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TOPOGRAPHICAL AND GEOLOGICAL AMPLIFICATION: CASE STUDIES AND ENGINEERING IMPLICATIONS *

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ABSTRACT

Topographical and geological amplification that occurred during past earthquakes are quantified using spectral ratios of recorded motions. Several cases are presented from the 1985 Chilean and Mexican earthquakes as well as the 1983 Coalinga (California) and 1987 Supersition Hills (California) earthquakes. The strong motions recorded in Mexico City during the 1985 Michoacan earthquake are supplemented by ambient motions recorded within Mexico City to quantify the now well known resonating frequencies of the Mexico City lakebed. Topographical amplification in Canal Beagle (Chile), Coalinga and Superstition Hills (California) are quantified using the ratios derived from the aftershocks following the earthquakes. A special dense array was deployed to record the aftershocks in each case.

The implications of both geological and topographical amplification are discussed in light of current code provisions. The observed geological amplifications has already influenced the code provisions. Suggestions are made to the effect that the codes should include further provisions to take the amplification due to topography into account.

1. INTRODUCTION

The fact that characteristics of ground motions are altered by site effects has deservedly been an important topic in the last two decades or more. The September 19, 1985 Michoacan, Mexico earthquake ($M_S = 8.1$) is the latest large earthquake that provided solid evidence of this phenomenon—both by recorded motions and by the vast destruction these motions imposed on

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significant number of engineered structures. The motions recorded in Mexico City—almost 400 km from the epicenter of the earthquake—clearly depicted that the motions in the lakebed of Mexico City were significantly amplified at approximately 0.5 Hz with durations much longer than the motions recorded at the epicentral region. This resulted in the double resonance of structures with fundamental frequencies in the neighbourhood of 0.5 Hz. It is fair to state that, during that earthquake, none of the structures falling in this category, escaped this prolonged resonance without inelastic response and/or total collapse.

The 3 March 1985 Central Chile earthquake ($M_S = 7.8$) also provided distinctive evidence of site effects–both topographical and geological. On the ridges of the Canal Beagle subdivision outside the coastal town of Vina del Mar, three- to five-story buildings suffered extensive damage. Aftershocks recorded by a temporary dense array deployed at Canal Beagle show that the topography played an important role in amplifying and altering the characteristics of the motions on the ridges. Furthermore, in Vina del Mar, there is also evidence from strong and weak motion recordings of amplifications due to local soil conditions.

The purpose of this paper is the summarize several recent documented case studies of topographical and geological amplification and deliberate on these effects from an engineering point of view. We will show examples from Mexico City of both strong motions recorded during the mainshock and weak motions recorded several months later that support the now well known vibrational characteristics of Mexico city lakebed. We will also present examples of strong and weak motions in Chile that illustrate both topographical and geological site effects. In addition, new data on topographical effects from Coalinga and Superstition Hills (California) earthquakes are also presented to confirm the presence of topographical amplification of seismic energy within the frequency bands of engineering interest.

In all of the cases presented herein, the weak motions were recorded by GEOS (General Earthquake Observation System) [1] using the three-component Mark [1] Products L22-3D velocity transducers.

2. TOPOGRAPHICAL EFFECTS

2.1. Canal Beagle (Chile) case

Topographical amplification at Canal Beagle is the only case to date where the evidenced structural damage on the ridge correlates well with the conclusions derived from spectral ratios of motions obtained at the top of the ridge with respect to the valley. That is, the range of frequencies of the spectral ratios at which amplification occurs correlates with the range of fundamental frequencies of the three- to five-story structures on the ridges [2–4].

In Fig. 1, velocity seismograms from a typical event are shown corresponding to a set of temporary dense array stations (CBA–CBG) established as shown in Fig. 2. Stations CBD and CBG did not record this or other events. The seismograms, plotted to the same scale, show the degree of amplification of motions at the ridge stations CBB, CBC, CBE and CBF as compared to CBA, which is in the canyon, as well as two reference stations: MUN in downtown Viña del Mar (an alluvial site 2 km from Canal Beagle) and VAL at Valparaiso (an amphibolite gneiss

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[1] These are commercial names of instruments used only and do not constitute endorsement of these products.

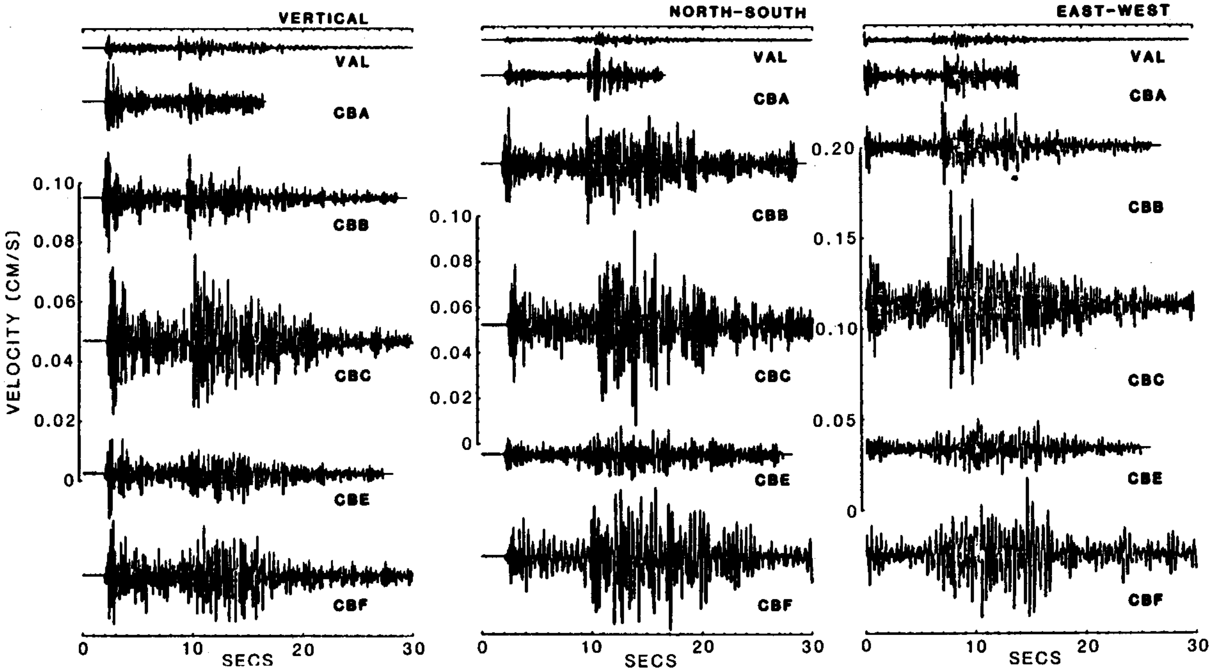

Fig. 1. A typical set of scaled velocity seismograms—event 2100652 corresponding to Julian 210 (July 29, 1985) at 06:52 GMT—for the vertical and horizontal components, respectively, from the reference station VAL and Canal Beagle stations CBA, CBB, CBC, CBE, and CBF. Stations CBB, CBC, CBE, and CBF are on the ridges.

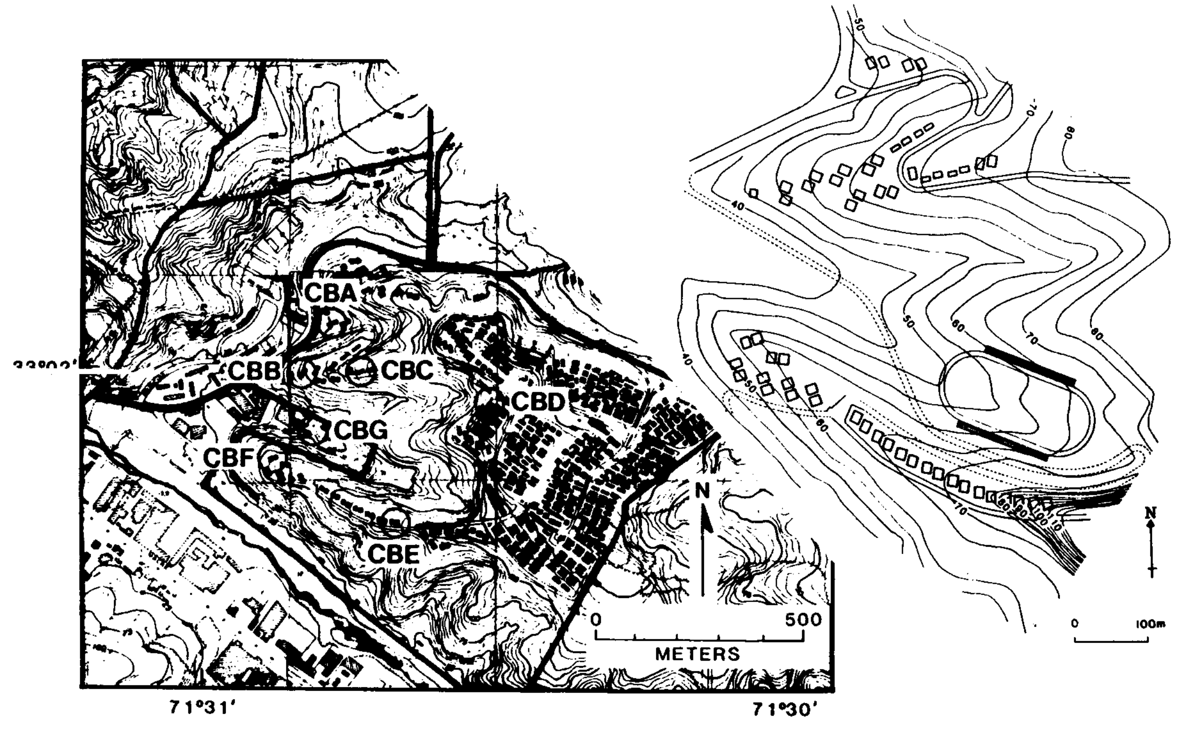

Fig. 2. Detailed topography of Canal Beagle. The ridges and the buildings on them as well as the stations established for aftershock studies are indicated.

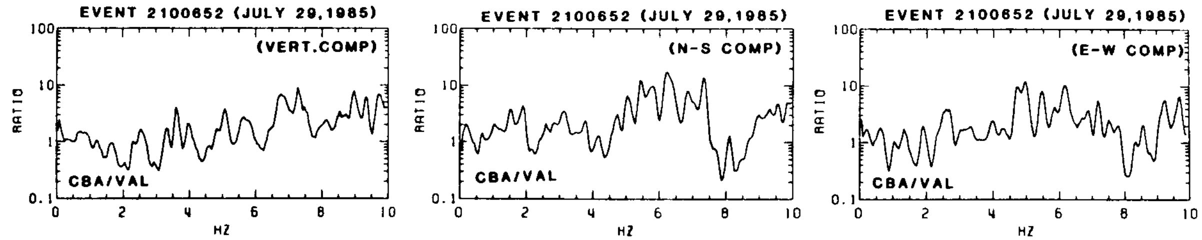

Fig. 3. Spectral ratios of event on July 29, 1985 (Julian 210) at 06:52 GMT for the vertical and horizontal components (NS and EW), respectively, of stations CBA/VAL.

rock site 6 km from Canal Beagle). The Canal Beagle subdivision stations (CBA–CBG) were all sited on alluvial deposits and decomposed granite (locally known as Maicillo). Specific information on the types or depths of layers of the ridge media is not available. In selecting the particular sites of stations, care was taken to have representative ridge, canyon, and main hilltop locations in order to be able to distinguish the ridge effect. Since the Canal Beagle stations are further away from the epicenter than the reference rock station, VAL, conservatively, the distance effect can be neglected; therefore, the spectral ratios of stations CBA/VAL provided in Fig. 3 display the frequency-dependent geological amplification at Canal Beagle relative to the rock station in Valparaiso. On the other hand, since Canal Beagle stations are close to one another (see Fig. 2 for scale) and are all sited on similar geology, the spectral ratio of motions at a ridge station with respect to the station CBA at the canyon represents the topographical amplification function, $T_t(\omega) = (A_2(\omega)/A_1(\omega))$ where $A_i(\omega)$ is the Fourier amplitude spectrum at station i. In Fig. 4, then, the frequency-dependent topographical amplification is clearly depicted in the spectral ratio plots (between 0–10 Hz) of stations on the ridges with respect to station CBA, which is in the canyon.

In general, the spectral ratios show that the frequency ranges for which horizontal amplification of motion occurs are 4–8 Hz for the canyon relative to the rock site (Fig. 3) and 2–4 Hz as well as 8 Hz for the ridges of Canal Beagle relative to the canyon (Fig. 4). The frequency range of 2–4 Hz is well within the fundamental frequencies of the four- and five-story buildings observed to be heavily damaged during the main event of March 3, 1985. On the other hand, the frequencies of the two four-story undamaged buildings in the canyon are outside the frequencies (4–8 Hz) for which amplification occurred in the canyon relative to the rock site. These spectral ratios (as well as others to follow) were smoothed with a triangular weighting function with width of 0.15 Hz. Other sets of velocity seismograms and superimposed spectral ratios from different events related to topography of Canal Beagle depict repeatability of frequency-dependent amplification and are documented elsewhere [2,3].

2.2. Coalinga (California) case

Following the May 2, 1983 Coalinga earthquake ($M_s = 6.5$), several accelerographs were temporarily installed to record aftershocks [5]. The general location map of the Coalinga anticline, Coalinga, the epicenter of the main shock (May 2), that of the May 9 aftershock, and the locations of the permanent accelerograph stations in the vicinity are shown in Fig. 5a. The geology of the region is best described as weathered sandstone at the surface and harder sandstone (Pliocene) below.

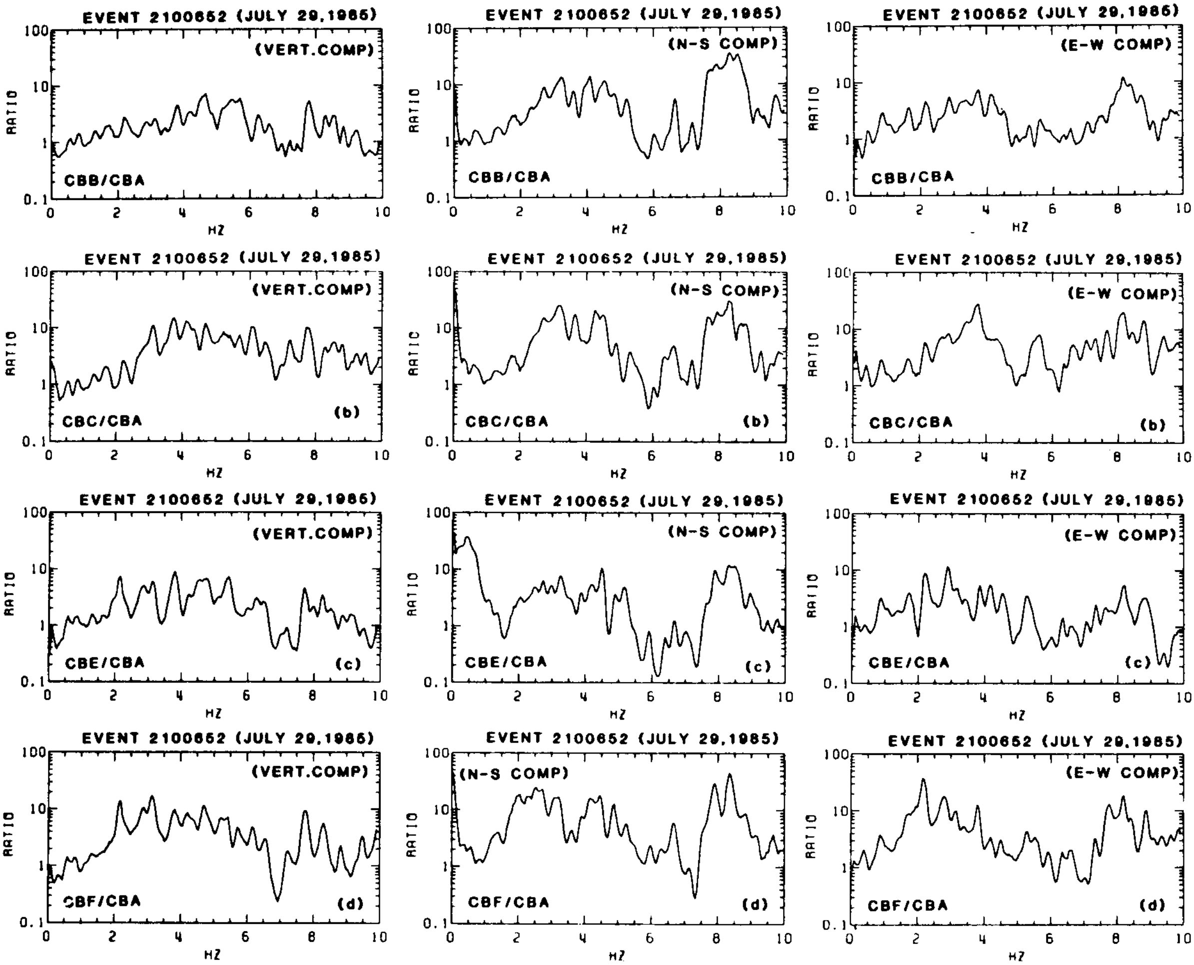

Fig. 4. (a) Spectral ratios of event on July 29, 1985 (Julian 210) at 06:52 GMT for the vertical and horizontal components (NS and EW), respectively, of stations CBB/CBA. Station CBB is on one of the ridges and station CBA is in the canyon. Spectral ratios of event on July 29, 1985 (Julian 210) at 06:52 GMT for the vertical and horizontal components (NS and EW), respectively, of stations (b) CBC/CBA, (c) CBE/CBA, and (d) CFB/CBA. Stations CBC, CBE, and CBF are on the ridges.

Several smaller ridges and gulleys are superimposed on the anticlinal hill. Four temporary and closely spaced accelerographs were installed at the top and in the two gulleys of a small ridge of the Coalinga anticline. These temporary stations shown in Fig. 5b are: ARF (Anticline Ridge Free Field-on the ridge, approximately 3 meters from an abondoned oil well rig pad); ARP (Anticline Ridge Pad); ARN (Anticline Ridge North–in the gulley); and ARS (Anticline Ridge South–in the gulley). While the accelerograph on the pad (ARP) was anchored, the accelerograph at ARF as well as ARN and ARS were placed under a pile of sand bags to prevent them from sliding or rocking.

For brevity, the uncorrected acceleration time histories of one of the several aftershocks (September 9, 1983 at 0916 UTC, $M_s = 5.3$) recorded by the temporary stations are provided in Fig. 6. The East–West component of the accelerograph of station ARP did not function properly during both events.

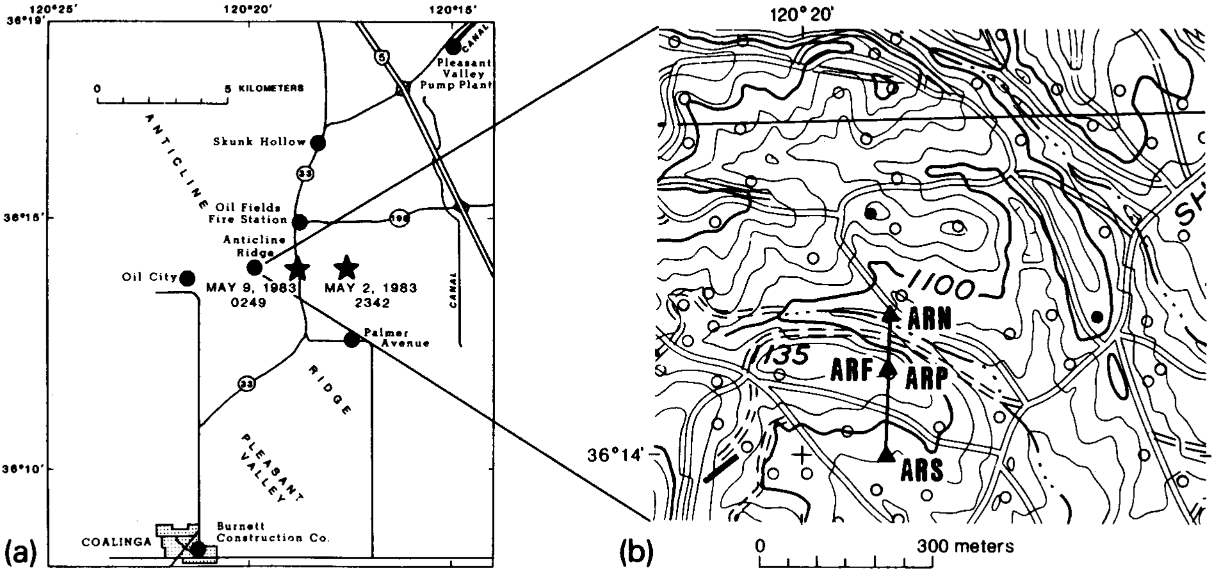

Fig. 5. (a) The general location map of Coalinga and Coalinga anticline. The epicenter of the main shock (May 2) and one of the aftershocks (May 9) as well as the locations of the permanent accelerograph stations (dots) are shown. (b) The topography of the small ridge at Coalinga anticline where temporary stations (ARF, ARP—both at the top of the ridge and ARN and ARS at the two gulleys north and south of the ridge) were established.

The spectral ratios derived from Fourier spectra of the corresponding component pairs (the ridge versus gulley stations) are depicted in Fig. 7. These ratios show amplification of motions by as much as a factor of 10, particularly between 1 to 6 Hz and at 7.5 Hz.

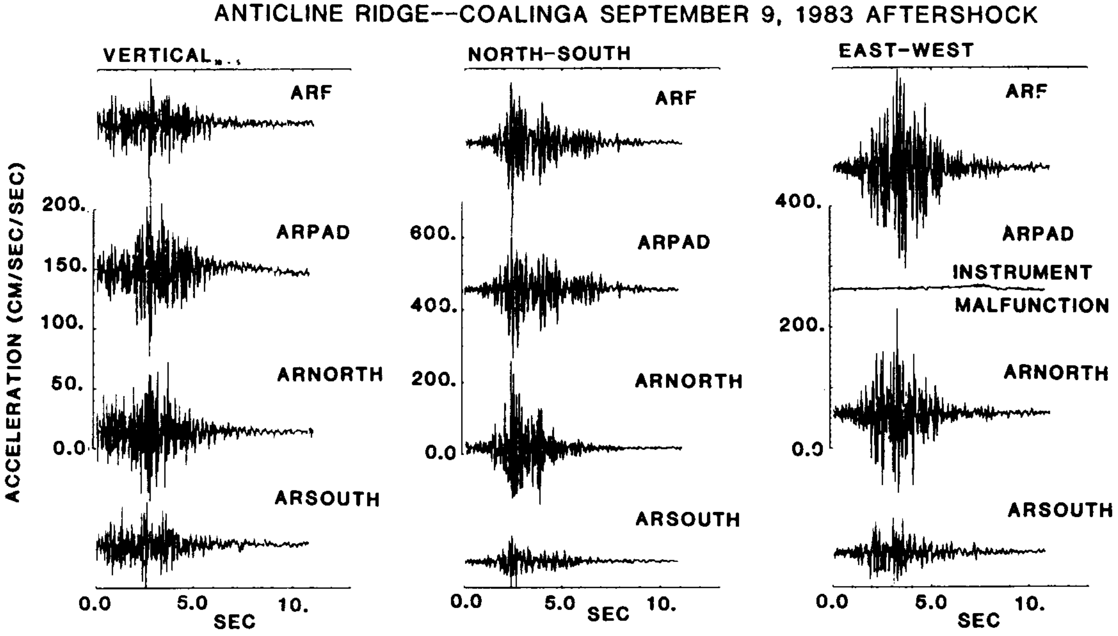

Fig. 6. A typical set of scaled acceleration motions at the Coalinga Anticline Ridge temporary array during the September 9, 1983 aftershock (0916 UTC, $M_s = 5.3$).

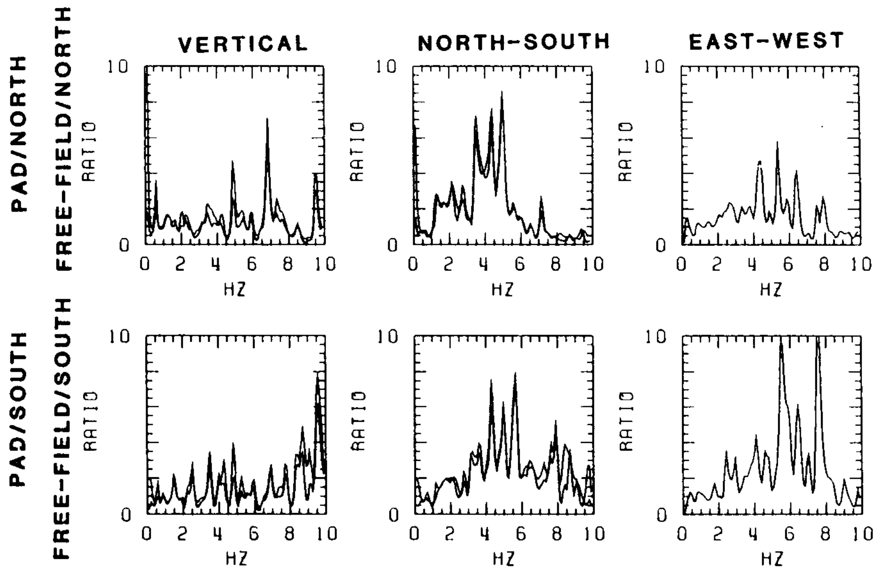

Fig. 7. Spectral ratios of the September 9, 1983 aftershock for the vertical and horizontal components (NS and EW), respectively. The vertical and North–South spectral ratios (the pad versus north, free-field versus north, pad versus south and free-field versus south) are superimposed.

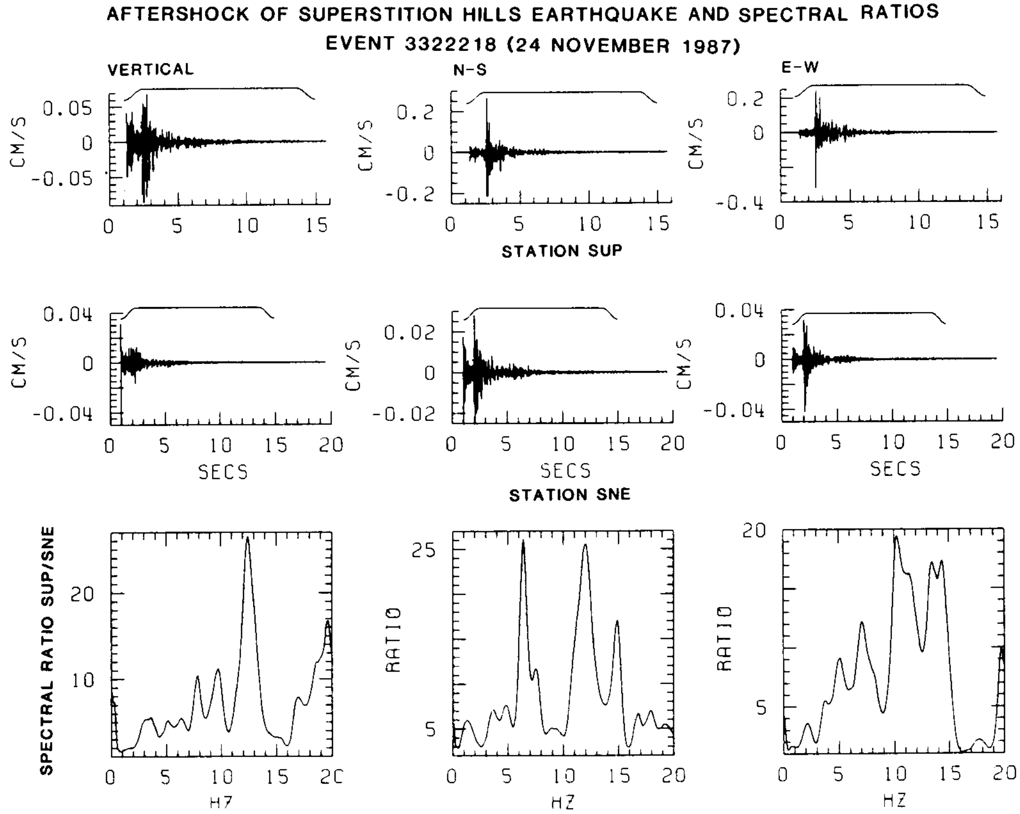

Fig. 8. A typical set of velocity seismograms and spectral ratios—event 3322218 corresponding to Julian 332 (November 28, 1987) at 22:18 GMT—for the vertical and horizontal components, respectively, of stations SUP and SNE.

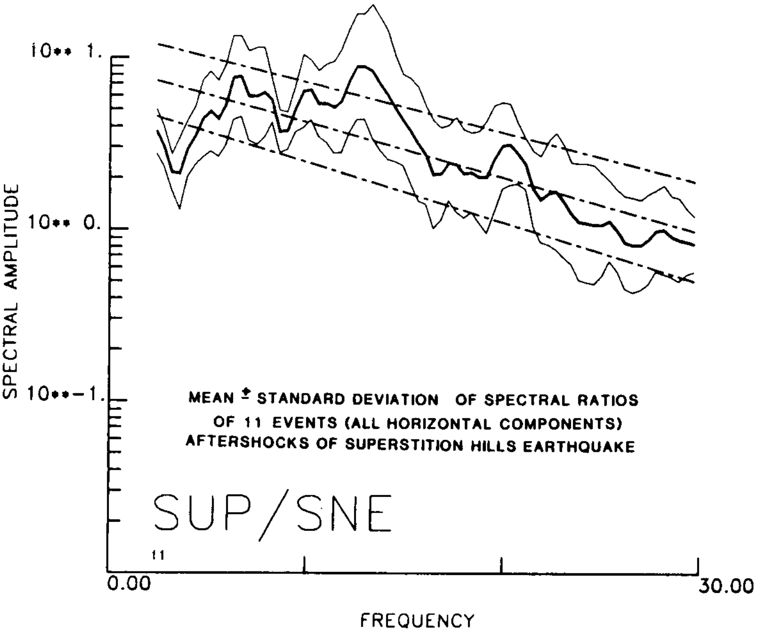

Fig. 9. Mean plus standard deviation spectral ratio plots for SUP/SNE derived from twenty-two horizontal components of eleven events.

2.3. Superstition Hills (California) case

During the 24 November 1987 (1315GMT) Superstition Hills (California) earthquake ($M_s = 6.6$), the USGS strong-motion station at the peak of Superstition Mountain (granitic rock and 7 km from the epicenter) recorded horizontal peak accelerations of 0.91*g* and 0.73*g* and a vertical peak acceleration of 0.65*g* [6]. Accelerations exceeding 0.5*g* persisted for approximately 12 seconds of the total record and thus prompted the speculation of the presence of topographical effects. Shortly after the mainshock, Andrews and Wennerberg [7] deployed three temporary digital recording stations (all on granitic rock)—at the top of the Superstition Mountain (SUP) and at its Northeast (SNE) and Northwest (SNW) flanks. In Fig. 8 a typical set of velocity seismograms and the corresponding spectral ratios are shown for a single event recorded at stations SUP and SNE. Figure 9 shows the mean and standard deviation of spectral ratio plots for SUP/SNE derived from the twenty-two horizontal components of eleven events. Both Figs. 8 and 9 show that between 2–12 Hz ground motion at SUP can be amplified by as much as a factor of 20. This degree of amplification is surprising given that the approximate slope of the mountain is only 6%.

3. Geological amplification

3.1. Mexico City case

The 19 September 1985 Michoacan earthquake was sufficiently well recorded both in Mexico City—approximately 400 km from the epicenter—and at the epicentral region by the recently

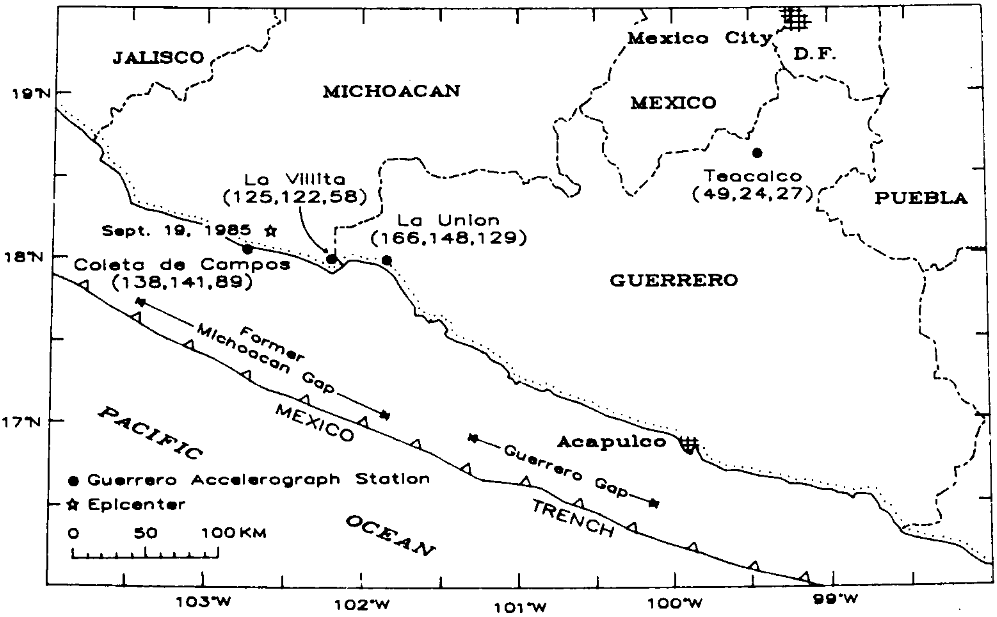

Fig. 10. General map of part of the Pacific coast of Mexico (revised and adopted from Anderson et al. [8], showing the epicenter of the 19 September 1985 ($M_s = 8.1$) Michoacan earthquake. Three of the several coastal stations and the Teacalco station (closest to Mexico City) of the Guerrero array are shown with peak accelerations in paranthesis for the NS, EW and vertical components, in that order.

installed 16 out of the planned 30 digital accelerographs of the Guerrero array, a joint project of UNAM (National Autonamous University of Mexico) and UCSD (University of California, San Diego) [8]. The Guerrero array records [8] as well as the records obtained in the Federal District of Mexico City illustrate the following:

● First, the peak accelerations at the epicentral area (Caleta de Campos, La Villita and La Union Stations), at Teacalco (~ 340 km from the epicenter and the only Guerrero array station close to Mexico City) (Fig. 10), and at UNAM (~ 400 km from the epicenter) were on the order of 0.15*g*, 0.05*g*, and 0.035*g*, respectively—indicating that the earthquake motions followed the expected attenuation. This is clearly demonstrated in Fig. 11, which presents the East–West components of the 19 September 1985 earthquake records starting from the epicentral coastal station of Caleta de Campos to UNAM in Mexico City. All of the coastal stations were on rock. UNAM station is on rock composed of lava overlying consolidated sediments.

● Second, the peak accelerations (of five stations in Mexico City shown in Fig. 12) of UNAM (rock), SCT (lakebed), VIV [2] (transition zone), TAC (Tacubaya-rock), and CDA (lakebed) were on the order of 0.035*g*, 017*g*, 0.043*g*, 0.034*g*, and 0.095*g*, respectively—clearly indicating large differences attributable to the unique subsurface conditions of Mexico City. The East–West component of station SCT is shown in Fig. 11 to demonstrate the amplification of the lakebed zone as compared to UNAM station.

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[2] The identification of Viveros with transition zone or hills zone is a disputed issue.

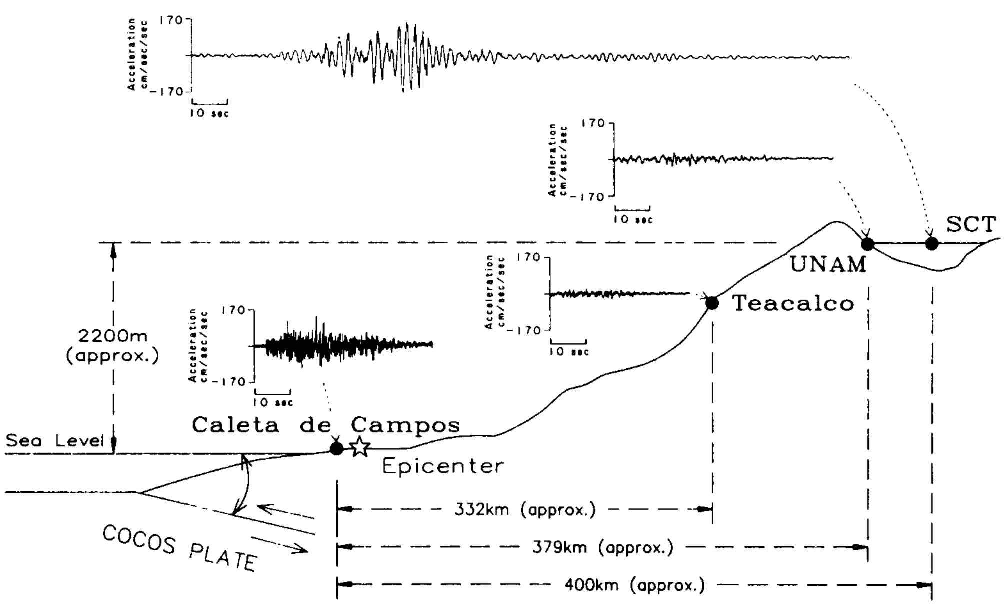

Fig. 11. Schematic section showing relative locations of the epicentral station at Caleta de Campos, Teacalco station (closest to Mexico City), and Mexico City stations, UNAM (hills zone) and SCT (lake zone). The seismograms are East–West components of 19 September 1985 acceleration time-histories (all plotted to the same scale) recorded at respective stations and demonstrate the attenuation of motions with distance from the coast as well as amplification of motions at the lakebed of Mexico City.

3.1.1. Amplification in Mexico City—strong motions.

Singh et al. [9], along with Kobayashi et al. [10,11] and Ohta et al. [12] present extensive results quantifying amplification of motions in the lakebed of Mexico City using both the strong-motion records of the 1985 event and microtremors. In particular, Singh et al. [9] report that in the lakebed as compared to the hill zones, the motions are amplified by 8 to 50 times and the motions at the hill zone sites in Mexico City when compared to the hard-rock coastal epicentral sites are amplified by a factor of 7.5 times at 0.5 Hz frequency—after correcting for the effect of distance.

In Fig. 13 spectral ratios determined from strong-motion records at some of the stations in Mexico City (shown in Fig. 12) are presented. These are then compared with spectral ratios determined from noise measurements made in January 1986 in different parts of Mexico City. The spectral ratios in Fig. 13, all plotted with the same format and scale to provide comparative evaluation, are calculated from Fourier amplitude spectra of acceleration time histories of 19 September 1985 records obtained at the lakebed zone stations: SCT (Ministry of Telecommunications and Transportation) and CDAO (Central de Abastos Office Building), at the transition zone station VIV (Viveros) and at the hills zone station TAC (Tacubaya), all with reference to the UNAM station. The surficial geological formation of these stations are given by Anderson et al. [8] as very soft soil (clay) for SCT and CDAO, soft soil for VIV, hard soil for TAC and rock (basalt) for UNAM. The amplification of motions in the lakebed zone (SCT and CDAO) as compared to the rock site (UNAM) was as much as 7–10 times in the horizontal direction at 0.4–0.5 Hz and 6 times in the vertical direction at 1.5 Hz. In the transition zone (VIV), amplification is about 4.5 times at 2 Hz in the horizontal direction. In the hills zone (TAC) compared to UNAM, no amplification can be claimed. Corresponding Fourier spectra for each

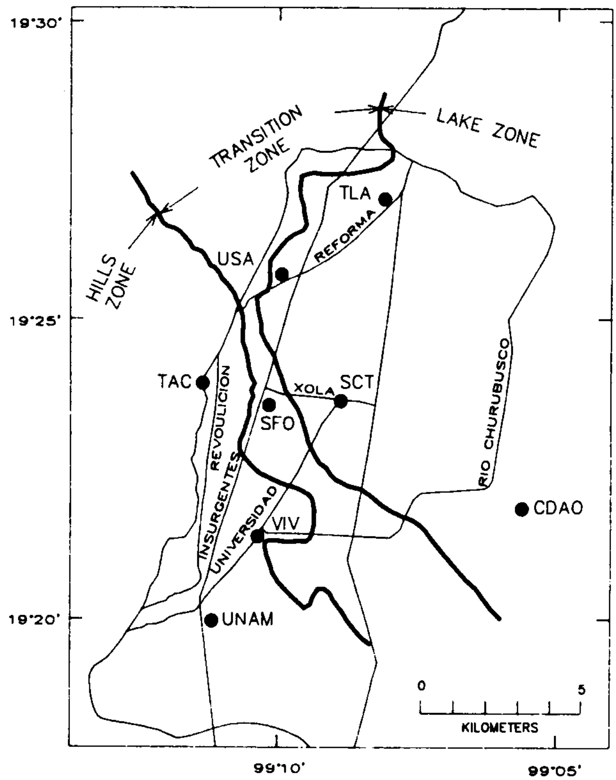

Fig. 12. Map showing the three zones of Mexico City as well as the locations of stations discussed in the manuscript. UNAM, SCT, CDAO, VIV and TAC are strong motion stations. SFO, USA and TLA are the temporary stations established in January 1986 to facilitate recording of weak motions. (Note: The location of Viveros being in the transition or the hills zone is a disputed issue.)

of the three components of all stations for which spectral ratios are provided are shown in Fig. 14. The figure substantiates once again the dominant low frequencies of the motions in Mexico City. All components of all stations exhibit dominant frequencies between 0.3–0.8 Hz.

3.1.2. Amplification in Mexico City—weak motion.

Next, in Fig. 15, similar spectral ratios obtained from weak motions (traffic noise) are presented for UNAM, SCT and CDAO stations (same locations as the strong-motion stations) and three new stations: USA (American Embassy basement), SFO (garden of a house on San Fransisco street) and at (TLA) (Tlatelolco—a government-sponsored social housing complex). Relative locations of the new stations are also shown on the map in Fig. 12. Stations USA and SFO are both within the boundaries of the transition zone. Station TLA is in the lakebed zone. The spectral ratios shown in Fig. 14 exhibit several distinctive characteristics. They all have amplitudes significantly larger by an order of magnitude than those spectral ratios from strong motions because the weak motions are not from the same source and their travel paths are not the same as those of the strong motions. Second, the SCT/UNAM spectral ratios peak at frequencies that correlate well with those from strong motions—at 0.5 Hz for horizontal and 1.5 Hz for vertical. On the other hand, the CDAO/UNAM spectral ratios from weak motions, while exhibiting peaks at frequencies of 1 Hz or less, does not show good correlation with those from

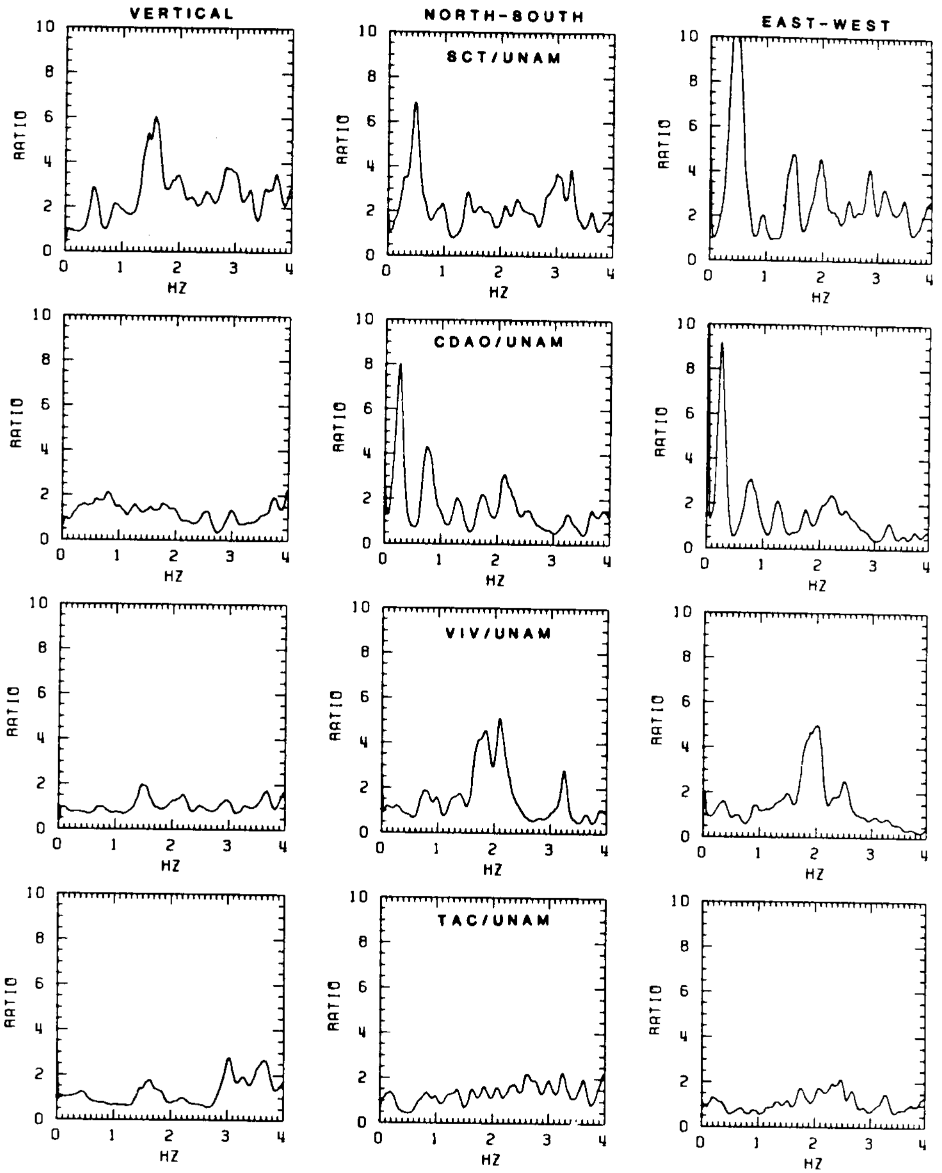

Fig. 13. Spectral ratios for the vertical and horizontal components (NS and EW), respectively, derived from the strong motion records of the 19 September 1985 earthquake. Ratios shown are for stations SCT, CDAO, VIV and TAC with respect to UNAM. All plots have the same format and scale to provide easy comparison. SCT and CDAO stations are in the lake zone, VIV is in the transition zone and TAC and UNAM are both in the hills zone. The plots clearly and quantitatively show the frequencies and amplitudes of amplification of motions experienced in Mexico City.

strong-motion records. However, there is clear evidence that at CDAO the weak motions did not have sufficient energy to excite the lower frequency which is apparent in the plots. The USA/UNAM spectral ratios exhibit amplification at 0.8–0.9 Hz in the horizontal direction while SFO/UNAM spectral ratios tend to have amplification between 1.0–1.3 Hz in the horizontal direction.

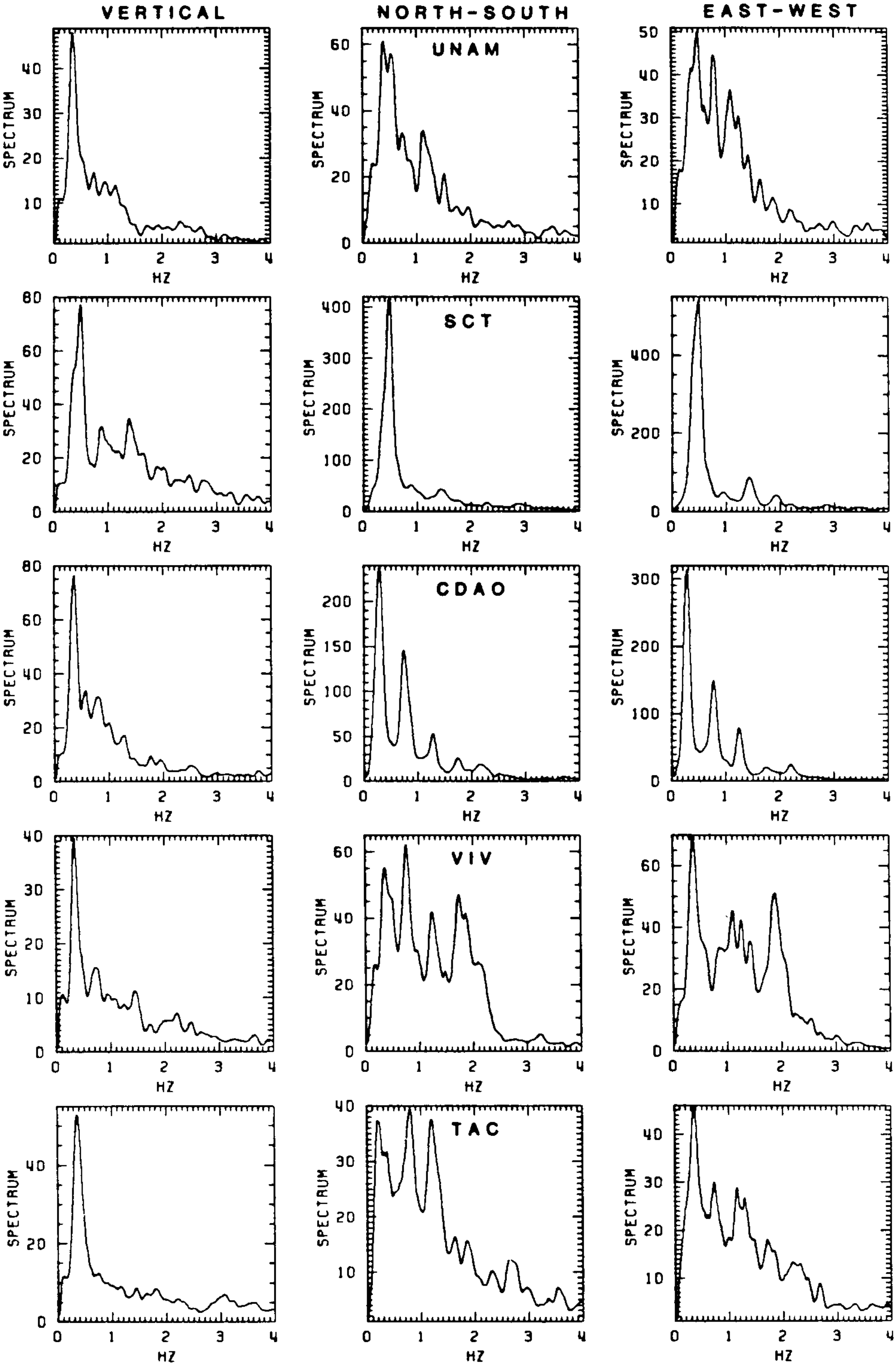

Fig. 14. Fourier spectra for the vertical and horizontal components (NS and EW), respectively, derived from the strong-motion records of stations UNAM, SCT, CDAO, VIV and TAC in Mexico City. All plots demonstrate the significant low-frequency energy at all stations.

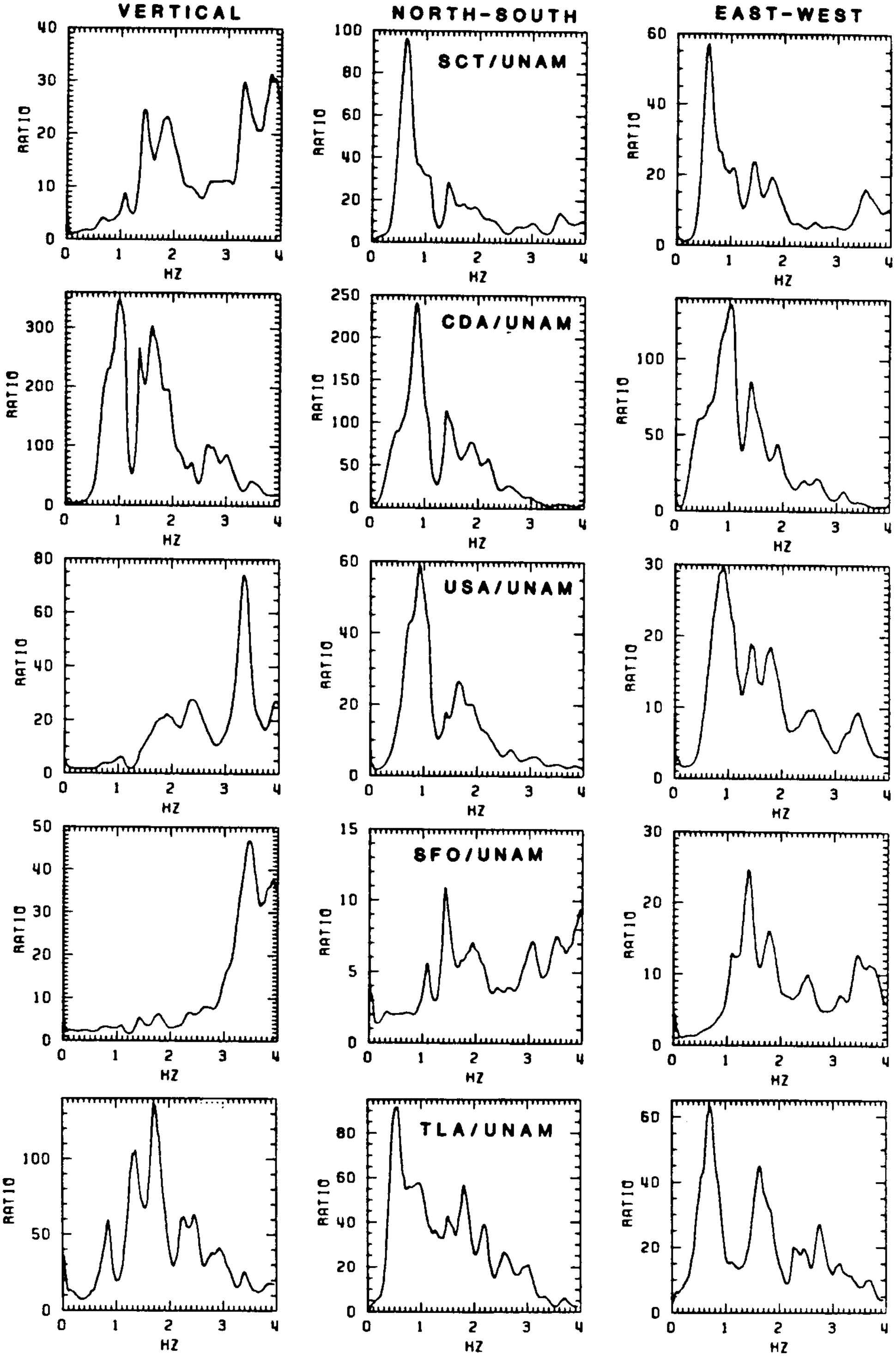

Fig. 15. Spectral ratios for the vertical and horizontal components (NS and EW), respectively, derived from weak motions recorded at stations CDAO, SCT, USA, SFO, TLA and UNAM. All plots are made with respect to UNAM. CDAO, SCT and UNAM stations are same as the strong-motion stations.

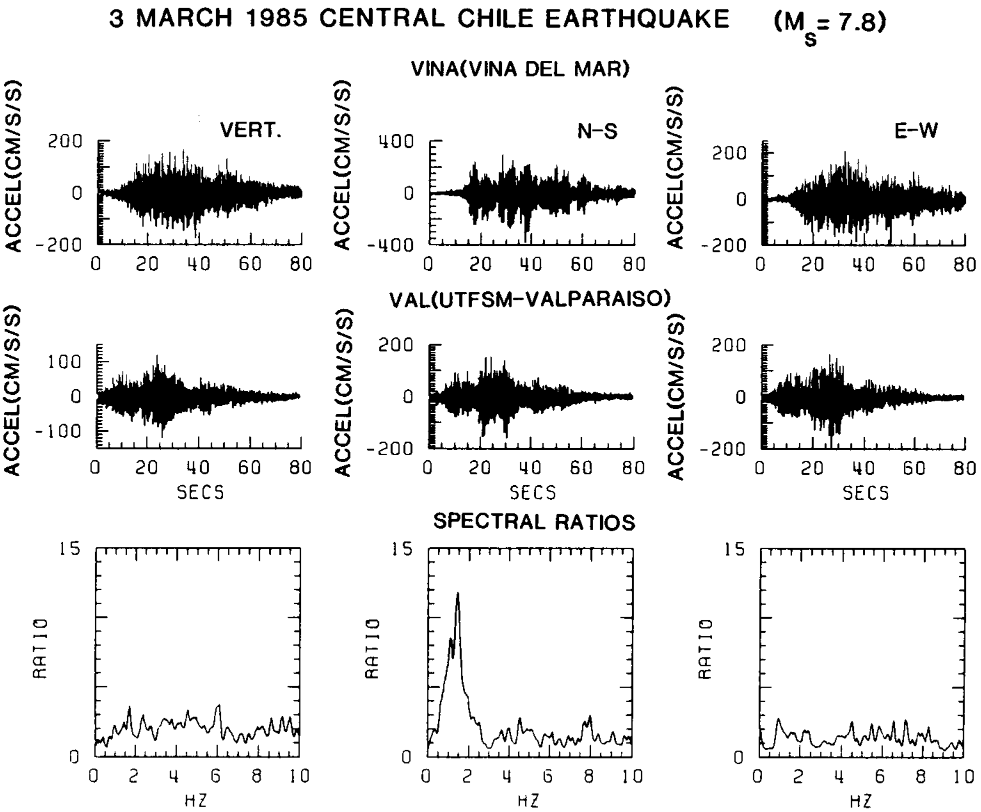

Fig. 16. Acceleration seismograms of 3 March 1985 Central Chile earthquake ($M_s = 7.8$) recorded at the strong-motion stations VINA (Vina del Mar) and VAL (UTFSM–Valparaiso) and their corresponding spectral ratios.

3.2. Central Chile

We will refer here to the following recording sites in Vina del Mar where during the 3 March 1985 earthquake surficial ground motions were amplified [3]: the permanent strong-motion stations VINA (at the basement of a ten-story building founded on alluvium) and VAL (the reference rock station in Valparaiso), and the temporary stations TRA (at the basement of a fifteen-story building founded on sand) and MUN (at the basement of a two-story building founded on alluvium). Stations VINA and MUN are within 200 meters distance of each other and both are about 1 km TRA. All three stations are within 6 km from VAL. Fig. 16, the acceleration seismograms, corresponding Fourier spectra and spectral ratios of VINA/VAL for the 3 March 1985 earthquake are provided. The horizontal components of the strong-motion seismograms were rotated to true North–South and East–West since the orientations of the accelerographs of the two stations were not similar. The spectral ratios show amplification by as much as a factor of 12 in the North–South direction within the frequency band 0.5–2 Hz. However, in the East–West direction, strong characteristics of amplification cannot be identified.

From the Fourier spectra of after shock recordings in Figs. 17 and 18, we can see that in Vina del Mar, the dominant frequencies of both the MUN (alluvial) and TRA (sand) sites are at 1.5 and 3.0 Hz. The spectral ratios of both stations with respect to VAL (rock site) indicate amplification particularly between 1–3 Hz.

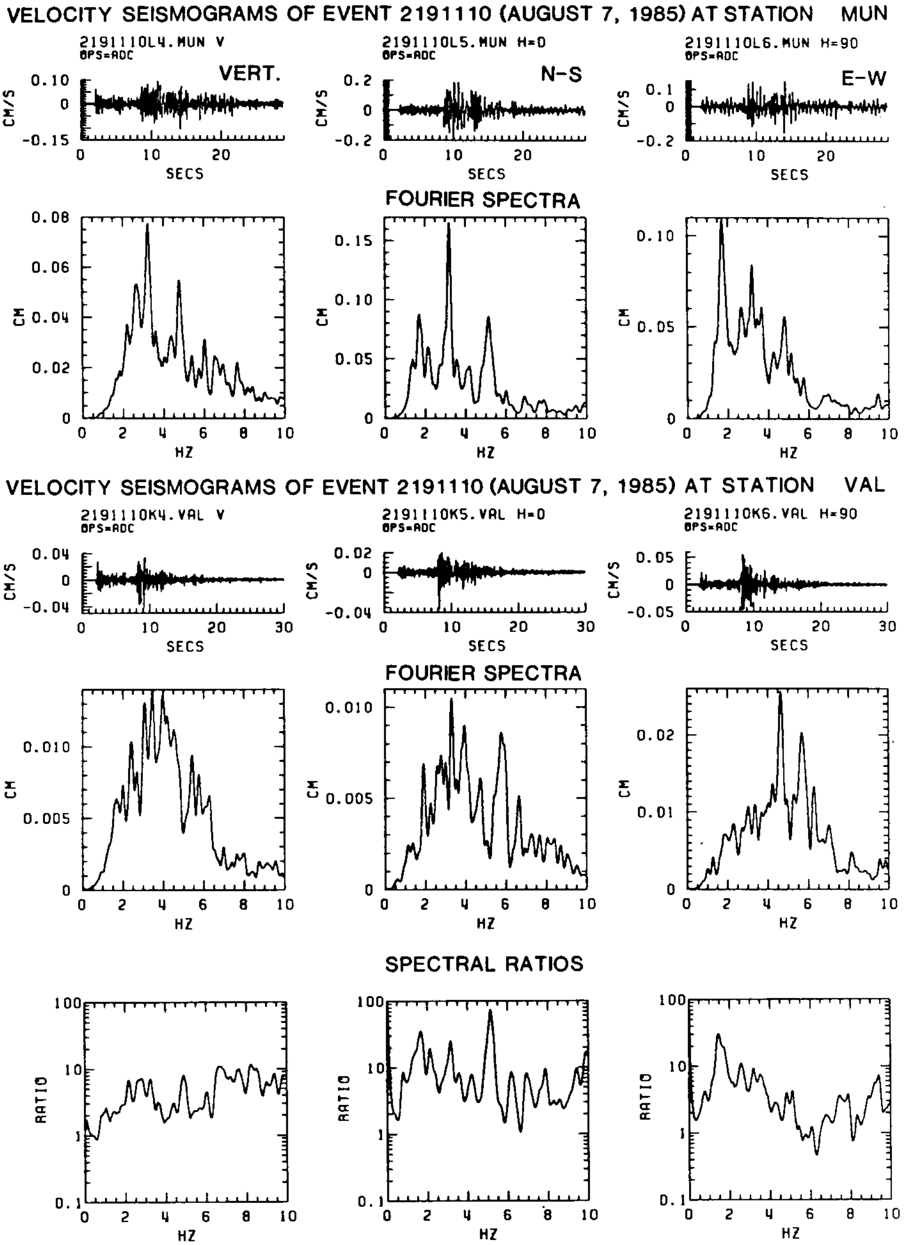

Fig. 17. Velocity seismograms recorded at MUN and VAL, their Fourier spectra and spectral ratios—event 2191110 corresponding to Julian 219 (August 7, 1985) at 11:10 GMT—for the vertical and horizontal components, respectively.

4. ENGINEERING IMPLICATIONS AND CONCLUSIONS

The case studies described above indicate qualitatively and in most cases quantitatively the ranges of frequencies for which amplification of seismic energy takes place due to some form of geological environment—be it topographical or geological.

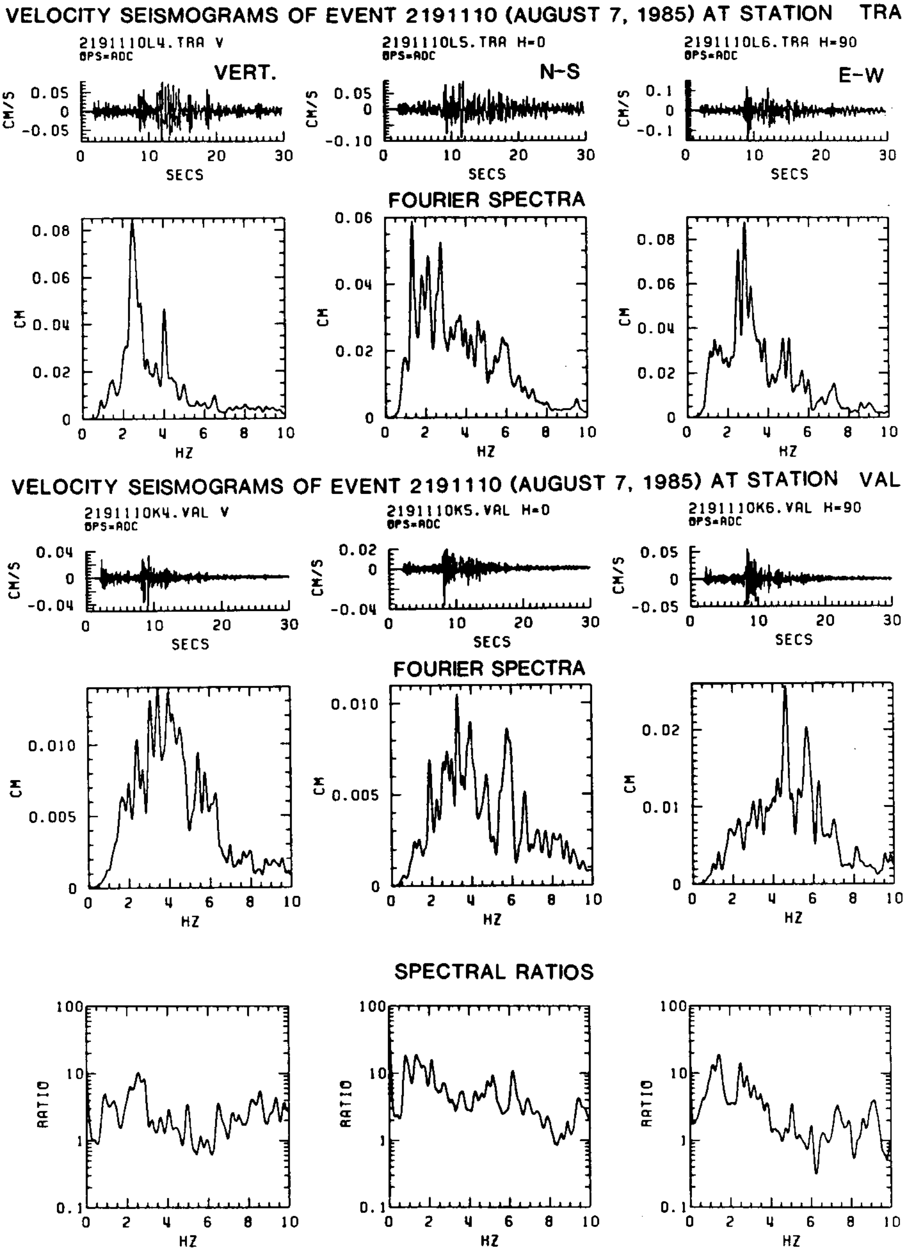

Fig. 18. Velocity seismograms recorded at TRA and VAL, their Fourier spectra and spectral ratios—event 2191110 corresponding to Julian 219 (August 7, 1985) at 11:10 GMT—for the vertical and horizontal components, respectively.

In general, the following implications can be stated for these cases:

- First of all, we need better and accurate characterization of the geological environment of the recording stations in order to avoid misleading conclusions. As an example, in various literature, the station in Vina del Mar is stated as being at the basement of a ten-story building founded on rock [13]. In reality, the building is founded on alluvial deposits the depth of which is unknown.

- Secondly, the source characteristics of recorded motions must be well defined. Weak motions may not excite all the significant frequencies of engineering interest due to insufficient vibrational energy. The common source (e.g. an earthquake) versus independent sources of excitation (e.g. traffic noise), although appearing to conserve the significant frequency bands, does appear to increase the amplitudes of spectral ratios because the particular frequencies that are excited vigorously during strong motions may not be excited as much during weak motion events. This produces variations in low denominator-high numerator in spectral ratio calculations and therefore results in higher amplitudes. Other causes of the differences in amplitudes of spectral ratios from strong motions versus weak motions may be due to nonlinearity during strong-motions or the possibility of high noise-to-signal ratio during weak motions.
- We all know that the geotechnical environment of a particular site is taken into account in most codes. The recently issued 1988 Uniform Building Code, for example, provides for soft soils and sands as compared to rock or stiff soils, a recommended normalized response spectra which for periods larger that 0.4 seconds reflects a maximum amplification of approximately 2.3 at 0.9 seconds. In addition, in the 1988 UBC, as recommended by SEAOC, an additional site factor, S_4 (for soil profiles containing more than 40 ft of soft clay and equal to 2.0) has been added-directly as a result of the site-response studies related to Mexico City subsurface condition. Furthermore, Zone Factor (Z) has been changed from a normalized factor with a maximum value of 1.0 for the most severe zone to the concept of estimated effective peak acceleration–with the most severe zone having $Z = 0.40$.
- There is now sufficient evidence indicating under certain conditions, seismic energy is amplified due to the effect of topography. However, the practical quantification of such effects have yet to be developed. Geli et al. [14] provided some recommendations on frequency bands of amplification based on aspect ratio concept (height/width). Although the data they used has large variance, they show that significant variations in amplification occurs due to layering of a ridge.
- It is therefore important that topographical effects should be seriously considered particularly in highly seismic regions that are heavily populated. As was done in the past and present versions of codes, we suggest to include in the codes a recommendation to the effect that special attention be given when designing structures in heavily populated ridges in seismic areas. To go one step further, perhaps, a recommendation to the effect that design base shear coefficients should be increased by some percentage is in order.
- The case studies presented in this paper and related studies by others prompts the final recommendation that serious emphasis be given to microzonation of regions with high seismicity. Such effeorts are now being made for the heavily populated coastal towns of Central Chile, the lakebed of Mexico City and therefore it is past due that it be carried out for the San Fransisco Bay area and the Los Angeles Basin.

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