ZONING VERIFICATION IN MEXICO CITY USING STRONG MOTIONS OF THE M7.1 PUEBLA-MORELOS EARTHQUAKE OF SEPTEMBER 19, 2017

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Abstract

Mexico City suffers extensive damage from large earthquakes that originate at far distances due mainly to densely built areas on a filled lakebed. Seismic design codes in Mexico recognize the site-specific issues in Mexico City by acknowledging zones that represent lakebed as being riskier compared to other Mexico City areas. At the time of the 19 September 1985 **M**8.1 Michoacán Earthquake, (a) the seismic zoning map comprised only three zones (Hills [now Zone I], Transition [now Zone II] and Lake Zone [now Zone III] and (b) a limited number of permanent strong motion stations (~6) existed. Since 1985, the seismic zonation maps have evolved: (a) the Lake Zone (now Zone III) into 4 sub-zones (a, b, c and d) and (b) the number of strong motion stations has increased significantly (~25) and recorded the 19 September 2017 **M**7.1 Puebla-Morelos earthquake. To identify the site frequency [f] (period [T]) at the specific location of a strong motion station within a particular zone or sub-zone (Zone I, II and III a,b,c,d), two well-known methods (H/H and H/V) for determining spectral ratios are employed using these records. The predominant site periods identified by both methods are in good agreement with those interpolated from the zoning-site period maps of Mexico City in the 2004 Seismic Design Code. Such verification is a testament to the benefits of improved zoning and greater distribution of strong motion network stations, and sets a good example for applications in other seismic regions.

Introduction

On September 19, 2017, the **M**7.1 Puebla-Morelos earthquake occurred at 18:14:40 GMT (13:14:40 local time) at epicentral coordinates 18.40 North latitude and 98.72 West longitude and a depth of 57 km (The National Seismological Service of Mexico [SSN]). The United States Geological Survey (USGS) give the epicentral coordinates as 18.5838N and 98.3993W and depth as 51 km. GEER report (2017) describes the earthquake as occurring "in a complex region of normal and reverse faults with a regional tectonic mechanism associated with the subduction of the Cocos plate under the North American plate. The epicenter was located 12 km southeast of the city of Axochiapan in the State of Morelos. As expected, there was no surface expression of the fault rupture reported by any of the reconnaissance teams dispatched to the area". Additional information on the seismological aspects, tectonics and intensity and shake maps related to this event can be found at the USGS web site https://earthquake.usgs.gov /earthquakes/eventpage/us2000ar20#executive (*last visited 08/03/2018*)

It is well known that previous earthquakes occurring at far distances from Mexico City have caused significant loss of life and extensive damage within the city. Perhaps the most significant of such events is the 19 September 1985 **M**8.1 Michoacán earthquake (Çelebi et al., 1987, Stone et al., 1987, Anderson and others, 2016). At an epicentral distance of ~400 km, this event caused 4287 casualties and 5728 buildings to either collapse or suffer heavy damages (Çelebi et al., 1987, Stone et al., 1987). Relative locations of the 1985 and 2017 earthquake epicenters, and epicentral distances from Mexico City are shown in Figure 1. We note that while the epicenter of the 1985 earthquake was almost 4 times farther away from Mexico City than the 2017 event, its magnitude was an order of magnitude larger. It is also well known that the main reason why Mexico City suffers extensive damage from distant earthquakes is that it is mainly and densely built on a filled lakebed (GEER, 2017). Hence, seismic design codes in Mexico recognize the site-specific zonation issues in Mexico City. The design codes have considered three zones that realistically represent Lakebed areas as riskier. For example, at the time of the 1985 earthquake, the seismic zoning map used in design codes comprised of only three zones (Hills [now Zone I], Transition [now Zone II] and Lake Zone [now Zone III] (Figure 2a *from* Çelebi et al., 1987). This older zonation map depicts only limited number of the current key strong motion stations, but also includes locations of temporary stations established in 1985 earthquake related aftershock studies (Çelebi et al., 1987) that are not repeated herein.

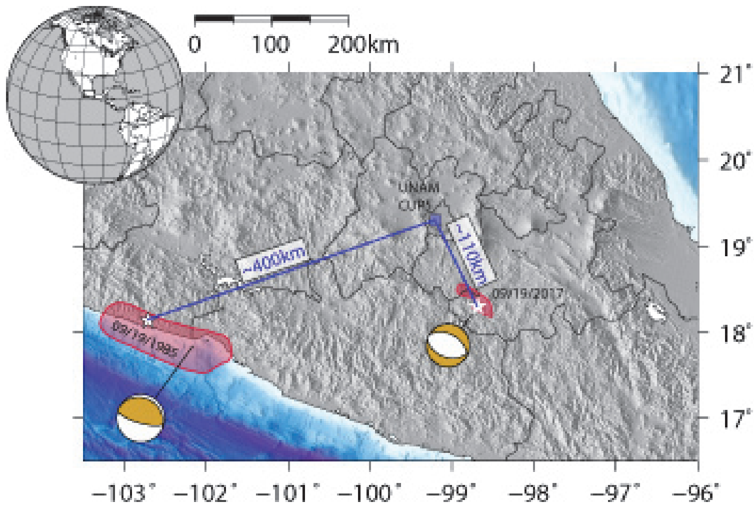

Figure 1. (a) Locations of the 1985 and 2017 earthquakes with respect to Mexico City.

The current seismic code further divides the Lake Zone (now Zone III) into 4 sub-zones. Figure 2b shows the current seismic zoning map of Mexico City that has been in effect since 2004 (Mexican Seismic Design Code of 2004) and modified to distinguish in color the four sub-zones (a, b, c and d) on the Lake Zone (Zone III). The map includes some of the stations in different zones that recorded the 19 September 2017 M7.1 earthquake. Station CUP5 used in this paper is in very close proximity to UNAM station that was the major reference station used in studies following the 19 September 1985 M8.1 Michoacán Earthquake (Çelebi et al., 2017).

Purpose of This Study

In this study, we analyze the spectral ratios computed from strong-motion data recorded by ~25 stations in Mexico City during the **M**7.1 19 September 2017 Puebla-Morelos earthquake. With these data, we aim to identify the predominant frequencies at select sites. When applicable, we compare these frequencies and spectral ratios with observed predominant frequencies from the 1985 earthquake. We also compare the frequencies and spectral ratios we compute with the current site periods (frequencies) from the seismic zoning map of Mexico City (Mexican Seismic Design Code of 2004). The scope of the paper will not include tectonics, seismicity, earthquake damage reconnaissance and/or assessment A detailed review of research on tectonics, seismicity, earthquake damage reconnaissance and/or assessment on the Mexico City basin can be found in Flores-Estrella et al. (2007).

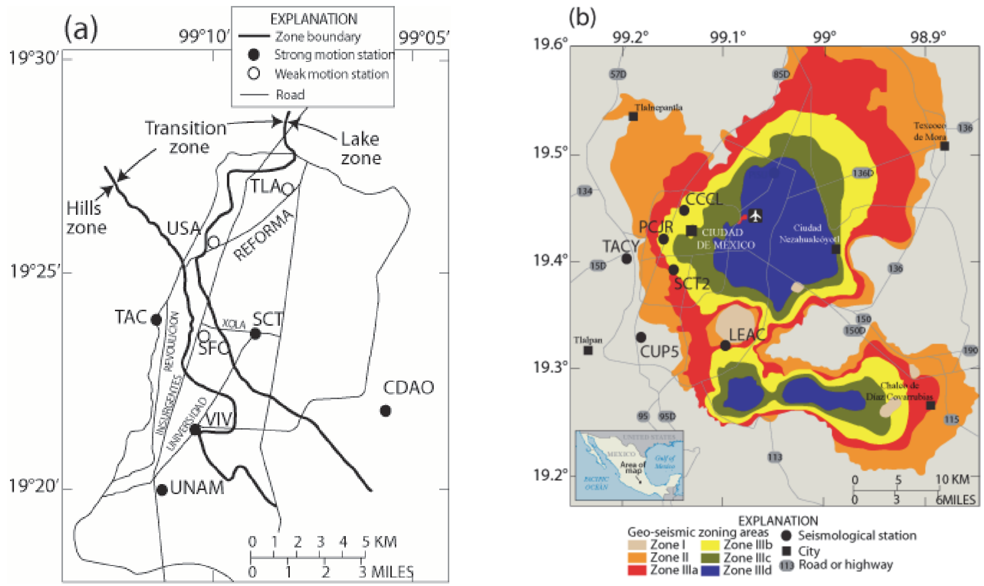

Figure 2.(a) Zoning Map in 1985(from Çelebi et al., 1987)*, (b) Zoning Map in 2017 (from 2004 Mexican Seismic Code). Note scale change between maps a and b.*

1987 Stations and Data

Figure 3a shows a Google Earth map with the locations of the stations in Mexico City that recorded the 2017 Mexico City-Puebla earthquake. These stations are operated by Institute of Engineering's (IINGEN) Strong Ground Motion Network of the Seismic Instrumentation Unit within the Engineering Seismology Laboratory of the Universidad Nacional Autonoma de Mexico (UNAM) and Centro de Instrumentación y Registro Sísmico (CIRES). In this figure, we show only those stations from which data were available to us and are used in this study. The map in Figure 3b shows predominant periods in the different zones (digitized by authors using the map in the Mexican Seismic Design Code of 2004. This map is used later in this paper to compare site periods from the code (obtained by interpolation of this map) with those site period from strong motion data of 2017 earthquake computed by spectral ratios.

Spectral Ratios

After standardization of the acceleration data which otherwise were not uniform in length of record and sampling ratio, we compute amplitude spectra of each channel of all stations and then smoothed them by applying a Hanning window using Matlab software (Mathworks, 2017). Spectral ratios, also known as the H/H method, are computed using the transfer function relationship:

$$R_{ij}(f) = A_{ij}(f)/A_{ref,j}(f) \qquad (1)$$

where

$A_{ij}(f)$ is the *j*th component of the smoothed amplitude spectrum at recording station *i* and similarly, $A_{ref,j}(f)$ is the *j*th component of the smoothed amplitude spectrum at the reference recording station. This relationship is valid assuming the differences in distance between the recording station *i* and reference station is negligible when compared to the epicentral distance of the reference station (~106 km, Figure 1). The background for such quantification of amplifications of motions as represented by spectral ratios *Rij(f)* is discussed in detail by Borcherdt (1970, 1976, Borcherdt and Glassmoyer, 1992).

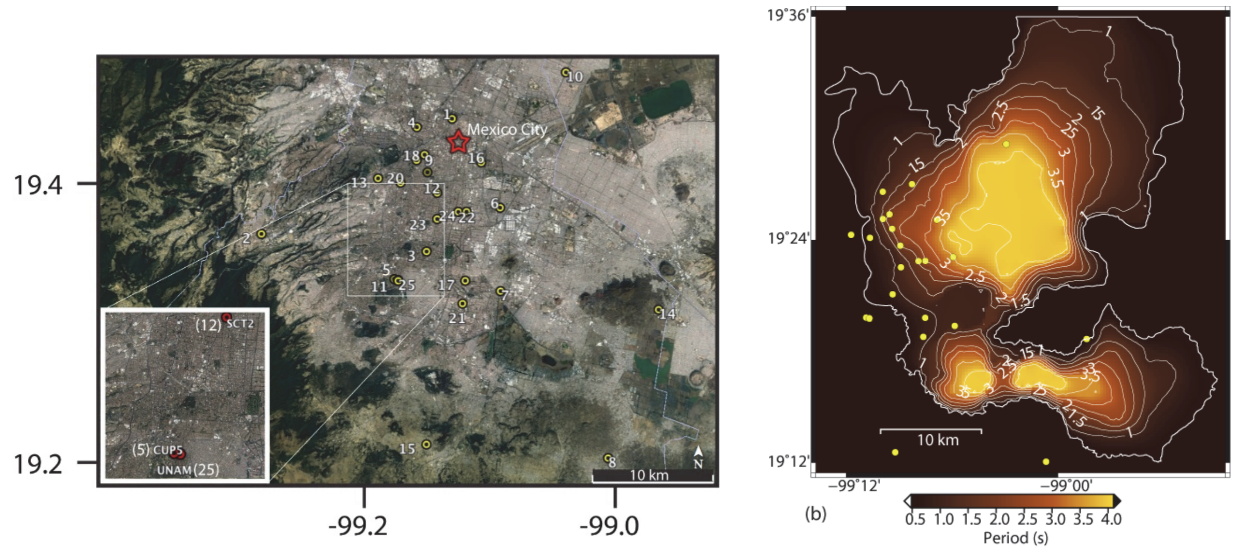

Figure 3. (a) Google Earth Map of Mexico City with strong motion stations used in this study, that recorded the earthquake of 19 September 2017 (yellow circles with station numbers labeled). In particular, SCT, CUP5 and UNAM stations are highlighted in red in the inset. (b) Map showing predominant periods in the different zones (digitized by authors using the map in the Mexican Seismic Design Code of 2004)

In addition to the above classic spectral ratio method, we also use H/V ratios, more widely known as Nakamura's Method (Nakamura, 1989, 2008). This method is normally used when there is no suitable reference station data that can be used to compute *Aref,j(f)* in Equation 1. As seen later, we successfully applied this method for the data from Zone II and Zone III.

For the sake of brevity, in general we will not present time-histories or amplitude spectra – except, however, for a couple of sample cases to demonstrate both methods. In Figure 4, for SCT2 station record in Zone IIIb, we show (a) mainshock acceleration time-histories in N-S, E-W and vertical directions, (b) amplitude spectra of the accelerations and (c) spectral ratio (H/V) for SCT2. It is noted that SCT2 is the same as the 1985 SCT station). The H/V spectral ratios clearly indicate that the dominant frequency (period) of SCT2 is ~0.5 Hz (2s), similar to those in the 1985 response spectra (Çelebi et al., 1987). In Figure 5 we repeat the same process for CUP5 [Zone I]: (a) time-histories, (b) amplitude spectra and (c) spectral ratios (H/V). As expected, there is predominant frequency within the 0-2 Hz window.

Next, in Figure 6a, we compute H/H or *Rij(f)= Aij(f)/Aref,j(f)* for SCT2 [*Aij(f)]* and CUP5 (*Aref,j(f))*. Figure 6b is identical to Figure 4c, in order to compare the two methods. It is clear that the comparison is excellent and both methods yield the dominant ~0.5 Hz site frequency for SCT2. This is a clear indication of the applicability of the H/V method for the motions recorded in Mexico City.

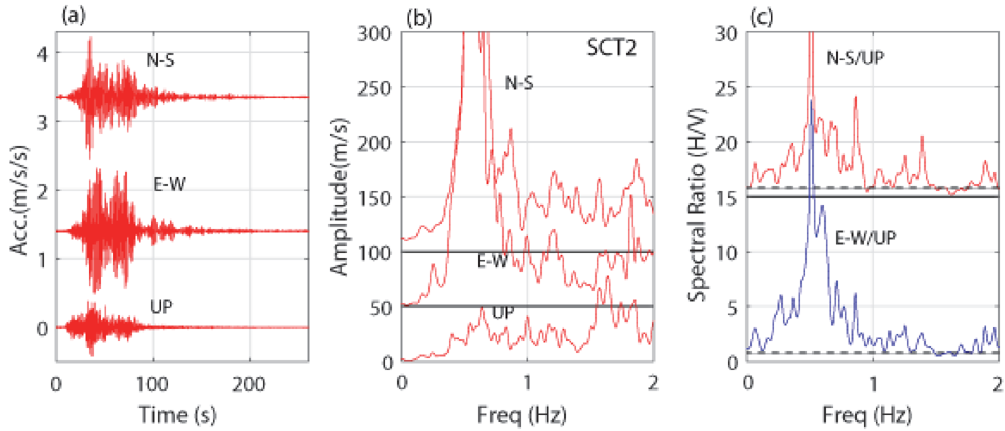

Figure 4. For SCT2 in Zone IIIb, (a) N-S, E-W and vertical mainshock acceleration time-histories, (b) amplitude spectra computed from accelerations and (c) spectral ratios using H/V of amplitude spectra.

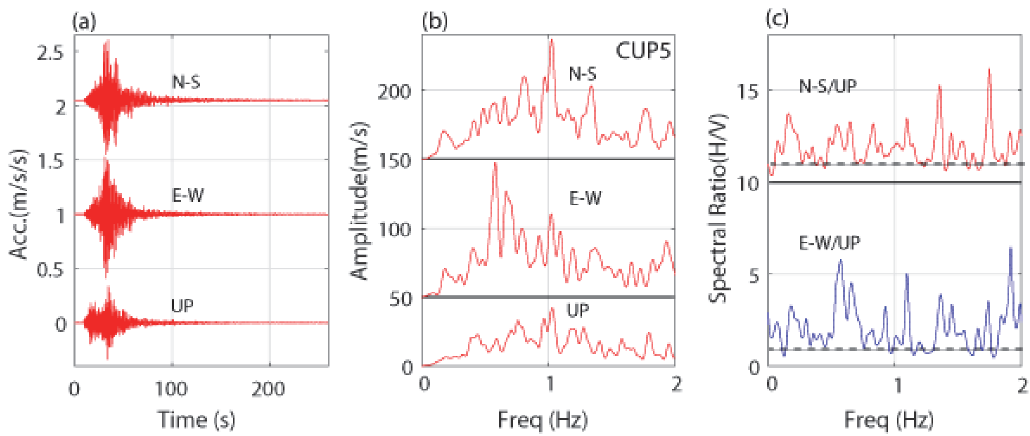

Figure 5 For CUP5 in Zone I, (a) N-S, E-W and vertical mainshock acceleration time-histories, (b) amplitude spectra computed from accelerations and (c) spectral ratios using H/V of amplitude spectra.

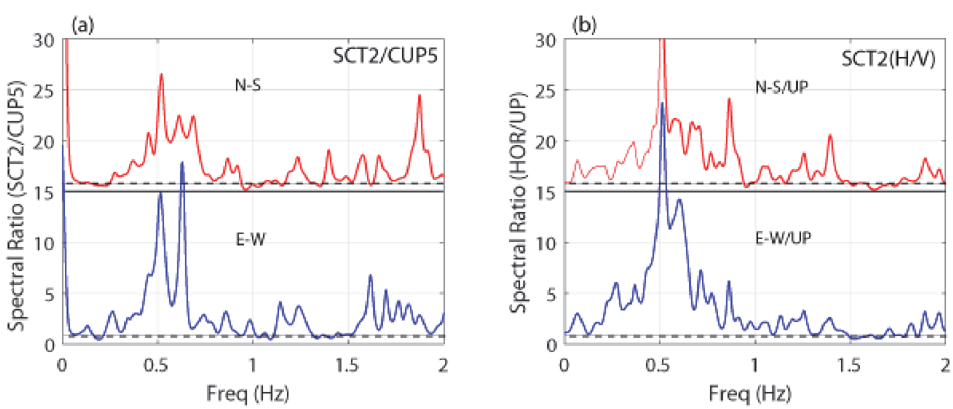

Figure 6. Comparison of (a) spectral ratios of SCT2 [Zone IIIb] w.r.t. CUP5 [Zone I] with those (b) spectral ratios computed using the H/V method only for SCT2 amplitude spectra. The peak that appears around 0 Hz is due to numerical computation – denominators being very small numbers.

Spectral Ratios for Zone II. We repeat the comparison of *Rij(f)= Aij(f)/Aref,j(f)* with H/V spectral ratios for only data from five Zone II stations (Figure 3a). Figures 7a and b show for five Zone II stations, spectral ratios computed in the NS and EW directions respectively using H/H or *Rij(f)= Aij(f)/Aref,j(f)* with CUP5 as the denominator, and similarly, Figures 7c and d show spectral ratios using the H/V method. At top part of each frame, an average of the five spectral ratios is also shown. What is indicated in this figure is the spread of Zone II site frequencies (periods) are between ~0.7-1.1Hz (~0.91-1.43s) consistent for both methods. Variations of site frequencies from one station to the next can be attributed to the variation of depth and log of each location. At top part of each frame in Figure 6, an average of the five spectral ratios within that frame is also shown. The averages also confirm frequencies (periods) between ~0.7-1.1Hz (~0.91-1.43s).

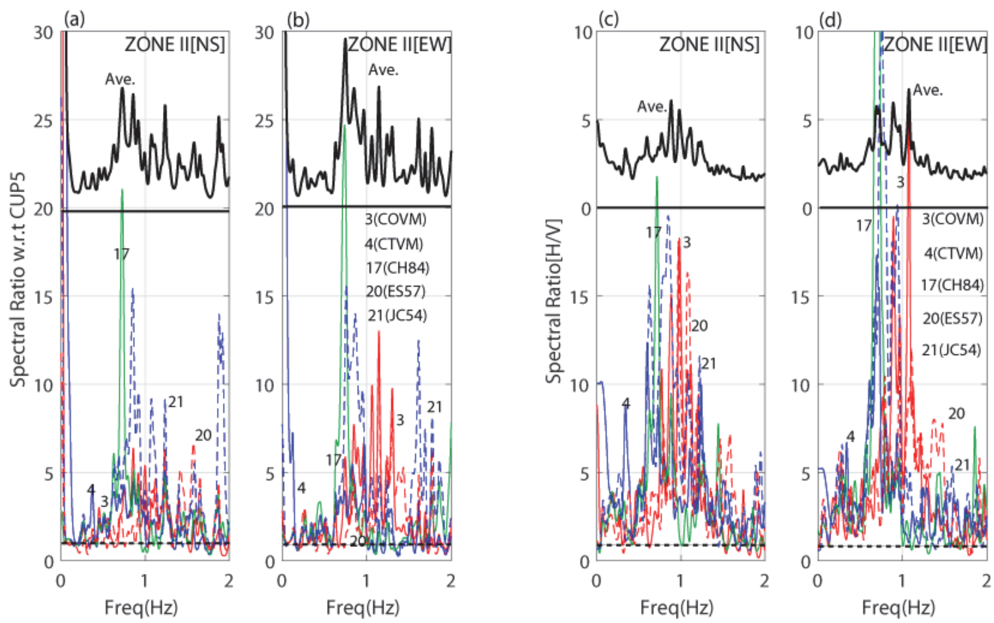

Figure 7. For five Zone II stations, (a) NS and (b) EW spectral ratios computed using Rij(f)= Aij(f)/Aref,j(f) with CUP5 as the reference site,, and similarly (c) and (d) spectral ratios using the H/V method. At top part of each frame, an average of the five spectral ratios is also shown.

Spectral Ratios for Zone III. Following the same process described above, in Figure 8 we compare the spectral ratios by both methods individually for the stations within each of the four Zone III divisions (Zones IIIa, b,c and d) (Figure 2b).The number of stations in each of the subgroups varies.

Figures 8a and b show *Rij(f)= Aij(f)/Aref,j(f)* with CUP5 as the denominator in all of the Zone III spectral ratio vs. frequency curves computed from accelerations recorded in (a) NS and (b) EW directions of the stations (identified by a numbering in Figure 3a. What is clear in Figure 8a and b is a trend toward increasing dominant frequency from Zone IIId to Zone IIIa (bottom to top). For example, for Zone IIId, f (or T) is ~ 0.25 Hz (~4.0s) and for Zone IIIa, f or T is ~ 0.65-0.8 Hz (~1.25-1.54s). There is small variation between Zone IIIc and d (e.g. f or T is ~ 0.8 – 1.0 Hz (~1.0-1.25s).

Similarly, Figure 8c and d show the spectral ratio vs. frequency curves computed by the H/V method from accelerations recorded in (c) NS and (d) EW directions of the stations (identified by the numbering in Figure 2a). The trends towards higher frequencies for Zone IIId to IIIa and individual site frequencies (or ranges of frequencies) are very similar to those observed in Figure 8a and b.

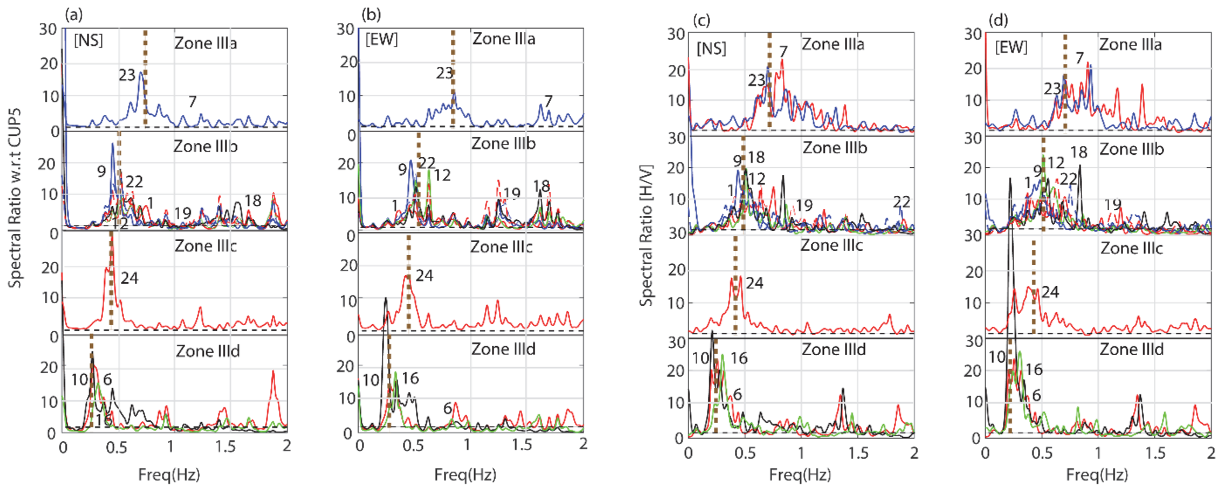

Figure 8 Using accelerations recorded in all of the four Zone III stations (Figure 3a), spectral ratios computed with respect to CUP5 as the denominator in (a) NS and (b) EW directions and similarly, spectral ratios computed by the H/V method in (c) NS and (d) EW directions. Dashed vertical lines are intended to depict the changing trend of frequencies from Zone IIId to IIIa.

Discussion and Conclusions

Spectral ratios computed using acceleration time histories recorded at multiple stations in Mexico City during the September 19, 2017 earthquake allow identification of site frequencies (periods). In this study, spectral ratios computed by two methods [(i) H/H (or *Rij*) and (ii) H/V] are similar. Figure 9 shows a comparison of site periods (T) (frequencies[f] indicated by predominant peaks in spectral ratios using both methods (for Zone II and Zones III a,b,c and d) with those interpolated from the predominant site period map presented in Figure 3b, a digitized version of the Seismic Zoning Maps currently in effect in Mexico City (2004).

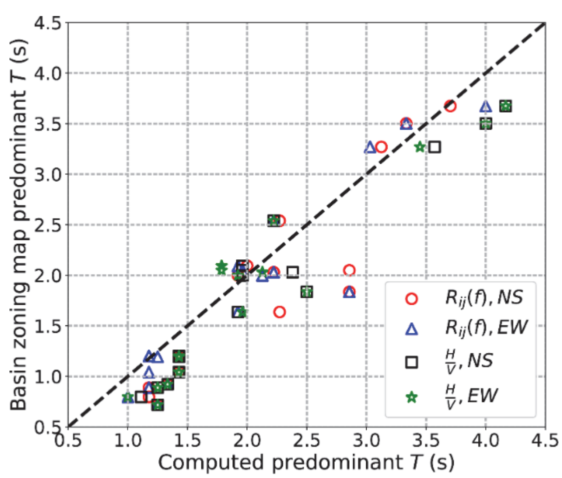

Figure 9. Comparison of predominant site periods: zoning map of 2004 Code versus those determined from H/h (or Rij) and H/V ratios. Diagonal dashed line represents a 1:1 correspondence.

Due to unknown but likely variations of depth and geological formations at each station location, as well as variations in shear wave velocities, the observed variations of periods (frequencies) are not unexpected. However, as seen in Figure 9, there is a clear trend toward higher site frequencies in acceleration from Zone IIId to Zone IIIa. This is consistent and justified as depth and shear wave velocities vary between 10-60 m within Zone III (2004 Mexico Seismic Design Code). The differences may be attributed to interpolation from the maps, or peak picking of the frequencies from ratios.

We conclude that predominant site periods (frequencies) identified from spectral ratios computed for ground motions recorded in Mexico City during the mainshock of the 2017 (**M**7.1) Puebla-Morelos earthquake are in relatively good agreement with those indicated in the site period map of the 2004 Mexican Seismic Design Code. The agreement is best for Zone III, and relatively good for Zone II stations. The differences can be attributed to one or a combination of several factors including (a) interpolation errors from the maps, (b) peak picking errors of the frequencies from spectral ratios, (c) variations of depth, (d) associated Vs values of the underlying soil at the different locations and (e) differences in H/V to H/H (soil/rock) ratios. Most importantly, the differences are most likely due to the physical difference between the H/H spectral ratio computed with respect to a reference station and the H/V spectral ratio computed with respect to vertical motion at same station. Furthermore, we conclude that the H/V method can be reliably used with Mexico City data. While the correlation of the predominant zoning-site periods of the observed data and those included in the maps of the 2004 code are satisfactory, it is hereby emphasized that such agreement does not at all imply that the spectral levels in the code are insufficient for earthquake resistant design of buildings in the lakebed zones of Mexico City. Additional studies of this effect are recommended.

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