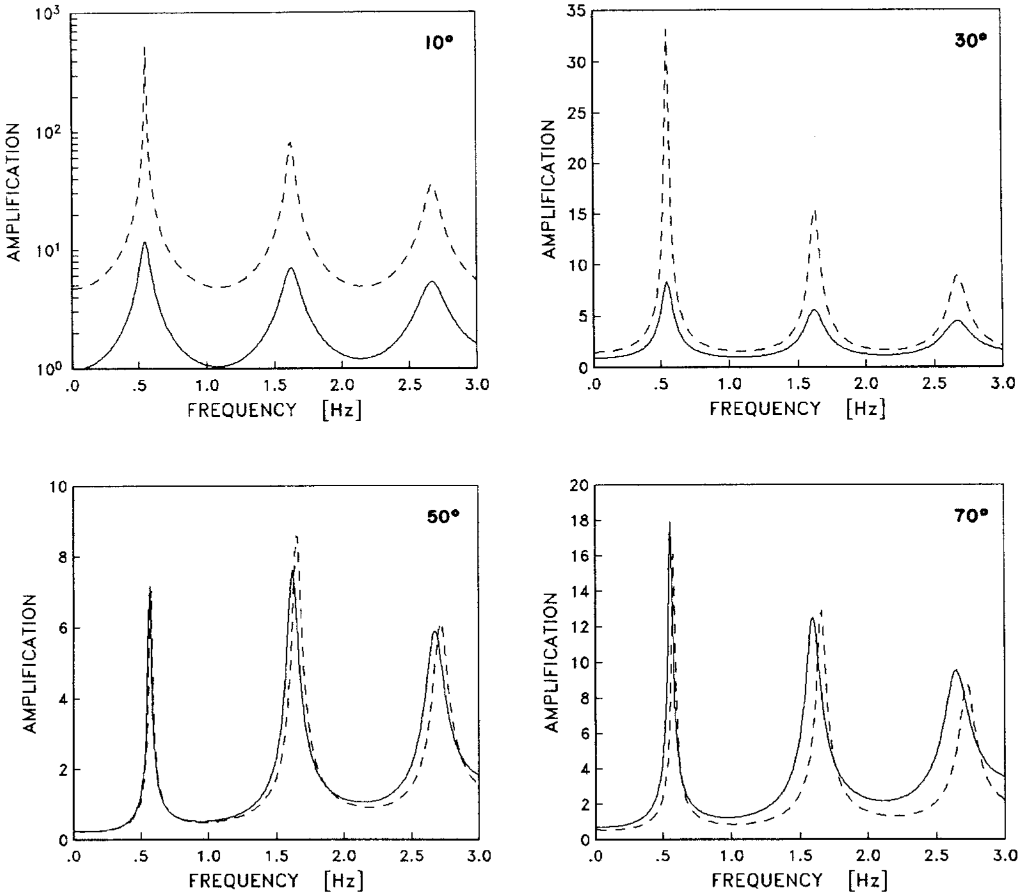


FIG. 2. Horizontal transfer functions for the stratigraphy given in Table 1 and four incidence angles of plane *SV* waves. Continuous line: ratio between horizontal motion at the surface and horizontal motion of incident waves. Dotted line: ratio between horizontal and vertical components of motion at the surface.

estimate of transfer function given by equation 6 (drawn with continuous line). For all angles of incidence, the frequencies of resonance are identified with good precision by Nakamura's ratio. The amplitude of the latter, as expected, is very high for small incidence angles (for vertical incidence it would be infinite), but its shape is very near to the true transfer function because the vertical component is almost flat, as shown in Figure 1b. For incidence angles of 50° and larger, we obtain quite good agreement between Nakamura's results and standard spectral ratios, both in the frequencies of resonance and in the amplification values at resonance. Thus, it appears that Nakamura's ratio is a good measure of the transfer function when the vertical component is not zero. Experimental results, however, show clearly that even if *S*-wave motion in the vertical component of seismic records is small, very seldom is it zero.

We have discussed possible reasons to explain why the technique by Nakamura could work for earthquake records. In the continuation of this paper we will show that this is indeed the case for earthquake records obtained in three cities in Mexico. These cities differ significantly in their geologic context and in the distance to the seismogenic zones. In each case we will compare the results obtained with standard spectral ratios relative to a reference station. Additionally, we compute results from Nakamura's technique at the reference station at each site. If Nakamura's technique holds, site amplification at the reference station obtained by this method is a measure of the appropriateness of the site selected as reference station.

EXAMPLES OF APPLICATION

Oaxaca, Oaxaca

During July and August 1991, a temporary network of seven digital, 3-component seismic stations operated within the city of Oaxaca. The stations used were PRS-4, portable seismographs by Scintrex (Ontario, Canada) which record on a solid state memory. The seismometers were triaxial Lennartz sensors LE-3D, with natural period of 1 sec. The response of the complete recording system is flat between 1 and 20 Hz. The purpose of the temporary network was to evaluate empirical transfer functions to propose a microzonation of this city (Lermo *et al.*, 1991). From the different soft soil sites covered with the seismic stations we have selected 3, located toward the center of the valley. The reference station, VHO, was located on a hill to the north of the valley, on metamorphic rock. Figure 3 shows the map with the distribution of these four stations in the field. Table 2 gives the epicentral locations and the coda magnitude of the events they recorded during operation. We include the value of peak velocity recorded by the horizontal components at each station. Peak velocity at the stations on soft soil are generally between 2 and 6 times larger than those recorded at the reference station, VHO.

The processing sequence was as follows. From each record we selected a window of 10 sec, including the intense part of the ground motion. This window was cosine tapered (5%) and Fourier transformed. The spectral amplitudes were then smoothed with a one-third octave band filter and used to compute spectral ratios relative to a reference site or relative to the vertical component.

The results obtained are presented in a synthetic form for the E–W component on Figure 4. The first row of this figure shows both, the empirical transfer functions relative to VHO and the results of applying Nakamura's technique, i.e., spectral ratios between the E–W and the vertical components. In each diagram, the thick lines correspond to Nakamura's technique, whereas thin lines indicate results relative to the reference station. Continuous lines show the average of transfer functions computed for individual records, and dotted lines give the mean plus or minus one standard deviation. Site effects as seen on these curves show a prominent peak of amplification between 1 and 2 Hz at TEQUIO, between 1 and 3 Hz at UBJ, and between 2 and 4 Hz at NOTX. Mean amplification is highest at TEQUIO and smallest at NOTX. There is a very good agreement between both sets of empirical transfer functions. In all three cases, the main peak of the average transfer functions computed relative to the vertical component lie within one standard deviation of the average transfer functions relative to VHO. At frequencies higher than the fundamental resonant peak, Nakamura's technique shows higher amplitudes than does standard spectral ratios. The second row of the figure shows the result of Nakamura's technique for VHO, the reference station. We show three figures for VHO as each one uses only those earthquakes included in the corresponding soft soil station. The results for VHO indicate that the observed peaks on the soft

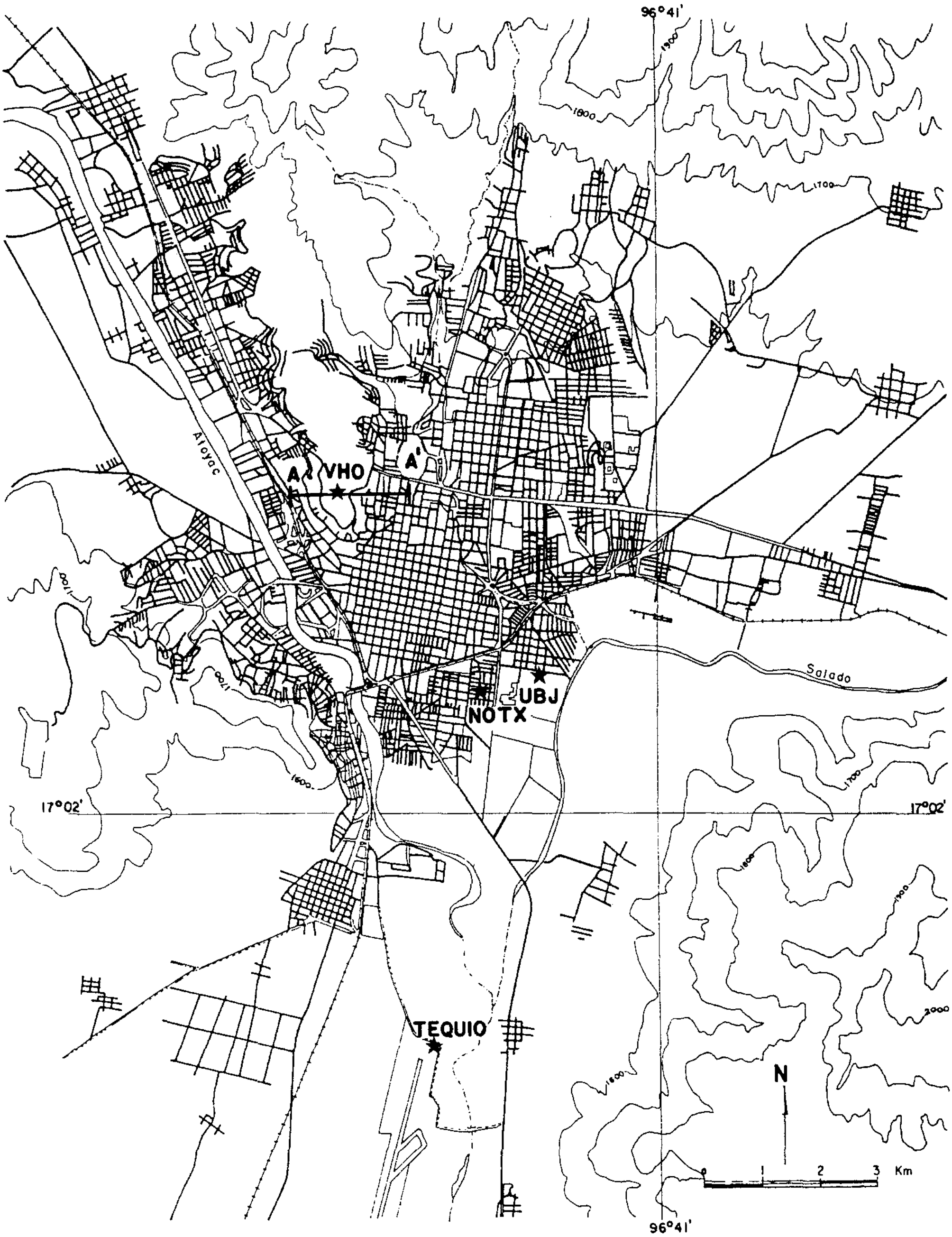


FIG. 3. Distribution of velocity seismographs in the city of Oaxaca. The reference station is VHO.

soil sites do correspond to local amplification as they are not present in the reference station.

Results for the N–S motion component are shown in Figure 5, in the same format as for the E–W component. The transfer functions relative to VHO (thin lines) have the same shape as those of the E–W component, but amplitudes are higher, a difference that adds to the incertitude of results computed with

TABLE 2

EVENTS RECORDED BY THE OAXACA, OAX. NETWORK

Date	Lat. N	Long. W	M_c	Recorded by	Peak Hor. Vel. [cm/sec] N-S	Peak Hor. Vel. [cm/sec] E-W
910728	16.53	95.36	5.0	UBJ	2.67	3.39
				NOTX	1.63	2.11
				VHO	0.44	0.55
910728	17.55	96.79	3.1	UBJ	0.05	0.04
				VHO	0.01	0.04
910728	17.10	96.25	3.0	NOTX	0.04	0.03
				VHO	0.01	0.01
910728	18.40	94.72	4.5	UBJ	0.71	0.99
				VHO	0.07	0.12
910729	18.20	97.05	3.5	UBJ	0.20	0.20
				VHO	0.01	0.01
910729	16.76	96.94	2.9	UBJ	0.05	0.03
				NOTX	0.03	0.02
				VHO	0.02	0.02
910730	16.60	94.27	4.7	NOTX	0.65	0.59
				VHO	0.21	0.40
910731	16.03	97.02	4.2	NOTX	0.14	0.11
				VHO	0.04	0.05
910817	16.81	96.10	4.2	TEQUIO	0.36	0.41
				VHO	0.10	0.13
910818				TEQUIO	0.67	0.42
				VHO	0.11	0.15
910818	16.26	97.70	4.5	TEQUIO	1.13	0.85
				VHO	0.17	0.31
910819	19.34	93.46	4.5	TEQUIO	0.22	0.14
				VHO	0.06	0.08

standard spectral ratios. Results for Nakamura's ratio are very similar for the sediment stations for both horizontal components. Thus, although Nakamura's ratio has the same shape as transfer functions relative to VHO, its amplitudes are lower, especially at TEQUIO and UBJ. As regards the results for the reference station, the average site transfer function for VHO has slightly larger amplitudes in the E-W than in the N-S component.

One feature that is consistently observed on Nakamura's technique results for the reference station, VHO, is a systematic peak of amplification at 5 Hz on both components of ground motion. This peak attains a factor 4 in average, indicating that our reference station may also be affected by site effects. Obviously, this may not be corroborated using spectral ratios, however, it is very tempting to interpret this amplification as a hard rock site effect, such as topographic amplification (e.g. Bard, 1982; Tucker *et al.*, 1984; Geli *et al.*, 1988). Indeed, VHO was installed on top of a hill. Figure 6 shows the topographic profile roughly in the E-W direction across VHO (section AA′ in Fig. 3); an asymmetric low hill with a 160 m maximum height variation over a horizontal distance of 2000 m. In order to estimate the resonant frequency of this topographic feature, we have computed the 2-D transfer function of the profile shown on Figure 6 to vertical incidence of *SV* waves, using a recently developed boundary integral formulation (Sánchez-Sesma and Campillo, 1991). We assumed a *P*-wave velocity of 1500 m/sec and *S*-wave velocity of 500 m/sec,

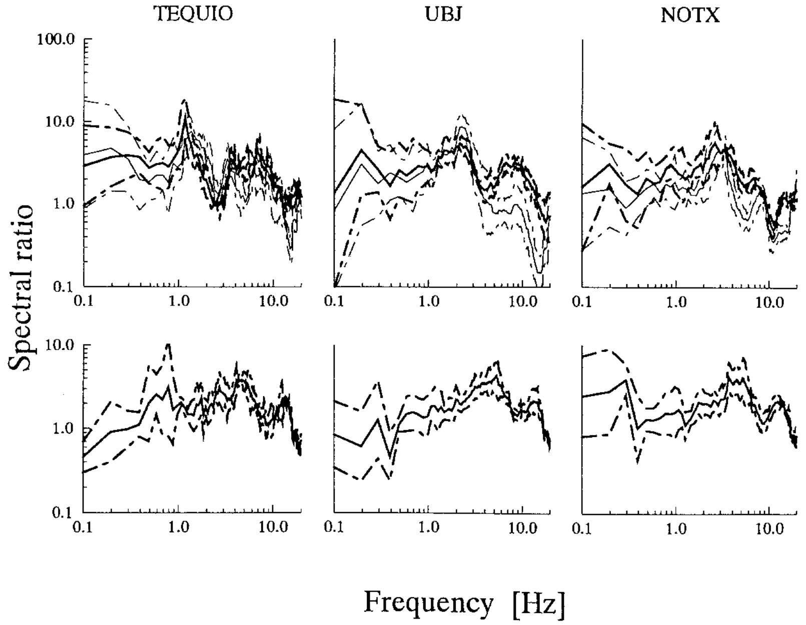


FIG. 4. Results obtained for the four stations of the Oaxaca network, E–W component. The first row of three figures shows both, the empirical transfer functions relative to VHO (thin lines) and the results of applying Nakamura's technique (thick lines). Continuous lines show the average of transfer functions, and dotted lines give the mean plus or minus one standard deviation. The second row of figures presents the results of the technique by Nakamura obtained for the reference station VHO. We show three figures for VHO as each one uses only those earthquakes recorded also by the corresponding soft soil station.

based on unpublished results of small seismic refraction profiles carried out by ourselves in 1991. Results are shown on Figure 7, both for horizontal and vertical motion components. In these figures we observe the usual response of topographic features: amplification on convex parts of it and deamplification on concave parts (Bard, 1982). Maximum amplification for the horizontal component attains 86% (in Fig. 7 the free field value for the horizontal component is 2), whereas the vertical component reaches a value of 1.6. Maximum amplification occurs at 6.5 Hz for the horizontal component, and a 5.3 Hz for the vertical component, in very good agreement with the experimental results obtained with Nakamura's technique. There is a significant difference between maximum amplification predicted by the model and that observed with Nakamura's ratio, however, it is well known that oversimplified models usually underestimate significantly ground motion amplification due to topographic features (see Geli *et al.*, 1988, for a thorough discussion).

Acapulco, Guerrero

In a recent study, Gutierrez and Singh (1992) compared standard spectral ratios from strong motion records with microtremor data in order to determine site effects at some soft soil sites in Acapulco, Guerrero. We have taken advantage of the strong motion records obtained to test Nakamura's technique in another environment. Field data at three sites (ACAC, ACAD and ACAZ) was obtained using force balance digital accelerographs DCA-333 by Terra Technology with 30 Hz natural period and 0.7 fraction of critical damping. Site VNTA, the reference station, was instrumented with a force balance digital accelerograph DSA-1 by Kinemetrics (Pasadena, CA, natural period of 50 Hz and 0.7

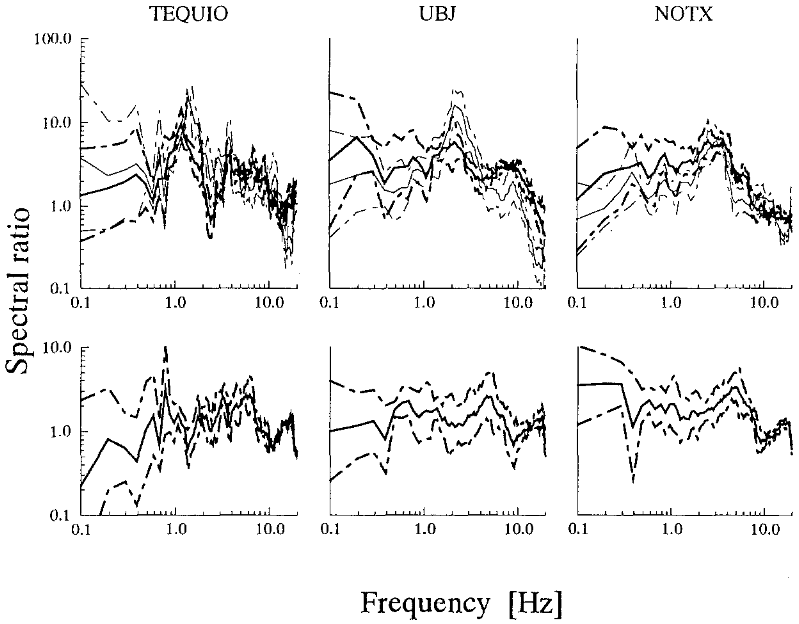


FIG. 5. Results obtained for the four stations of the Oaxaca network, N-S component. The first row of three figures shows both, the empirical transfer functions relative to VHO (thin lines) and the results of applying Nakamura's technique (thick lines). Continuous lines show the average of transfer functions, and dotted lines give the mean plus or minus one standard deviation. The second row of figures presents the results of the technique by Nakamura obtained for the reference station VHO. We show three figures for VHO as each one uses only those earthquakes recorded also by the corresponding soft soil station.

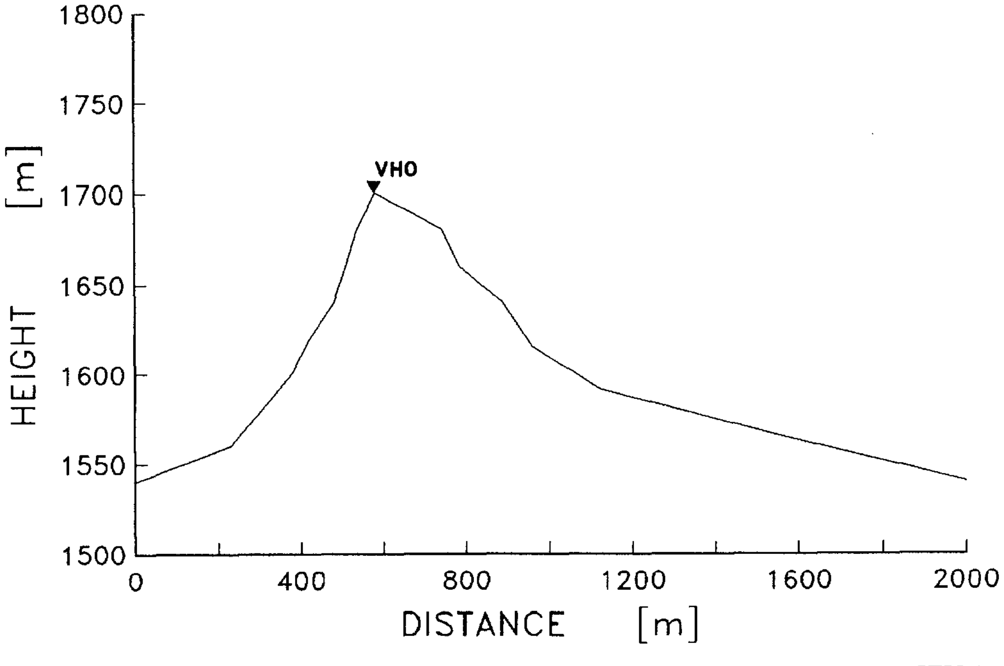
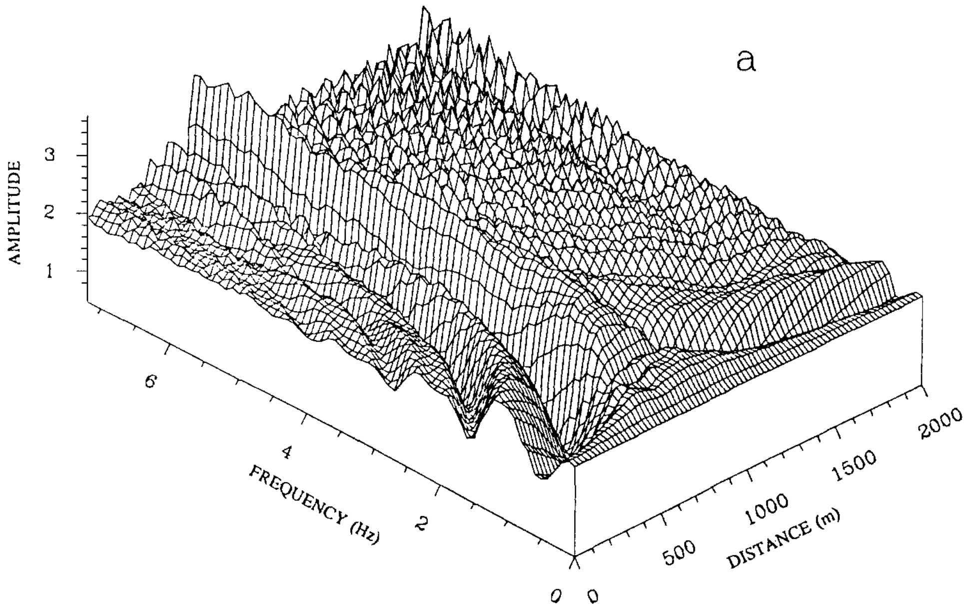


FIG. 6. Topographic profile along the line AA′ shown on Figure 3. The reference station VHO is located at the top of the hill.



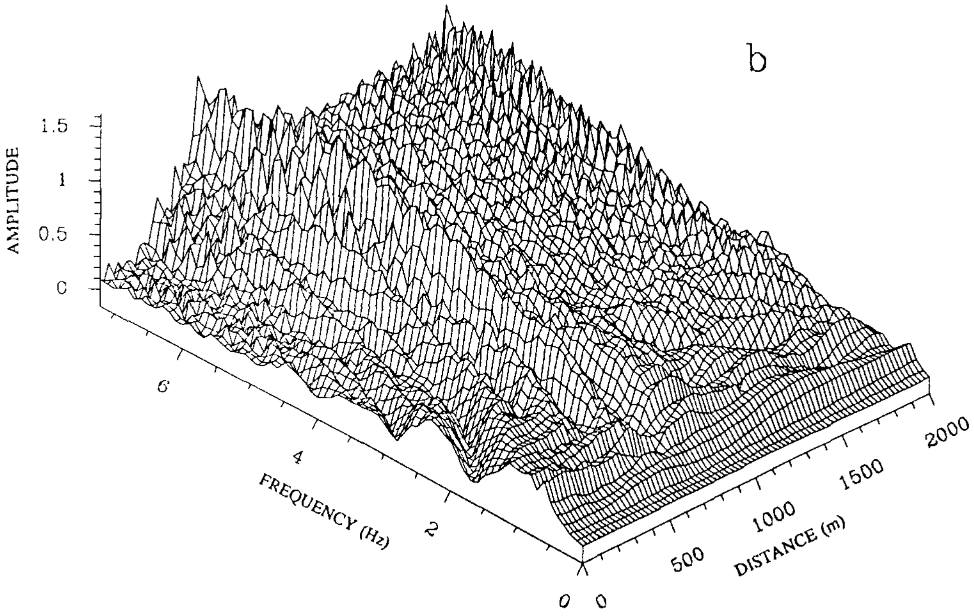


FIG. 7. Transfer functions for vertical incidence of *SV* waves on the topographic profile shown on Figure 6 as a function of distance along the profile and frequency. (a) Horizontal component. (b) Vertical component.

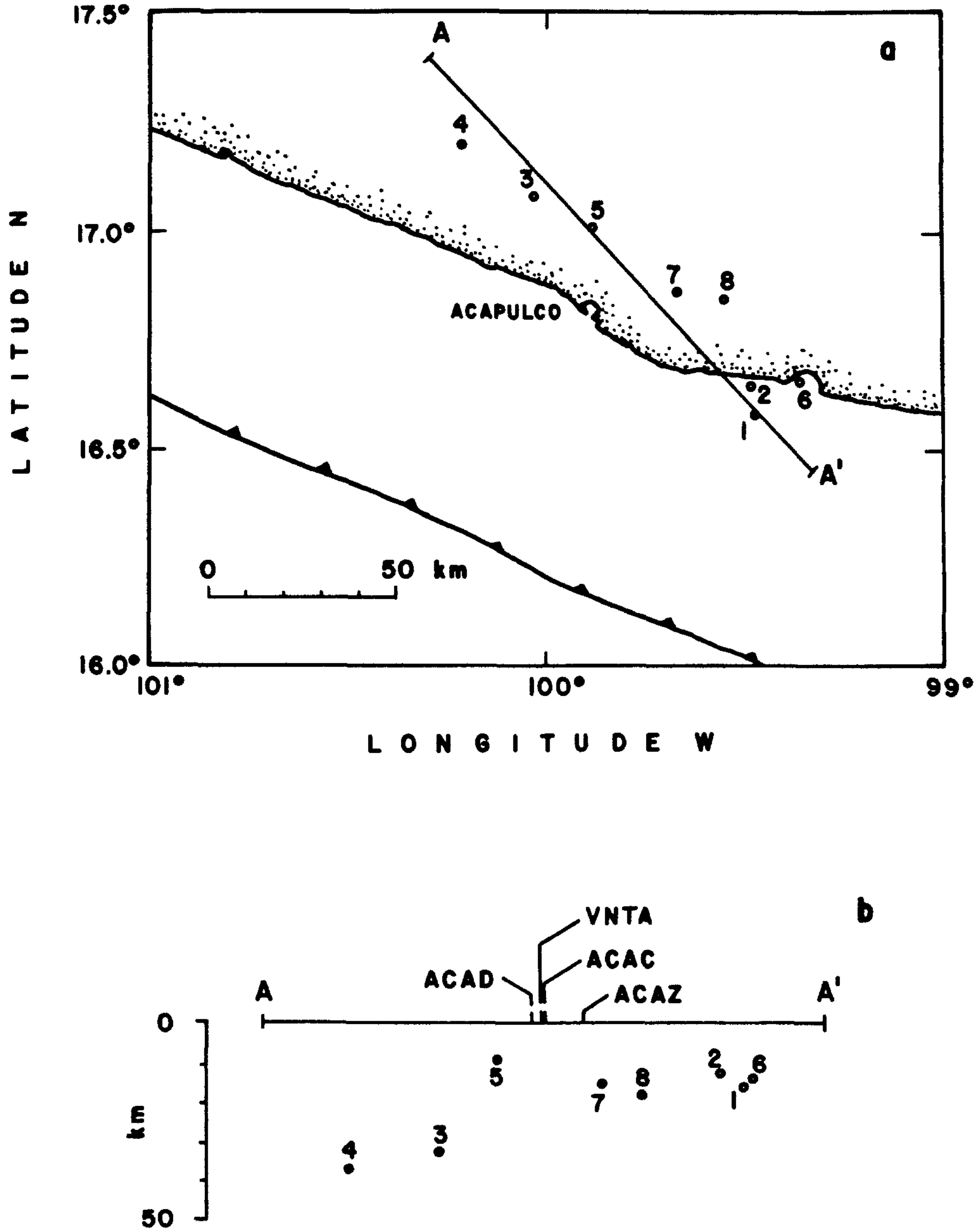


FIG. 8. (a) Map of the region around Acapulco showing Acapulco Bay and the epicenters of the events enlisted in Table 3. (b) Section along AA', shown in (a), showing the depth distribution of events.

fraction of critical damping). We have used stations ACAC, ACAD, ACAZ, and VNTA of Gutierrez and Singh (1992). However, we have not used the same set of events they studied. This is due to the fact that from the eight earthquakes they analyzed, only five triggered all four stations. Since the study by Gutierrez and Singh (1992), three more earthquakes have triggered the four stations of the network. We have used then five events of Gutierrez and Singh (1992) with records on all the stations and three more events. Figure 8 shows the location of the stations and the epicenters of the selected events. Table 3 gives hypocenter locations and coda magnitude for this data set, taken from Anderson *et al.* (1991a, 1991b). In Table 3 we have included the value of peak acceleration recorded by the horizontal components at each station. Peak acceleration at VNTA is generally lower than at stations on soft soils, with the exception of two events; The variability in the peak acceleration at the different stations is larger than for velocity records. This may be caused by the higher frequency content of acceleration records.

Gutierrez and Singh (1992) found, to a first approximation, that site effects in Acapulco were independent of source depth and location. However, additional effects may come from the directivity of the source, a factor neglected by Gutierrez and Singh (1992). This possibility was investigated by computing Nakamura's ratio for the N–S and E–W components, and for radial and transverse components for each record.

TABLE 3

EVENTS RECORDED BY THE ACAPULCO, GRO. NETWORK

	Date	Lat. N	Long. W	Depth [km]	M_c	Recorded by	Peak Hor. accel. [cm/sec^2]	
							N–S	E–W
1	890425	16.58	99.48	17	6.5	VNTA	28.96	62.20
						ACAZ	148.13	146.91
						ACAC	101.14	108.80
						ACAD	330.52	329.78
2	890502	16.64	99.51	13	5.1	VNTA	8.25	8.80
						ACAZ	39.85	34.64
						ACAC	53.90	41.12
						ACAD	72.94	58.21
3	890817	17.12	100.04	26	4.8	VNTA	14.43	20.25
						ACAZ	22.50	21.71
						ACAC	16.96	12.98
						ACAD	59.73	78.03
4	891008	17.19	100.21	36	5.0	VNTA	9.82	10.68
						ACAZ	15.28	24.13
						ACAC	14.13	11.61
						ACAD	42.89	48.04
5	900306	17.01	99.89	9	4.4	VNTA	16.77	19.05
						ACAZ	17.71	14.34
						ACAC	35.15	26.24
						ACAD	43.60	47.17
6	900404	16.65	99.37	15	5.0	VNTA	5.31	7.74
						ACAZ	20.25	18.82
						ACAC	13.36	18.91
						ACAD	15.11	15.11
7	900709	16.86	99.67	16	4.5	VNTA	19.03	28.80
						ACAZ	15.31	21.05
						ACAC	11.48	11.48
						ACAD	11.01	17.71
8	900710	16.83	99.57	18	4.8	VNTA	16.15	24.73
						ACAZ	59.34	49.77
						ACAC	47.85	80.39
						ACAD	55.90	76.08

The processing sequence was the same followed by Gutierrez and Singh (1992). Results are summarized in Figures 9 and 10. The first row of Figure 9 shows both, the empirical transfer functions relative to VNTA and the results of applying Nakamura's technique, i.e., spectral ratios between the E–W and the vertical components. In each diagram, the thick lines correspond to Nakamura's technique, whereas thin lines indicate results relative to the reference station. Continuous lines show the average of transfer functions computed for individual records, and dotted lines give the mean plus or minus one standard deviaVtion. We observe a very good agreement between the average transfer functions obtained with both techniques for ACAZ and ACAD. A fair agreement is obtained for ACAC, although Nakamura's ratio predicts a lower amplitude than that of standard spectral ratios. Dispersion of individual spectral ratios is less for Nakamura's ratios than for standard spectral ratios. The second row of Figure 9 shows the result obtained with Nakamura's ratios using rotated signals in the transverse direction. Again, continuous lines show the average transfer function, whereas dotted lines give the mean plus or minus one standard deviation. There are no significant differences between results for the transverse and those for the E–W component for stations ACAZ and ACAD. At station ACAC, transverse spectral ratios have slightly larger amplitude and show better resolution of the resonant peak than does E–W spectral ratios. This suggests strongly that the S-wave portion of the strong motion record results

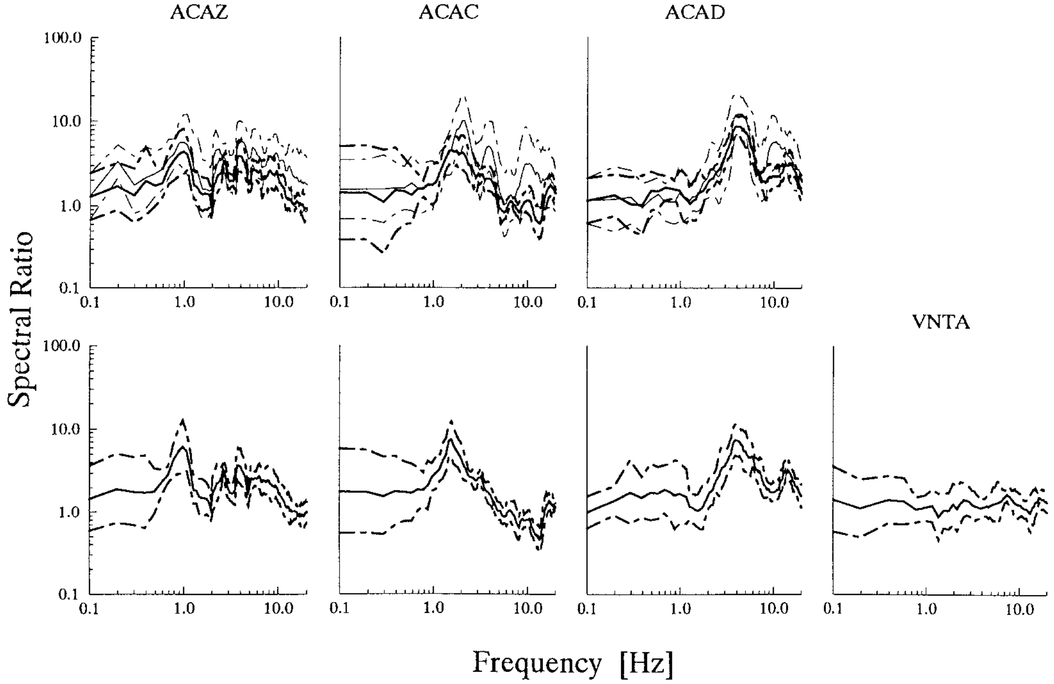


FIG. 9. Results obtained for the strong motion records of Acapulco stations, E–W component. Continuous lines show the average of transfer functions, and dotted lines give the mean plus or minus one standard deviation. The first row of three figures shows both, the empirical transfer functions relative to VNTA (thin lines) and the results of applying Nakamura's technique (thick lines). The first three figures of the second row shows Nakamura's ratio for the rotated transverse component, relative to the vertical, for the corresponding soft soil station. The lower rightmost diagram presents Nakamura's ratio for E–W component at VNTA.

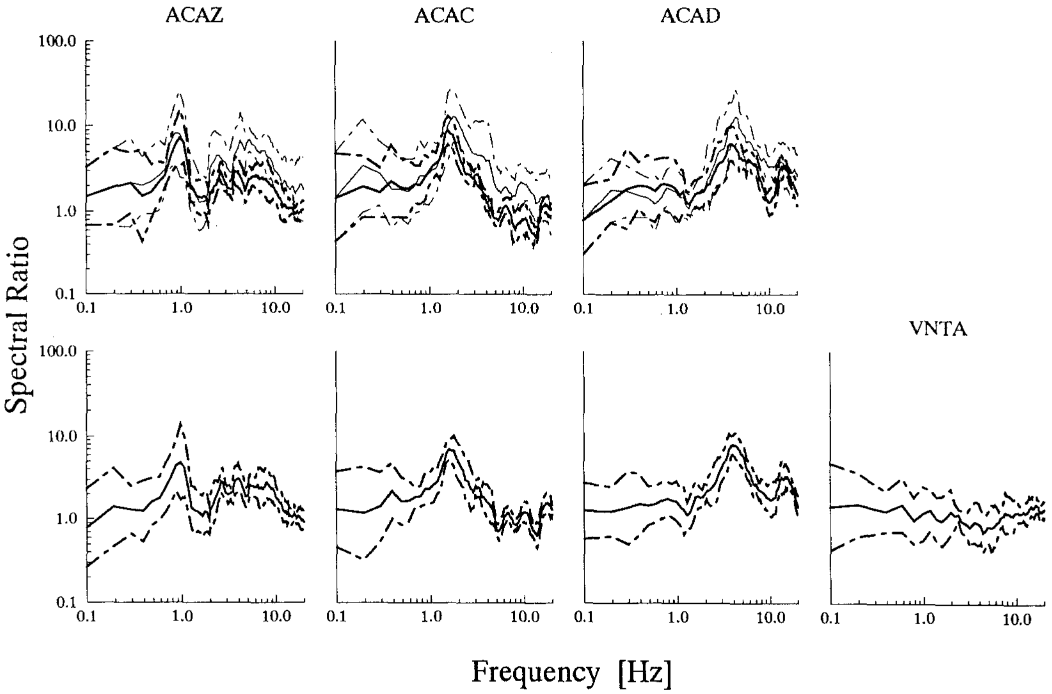


FIG. 10. Results obtained for the strong motion records of Acapulco stations, N–S component. Continuous lines show the average of transfer functions, and dotted lines give the mean plus or minus one standard deviation. The first row of three figures shows both, the empirical transfer functions relative to VNTA (thin lines) and the results of applying Nakamura's technique (thick lines). The first three figures of the second row shows Nakamura's ratio for the rotated radial component, relative to the vertical, for the corresponding soft soil station. The lower rightmost diagram presents Nakamura's ratio for N–S component at VNTA.

from energy incident from many directions. The average behavior of empirical transfer functions has a stronger dependence on local site effects than on directivity of the source. Figure 10 shows similar results for the N–S component (first row of the figure) and radial component for Nakamura's technique (in the second row). As regards the N–S spectral ratios, the same observations apply as for the E–W component: less dispersion of individual ratios with Nakamura's technique, and excellent agreement in the average behavior between standard spectral ratios and Nakamura's ratio both, for the frequency of occurrence of maxima, and for their amplitude. Again, we observe small differences between Nakamura's ratios for N–S and radial components. This time, it is station ACAD the one that shows the larger differences, although results for ACAZ and ACAC are very similar. Finally, in both figures the results of Nakamura's technique for VNTA, the reference station, (diagram at the bottom right in both figures) show clearly that this station is adequate to estimate incident motion under soft sediments for the other stations. The average transfer function for VNTA is flat with unit amplification.

Mexico City

A final example of application is the case of Mexico City, where site effects are extremely important and were responsible for significant destruction during the September 1985, Michoacán earthquake. There have been several studies of empirical transfer functions, first with the data from the 1985 earthquakes, and after that with the data obtained with the new accelerograph network of Mexico City. Results have been published by Singh *et al.* (1988a and b). Our aim here is not to make extensive computations using all available data, but rather to show that Nakamura's technique works well also in the extreme local site conditions of Mexico City, where amplification occurs at very low frequencies. To this end, we have selected four representative sites and chosen a sample of earthquakes recorded on all these four stations. The sites selected for study are CDAO, DFRO, and SCT1 sites in the lake bed zone, SXVI in the transition zone and CU as reference station, in the hill zone. The instruments at these sites are force balance digital accelerographs DCA-310 and DCA-333 by Terra Technology with 30 Hz natural period and 0.7 fraction of critical damping. Pertinent data of our data set is given in Table 4, compiled from Ordaz and Singh (1992), to the exception of event number 5 obtained from Anderson *et al.* (1991b). In Table 4, we have included peak acceleration values recorded by the horizontal components. The same comments as for the case of Acapulco apply. All of the events occurred in the subduction zone, to the south of Mexico City and at distances ranging from 300 to 400 km. The processing sequence was the same used for the data from Oaxaca with the difference that, as the intense ground motion part is very long in Mexico City, we have used a window of 20 sec.

The results obtained are shown on Figures 11 and 12, for E–W and N–S components, respectively. The format of the figures is the same used in the case

TABLE 4

EVENTS RECORDED AT MEXICO CITY

Date	Lat. N	Long. W	Depth [km]	M_s	Recorded by	Peak Hor. accel. [cm/sec]	
						N-S	E-W
850919	18.14	102.71	16	8.1	CU	28.12	33.50
					CDAO	69.16	80.40
					SXVI	44.11	42.42
					SCT1	97.97	167.92
850921	17.62	101.82	20	7.6	CU	2.22	1.95
					CDAO	48.66	32.30
					SXVI	21.48	26.28
880208	17.50	101.14	20	5.8	CU	13.08	9.97
					CDAO	9.71	5.35
					DFRO	8.15	7.88
890425	16.58	99.48	17	6.9	CU	14.76	13.00
					CDAO	27.85	34.17
					SXVI	23.36	16.28
					SCT1	37.49	37.89
					DFRO	45.57	55.04
900511	17.05	100.84	12	4.9	CU	3.05	1.54
					CDAO	5.43	4.01
					SCT1	4.45	3.76
					DFRO	4.41	4.45
900531	17.12	100.84	21	5.8	CU	1.20	0.96
					CDAO	9.22	15.37
					SXVI	5.58	6.90
					SCT1	8.46	5.49
					DFRO	11.04	9.96

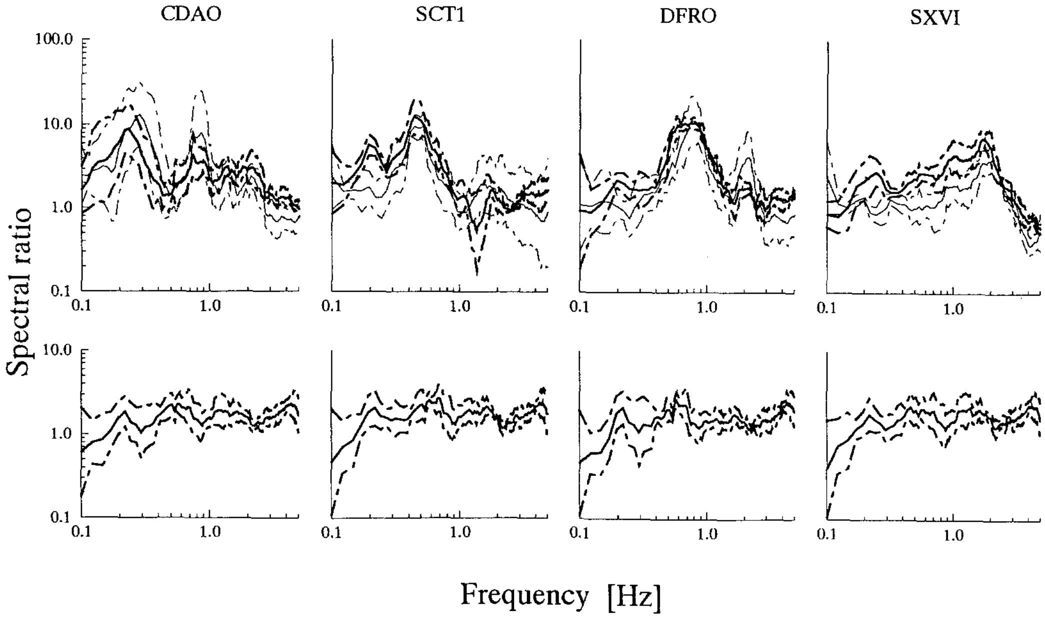


FIG. 11. Results obtained for the acceleration records of Mexico City stations, E–W component. The first row of four figures shows both, the empirical transfer functions relative to CU (thin lines) and the results of applying Nakamura's technique (thick lines). Continuous lines show the average of transfer functions, and dotted lines give the mean plus or minus one standard deviation. The second row of figures presents the results of the technique by Nakamura obtained for the reference station CU. We show four figures for CU as each one uses only those earthquakes recorded also by the corresponding soft soil station.

of Oaxaca. The first row of Figure 11 shows both, the empirical transfer functions relative to CU and the results of applying Nakamura's technique, i.e., spectral ratios between the E–W and the vertical components. In each diagram, the thick lines correspond to Nakamura's technique, whereas thin lines indicate results relative to the reference station. Continuous lines show the average of transfer functions computed for individual records, and dotted lines give the mean plus or minus one standard deviation. There is a very good agreement between both average curves for the four stations considered. CDAO and DFRO show clearly resonance at a fundamental mode both for standard spectral ratios and for Nakamura's ratio. For these stations, standard spectral ratios also show a higher order harmonic resonance, that does not appear in Nakamura's curve. Average amplification values for the E–W component are around a factor 10 (however with a large dispersion, especially at CDAO) at frequencies between 0.3 and 0.8 Hz depending on the site. SXVI also shows a peak of amplification (around a factor 4) for a frequency of 2 Hz. The second row of Figure 11 shows the result of Nakamura's technique for CU, the reference station. We show four diagrams for CU as each one uses only those earthquakes included in the corresponding soft soil station. No significant trend appears, and in all of the curves for CU, values are around one for the frequency range investigated.

Figure 12 presents the results for the N–S component in the same format as before. We find a very good agreement between both average curves for CDAO and DFRO. Agreement is not so good for stations SCT1 and SXVI, where amplitude is overestimated by Nakamura's ratio. The reason for this is that

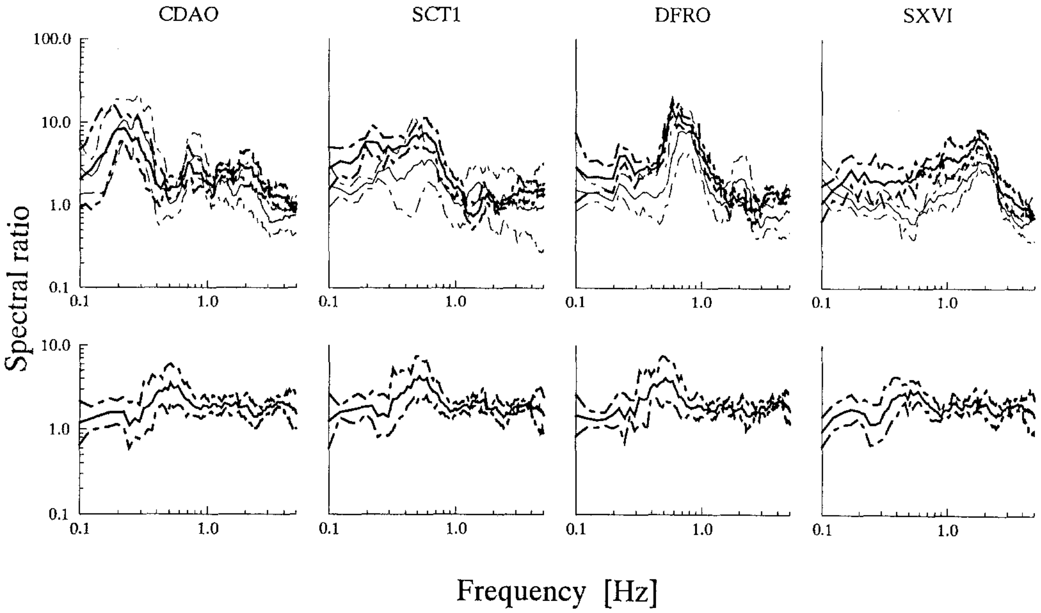


FIG. 12. Results obtained for the acceleration records of Mexico City stations, N–S component. The first row of four figures shows both, the empirical transfer functions relative to CU (thin lines) and the results of applying Nakamura's technique (thick lines). Continuous lines show the average of transfer functions, and dotted lines give the mean plus or minus one standard deviation. The second row of figures presents the results of the technique by Nakamura obtained for the reference station CU. We show four figures for CU as each one uses only those earthquakes recorded also by the corresponding soft soil station.

Nakamura's ratio has similar amplitudes for both horizontal components, whereas standard spectral ratios are lower for the N–S than for the E–W component. The frequency of occurrence of resonance is however well predicted in all four cases. Finally, the second row shows Nakamura's ratio computed for CU, the reference station. There appears no significant trend. In all four diagrams, values are around one for the frequency range investigated. The only exception is a small bump that occurs at about 0.5 Hz. We observe no other indication of the high amplification observed in the hill zone sites by Ordaz and Singh (1992). We conclude that Nakamura's ratio can only give indications of site effects due to the very local stratigraphy around the station. The amplification observed by Ordaz and Singh (1992) is a regional feature and probably lies beyond Nakamura's ratio resolution.

CONCLUSIONS

Spectral ratios is an attractive technique to empirically evaluate site effects due to local geology or topography. However, due to current instrumentation, simultaneous records both in the soft soil site and in the reference hard rock station are not always obtained. This situation imposes long periods of observation even in regions of moderate to high seismicity. In this paper we have proposed the applicability of Nakamura's technique to estimate site effects using spectral ratios from only one station. This technique, originally proposed to analyze microtremor records interpreted as Rayleigh waves, has been used in this paper to compute empirical transfer functions for the energetic *S*-wave part of a small sample of earthquake records obtained in three cities in Mexico. In each case we have compared the results obtained using Nakamura's procedure with those obtained from the standard computation of spectral ratios.

In all the cases studied we have obtained a very good agreement between results from Nakamura's ratio and those obtained from the standard spectral ratio technique. It should be mentioned that in all cases, acceleration or velocity levels are very small (Tables 1 to 4) and thus, we deal essentially with linear behavior. We observe less dispersion in Nakamura's ratios than for standard spectral ratios. Our results show that the technique by Nakamura gives a robust estimate of the frequency and amplitude of the first resonant mode, although higher modes do not appear. We have shown that it works well for site effects due to topographic features or sedimentary deposits. Finally, the results presented in this paper suggest first, that spectral ratios evaluate an average response of a simple plane layer stratigraphy to plane waves incident from many different angles, and second that in soft soil stations, site effects have more importance than any effect related to the source, even in the near field.

We are aware that further study is needed to evaluate the limits of the technique, and to better understand the reasons for its success. However, the results obtained in this paper strongly suggest that site effects can be evaluated using spectral ratios from only one station, at least where site amplification is caused by a relatively simple local geology or topography. This condition however is also required to apply standard spectral ratios. The technique by Nakamura provides an economic alternative to empirical evaluation of site effects and allows to obtain results when the reference station fails to record the events recorded on soft soil sites or when the reference station itself is affected by site amplification.

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