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The Culprit in Mexico City—Amplification of Motions

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Mexico City has repeatedly suffered from the long-distance effects of the earthquakes that originate as far away as the subduction trenches near the Mexican Pacific Coast. The Michoacan, Mexico earthquake of 19 September 1985 was no exception and caused extensive damage to property and numerous loss of lives. The unique subsurface condition resulting from the historical lakebed has distinct resonant low frequencies around 0.5 Hz. The strong earthquake motions from long distances as well as the locally originating weak motions cause large amplifications at resonant low frequencies in the subsurface environment of Mexico City lakebed. In this paper, the resonant frequencies and associated amplification of motions in Mexico City are quantified in terms of spectral ratios using 19 September 1985 strong-motion data and weak motions recorded in January, 1986. These ratios confirm that the amplification of motions at resonant frequencies due to the subsurface conditions is indeed the culprit.

INTRODUCTION

The Michoacan, Mexico earthquake of September 19, 1985 (M_s = 8.1) was one of the few earthquakes of this century that caused extensive loss of life and property [Rosenblueth and Meli (1986), Bertero (1986) and UNAM (Autonamous National University of Mexico) (1985)]. The official estimate of human toll is 8000. Approximately 300 buildings in Mexico City collapsed during the main event. However, with the number of buildings demolished because they were beyond repair, the total number of buildings lost were about 1100. While the epicenter of the earthquake was near the Pacific coast of Mexico (18.182°N, 102.573°W, origin time 13:17:47.8 UT) [NEIS (1985), and Anderson and others (1986)] and there was some damage on the coastal region, the main impact and destructiveness of the earthquake was experienced in the lakebed zone of Mexico City—approximately 400 km from the epicenter. The long distance from the source to the principal area of destruction was one unique feature of the earthquake. A second unique feature is related to the subsurface conditions of Mexico City—in that there was substantial amplification of the low-frequency motions. In one respect, the second factor described is the cause of the first for if it were not for the subsurface conditions of the lakebed of Mexico City there would not have been the long-

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distance effect of the earthquake and the normal attenuation relationships would have applied.

The earthquake was recorded extensively at the epicentral coastal zone by the recently installed 16 of the planned 30 digital accelerographs of the Guerrero array—a joint project of UNAM and UCSD (University of California, San Diego) (Anderson and others, 1986)—and at several sites in Mexico City.

Mexico has been prone to severe earthquakes in the past and Mexico City has repeatedly suffered from the long-distance effects of the earthquakes that originate at the subduction trenches near the Mexican Pacific Coast (Figure 1). The amplification of motions in Mexico City generated from strong motions originating at the Pacific coast subduction zone was recognized during and after past earthquakes—particularly after the 1957 earthquake during which Mexico City suffered extensive damage as it did in 1985. The earthquake of 28 July 1957 ($M_s = 7.5$) with its epicenter near Acapulco (~270 km from Mexico City), as widely reported [Duke and Leeds (1959), Merritt (1957), Herrera and others (1965), Rosenblueth (1960), and Rosenblueth and Elorduy (1969)] caused extensive damage in Mexico City. As a result, numerous studies of the structural and architectural aspects of the buildings in Mexico City and of the subsurface conditions were carried out. Herrera and others (1965) studied amplification and resonant frequencies in the lakebed of Mexico City. Rosenblueth and Elorduy (1969) published response spectra (with spectral peaks between 1.5–2.5 seconds) from records obtained at UNAM and other locations in the lakebed zone during the smaller 1962 and 1964 earthquakes (Zeevaert, 1964). Of particular interest are comparative displacement spectra from the 11 May 1962 earthquake obtained at the Latino–Americano building and Alameda Park only 600 meters away. The spectrum at the Latino Americano shows suppressed (by almost 50%) peaks because of preconsolidation realized through piles used in the periphery of the foundation.

These studies led to significant code changes then and later in 1976 to accommodate the unusual spectra of earthquake motions in Mexico City. For example, in the 1976 code, the design response spectrum peaks at a seismic coefficient of 0.24 between 0.8–3.3 seconds—however this coefficient then is reduced for ductility by a factor as much as 6—thus, in a sense nullifying the amplified seismic design coefficient. But the important point is that the amplification and associated resonant periods were recognized in 1957 and thereafter. The 1985 earthquake records provided concrete and detailed evidence of range of resonant periods and amplification of motion.

The purpose of this paper is to present quantified amplification ratios obtained from strong-motion records of the 19 September 1985 earthquake as well as weak motions recorded in January 1986. While structural design and construction problems existed, it should be repeated for emphasis that the main culprit in the destructiveness of this event was the unique subsurface conditions of Mexico City that gave rise to amplified seismic forces oscillating at resonant periods for long duration—some as long as 172 seconds or more (Anderson and others, 1986).

GROUND MOTIONS—EPICENTRAL AND AT MEXICO CITY

The Guerrero array records (Anderson and others, 1986) as well as the records obtained in the Federal District of Mexico City bring out the following facts:

• On September 19, 1985, there were two events separated by 24 seconds.

• The main event was followed by a strong aftershock on 21 September 1985 ($M_s = 7.7$).

• 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; Figure 1), 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 normal attenuation relationships. This is clearly demonstrated in Figure 2 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 material.

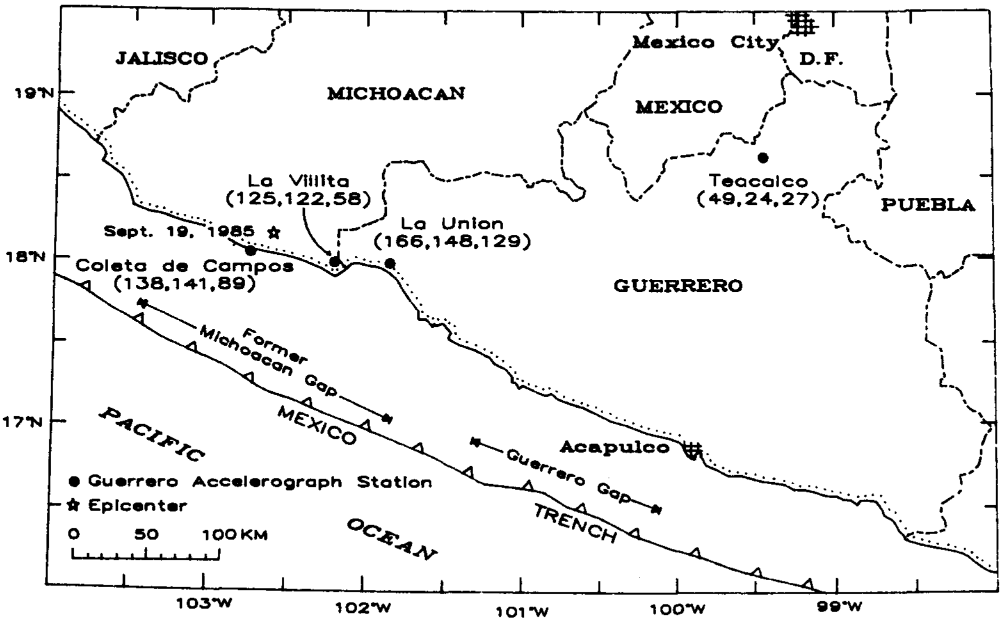

Figure 1 – General map of part of the Pacific coast of Mexico (revised and adopted from Anderson and others,1986) showing the epicenter of the 19 September 1985 (M_s = 8.1) Michoacan Earthquake. Three of the several coastal stations and the Teacalco station (closest to Mexico City) of the Guerrero array are shown with peak accelerations in paranthesis for the NS,EW and vertical components, in that order.

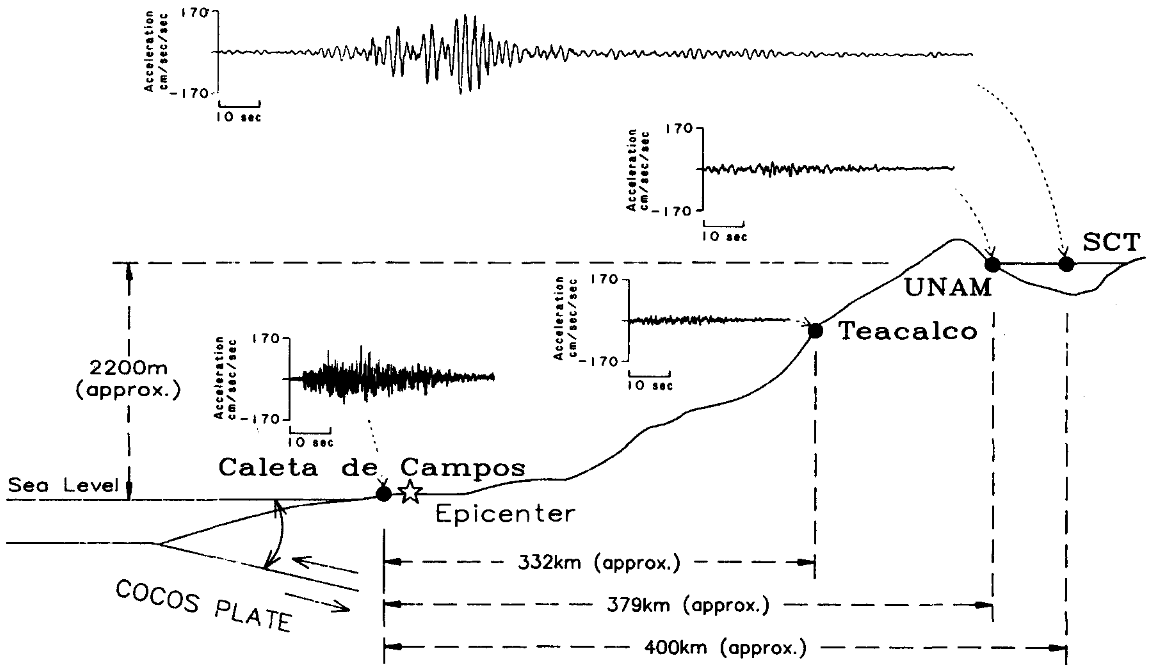

Figure 2 – Schematic section showing relative locations of the epicentral station at Caleta de Campos, Teacalco station (closest to Mexico City), and Mexico City stations, UNAM (hills zone) and SCT (lake zone). The seismograms are east-west components of 19 September 1985 acceleration time-histories (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.

- The peak accelerations (of five of the important stations in Mexico City seen in Figure 3)—UNAM (rock), SCT (lakebed), VIV* (transition zone), Tacubaya (rock), and CDA (lakebed)—were on the order of 0.035 g, 0.17 g, 0.042 g, 0.034 g, and 0.095 g, respectively—clearly indicating differences attributable to the unique subsurface conditions of Mexico City. The east-west SCT station acceleration component is shown in Figure 2 to demonstrate that this representative station in the lakebed zone recorded amplified motions as compared to UNAM station.

- The frequency contents of these motions indicate that at the lakebed zone as well as at the source there is significant 0.5 Hz energy (Singh and others, 1986).

AMPLIFICATION OF MOTIONS IN MEXICO CITY

Singh and others (1986), Kobayashi and others (1986a and 1986b), and Ohta and others (1986) 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 summary, and in particular the work of Singh and others (1986) 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 Figure 4, frequency dependent spectral ratios determined from strong motion records at some of the stations in Mexico City (shown in Figure 3) 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 Figure 4, 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 (Autonamous National University of Mexico, Institute of Engineering Patio) station. The surficial geological formation of these stations are given by Anderson and others (1986a and b) 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 of the three components of all stations for which spectral ratios are provided are shown in Figure 5. 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.

Next, in Figure 6, similar frequency dependent spectral ratios obtained from weak motions (traffic noise) are presented for comparable stations as in Figure 4 that provides spectral ratios from strong motions. While UNAM and CDAO stations are the same as before, two new stations are identified: USA (American Embassy basement) and SFO (garden of a house on San Fransisco street). Additional stations were established at Tlatelolco (TLA) (a government-sponsored social

*The identification of Viveros with transition zone or hills zone is a disputed issue.

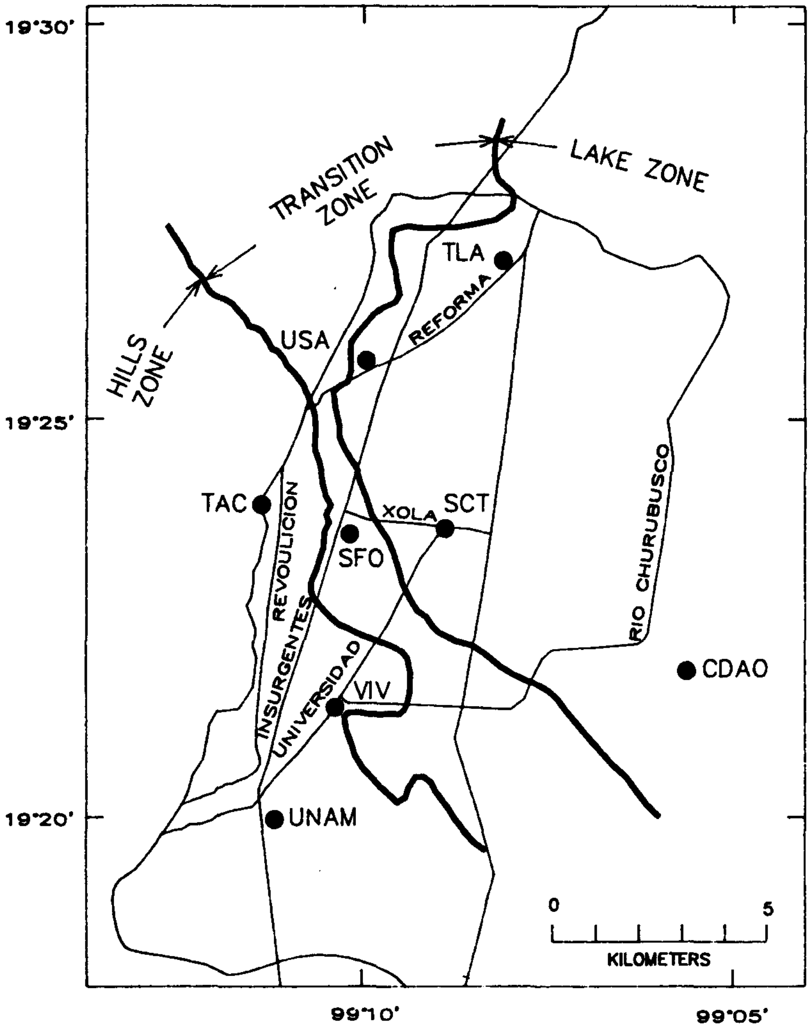

Figure 3 – Map showing the three zones of Mexico City as well as the locations of stations discussed in the manuscript. UNAM, SCT, CDAO, VIV and TAC are strong motion stations. SFO, USA and TLA are the temporary stations established in January 1986 to facilitate recording of weak motions. (Note: The location of Viveros being in the transition or the hills zone is a disputed issue).

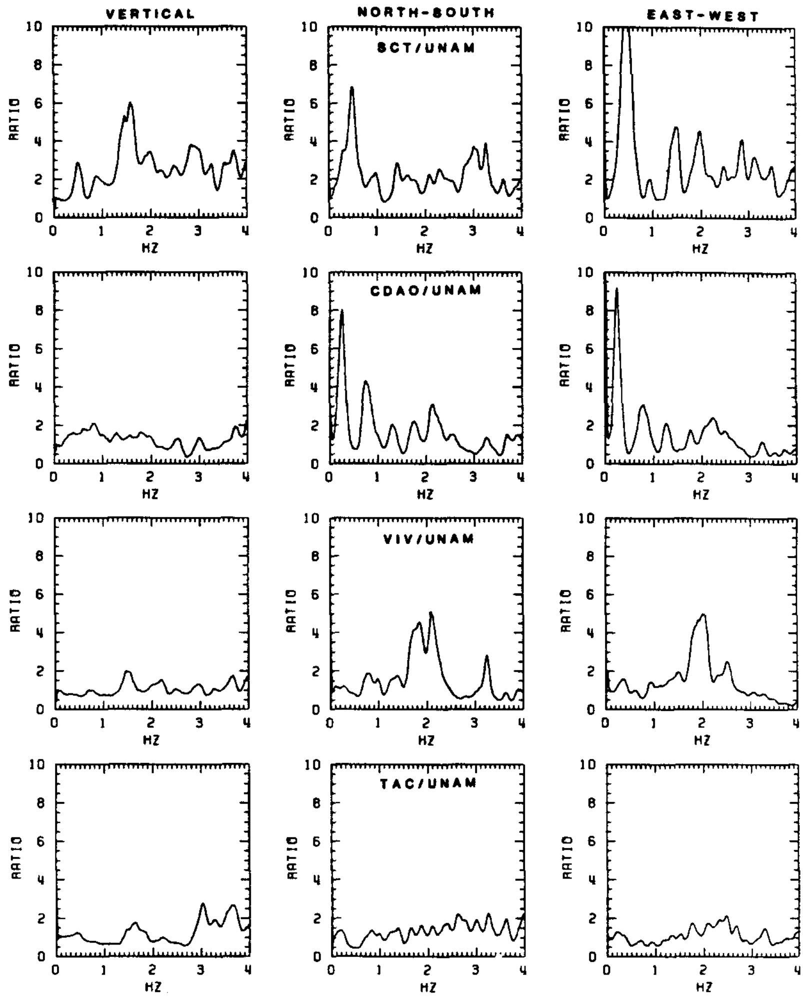

Figure 4 – Spectral ratios for the vertical and horizontal components (NS and EW),respectively, derived from the strong motion records of the 19 September 1985 earthquake. Ratios shown are for stations SCT, CDAO, VIV and TAC with respect to UNAM. All plot have same format and scale to provide easy comparison. 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.

housing complex); however these will be discussed in the next section. Relative locations of these stations are shown on the map in Figure 3. 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 Figure 5 exhibit several distinctive characteristics. They all have amplitudes significantly larger by an order of magnitude than those spectral ratios from strong motions. This is to be expected 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 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.

The weak motions were recorded by GEOS (General Earthquake Observation System) (Borcherdt and others, 1985) using the three-component package Mark* Products L22–3D velocity transducers.

The records were played back and processed to obtain Fourier amplitude spectra and spectral ratios using the amplification function relationship, $R_{\text{amplification}}(\omega)$:

$$R_{\text{amplification}}(\omega) = \frac{A_2 j(\omega)}{A_1 j(\omega)}$$

where $A_i j(\omega)$ is the jth component Fourier amplitude spectrum at recording station i. This relationship is valid assuming the differences in distances can be neglected. Quantification of amplification of motions by spectral ratios is discussed by Gibbs and Borcherdt (1974) and Rogers and others (1984). The spectral ratios were smoothed with a triangular weighting function with width of 0.15 Hz.

AMPLIFICATION AT TLATELOLCO—A CASE STORY

The Tlatelolco government housing complex is a case by itself because of the large number of structures and dwellers involved. The complex is best remembered by the Nuevo Leon Building of which one of the three blocks had overturned during the earthquake. Figure 7 shows a general layout of the complex. Nuevo Leon and other key buildings are identified in the figure. The construction of the complex was started in 1960 and completed in 1963. There were 102 buildings of various configuration and prior to the earthquake, approximately 150,000 people lived in 12,000 units. A year after the earthquake, only 85,000 people lived in the habitable units. Including the Nuevo Leon building mentioned above, 8 buildings were demolished. 22 buildings required major repair, 60 buildings required repair and the heights of 14 buildings were reduced by demolishing several of their upper floors in order to alter their dynamic characteristics. 7 of the 14 altered buildings were 23 stories and 20 m × 20 m in plan.

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

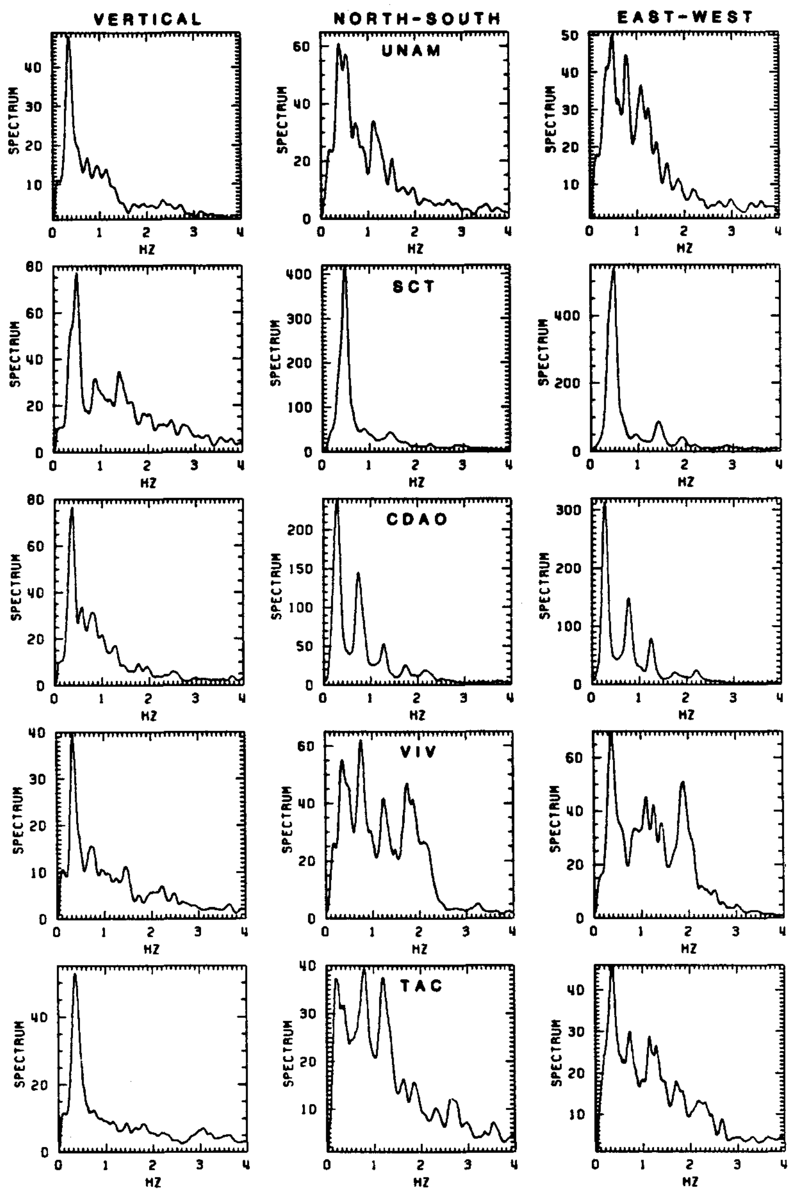

Figure 5 – Fourier spectra for the vertical and horizontal components (NS and EW),respectively, derived from the strong-motion records of stations UNAM, SCT, CDAO, VIV and TAC in Mexico City. All plots demonstrate the significant low-frequency energy at all stations.

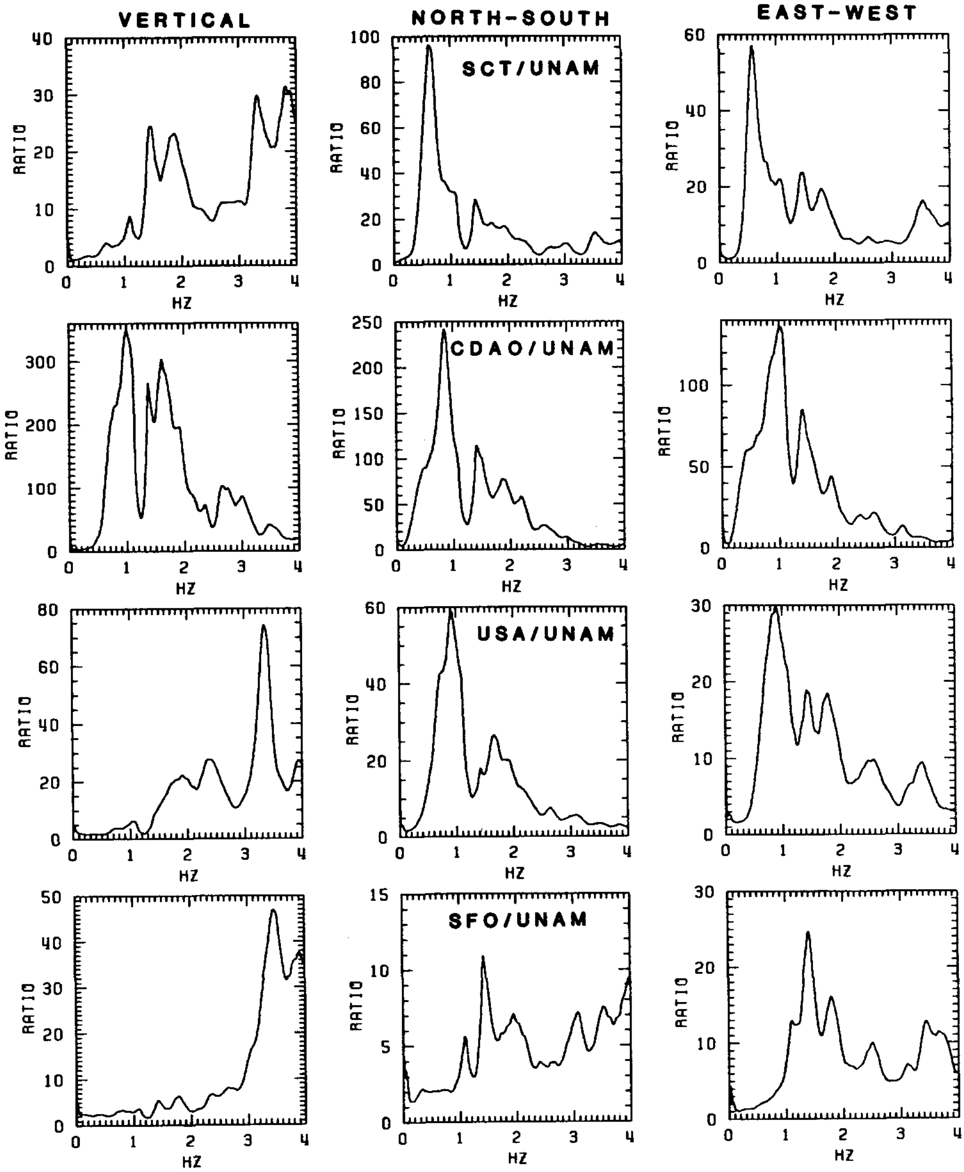

Figure 6 – Spectral ratios for the vertical and horizontal components (NS and EW),respectively, derived from weak motions recorded at stations CDAO, SCT, USA, SFO and UNAM. All plots are made with respect to UNAM. CDAO, SCT and UNAM stations are same as the strong-motion stations.

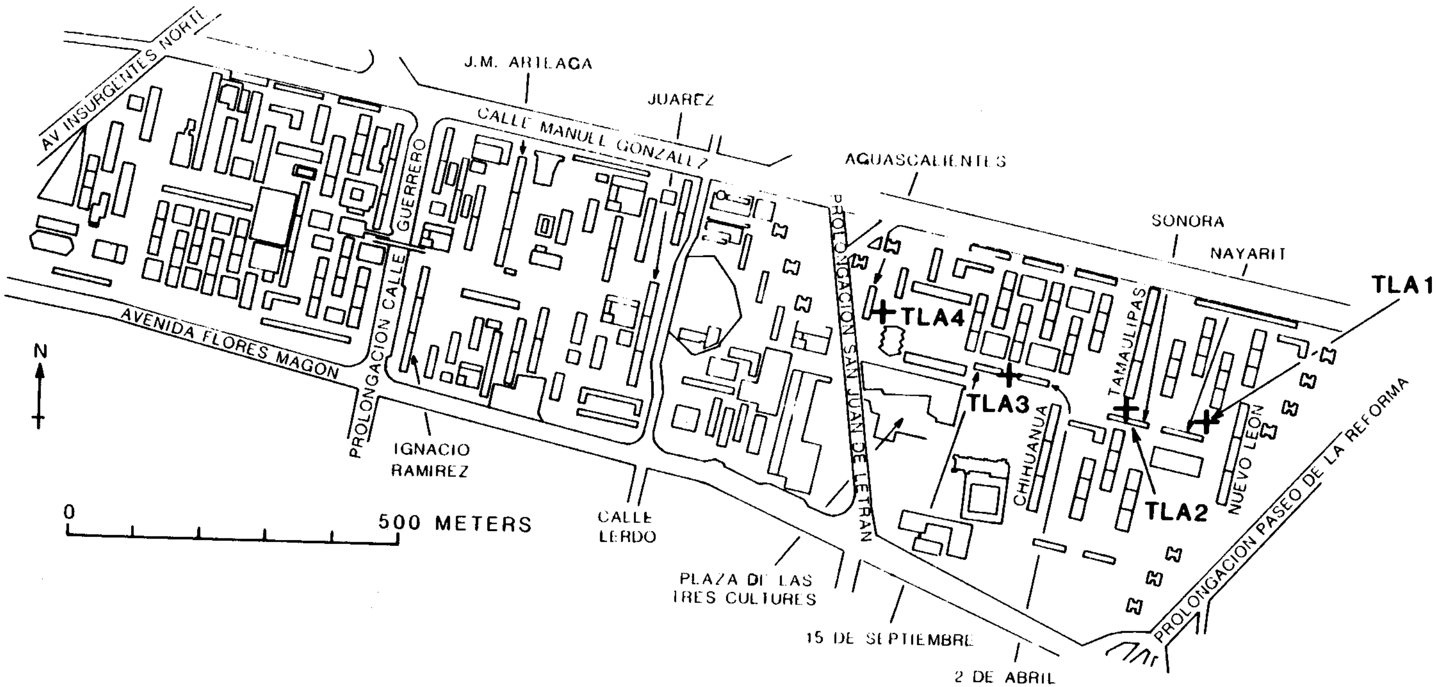

Figure 7 – General layout of the buildings at the Tlatelolco complex. Temporary stations established for noise measurements are identified.

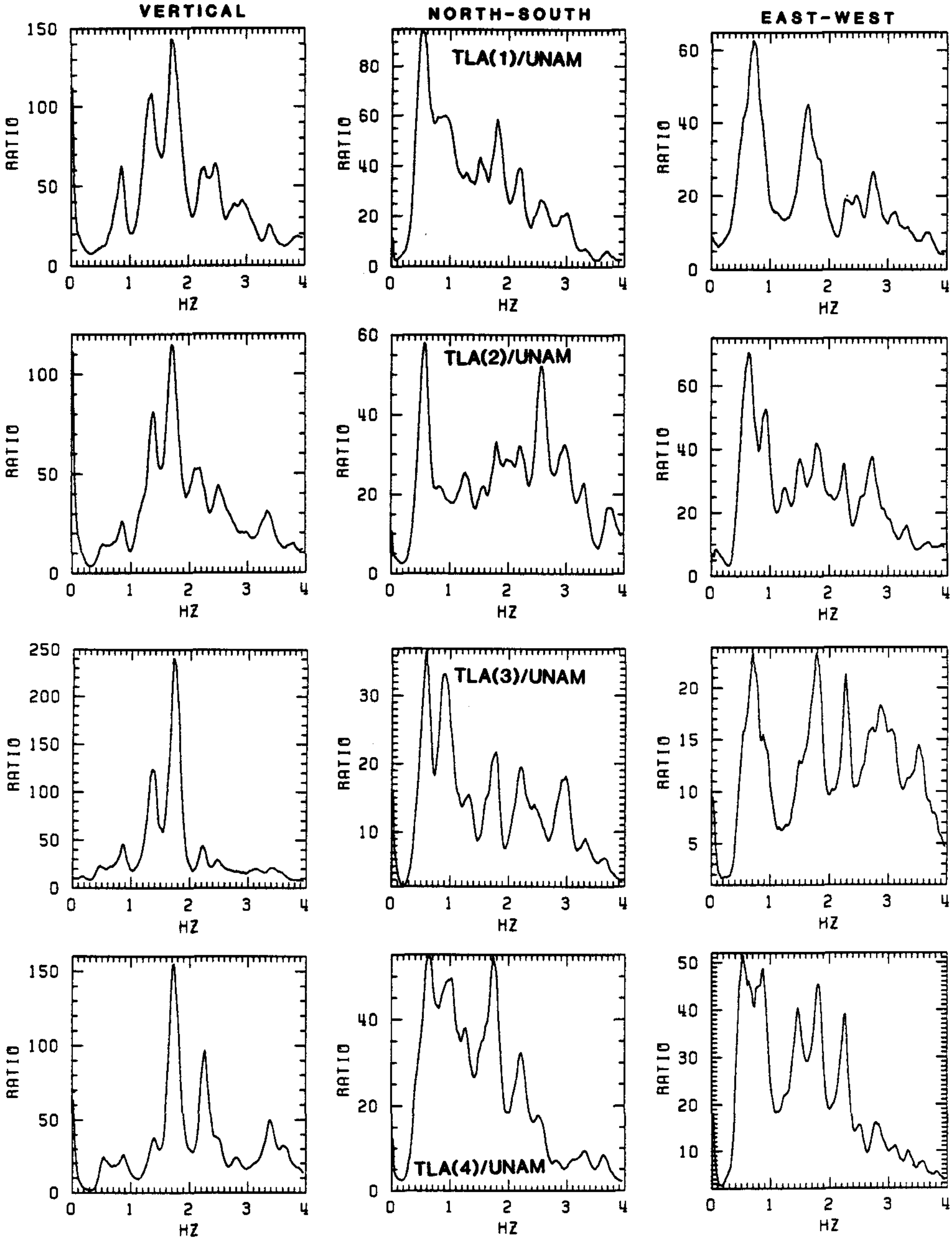

Figure 8 – Spectral ratios for the vertical and horizontal components (NS and EW),respectively, derived from weak motions recorded simultaneously at stations TLA(1) through TLA(4). All plots are made with respect to UNAM.

Four temporary stations [TLA(1) through TLA(4)] were established at a part of the Tlatelolco complex. The locations of these stations are identified in Figure 7. Traffic noise recordings were made simultaneously at these stations. From these measurements, spectral ratios with respect to UNAM were derived (Figure 8). TLA/UNAM spectral ratios as others show consistent horizontal amplification of motions at low frequency ranges of 0.5-0.7 Hz—clearly within the range of fundamental frequencies of the buildings in this complex.

CONCLUSIONS

The spectral ratios from strong motion records and weak motions exhibit the resonant frequencies for which amplification of motions were experienced in Mexico City during the 19 September 1985 Michoacan earthquake, the epicenter of which was approximately 400 km away near the Pacific coast of Mexico. While the spectral ratios from strong motions provide the resonant frequencies and amplitudes of amplification of motions at one location with respect to another, the spectral ratios from weak motions satisfactorily identify the resonant frequencies. Because the energy, path and source of the weak motions are not same as those of the strong motions; therefore, the weak motion spectral ratios should only be used to identify the resonant frequencies in Mexico City. Although other engineering and construction practices may have been contributing factors to the performance of the structures throughout Mexico City during the earthquake, the amplification of motions at resonant frequencies in the range of the frequencies of the structures played a significant role. This is exemplified by correlation of amplification of motions and the damages at Tlatelalco as well as throughout the lakebed of Mexico City. Thus the culprit.

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