Effects of the Subsidence on the Changes of Dominant Periods of Soils within Mexico City Valley

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SUMMARY:
In this work the variations of the dominant periods in Mexico City soil sites within a time window of 20 years are pointed out. These changes appear to be strongly correlated to regional subsidence. Therefore, a proposition is made to update the corresponding zonification map within the Technical Annex of Mexico City (Federal District) Building Code. The acceleration records on 85 stations of the Mexico City Accelerometric Network (MCAN) for an assortment of recent earthquakes were studied. Besides, 810 new measurements of microtremors were performed at various sites. From data analysis a relationship that describes this 20-years-variation is obtained. It reveals changes of up to 0.9s within a zone traditionally considered as *Lake* (zone IIId). This relationship allowed updating the available information, reaching 1300 data points that allowed the generation of a new seismic zonification.

Keywords: subsidence, basin of mexico, microtremor, seismic zonification

1. INTRODUCTION

As a consequence of the great Michoacán earthquake of September 19th, 1985 (M8.1) that produced unprecedented dead toll and infrastructure damage to Mexico City, the studies of dynamic soil properties, the seismic response of the city, the seismic hazard analysis and the zonification got a renewed interest. The city already had a zonification of three zones based on the geology: zone I (Hill zone) located at the higher parts of the basin, its soils are typically characterized by high strengths with little compressibility; the zone II (Transition zone) has soils composed by sand and silt; and the zone III (Lake zone) was divided in four subzones (A, B, C, and D) and comprises the ancient Texcoco and Xochimilco lakes, with soil types of volcanic origin, very soft and compressible, with very high water content, and low shear wave velocities. All this favor the amplification of seismic waves.

The first map of soil periods for Mexico City was issued in 1987. It was composed after data from 99 measurement points were gathered. Afterwards, measurements of both microtremors and strong motion data in many other points were conducted. Lermo *et al.* (1994) collected many of such measurements and performed new ones away from fixed stations or previous measure points. They also recorded small earthquakes using a temporal seismic network.

Lermo and Chávez-García (1994) studied 81 accelerometric stations and 409 records of microtremors, with a relatively high spatial density produced a map of dominant periods for the valley (see Fig. 1.1a). This map was the base for the isoperiod chart within the Complementary Technical Annex for Seismic Design (NTCDS for its name in Spanish) of the Mexico City (Federal District) Building Code (RCDF) (see Fig. 1.1b). The code specify that the limit between zones I and II is the line of dominant period Ts=0.5s, while the limit between zones II and III corresponds to Ts=1.0s.

a) b)

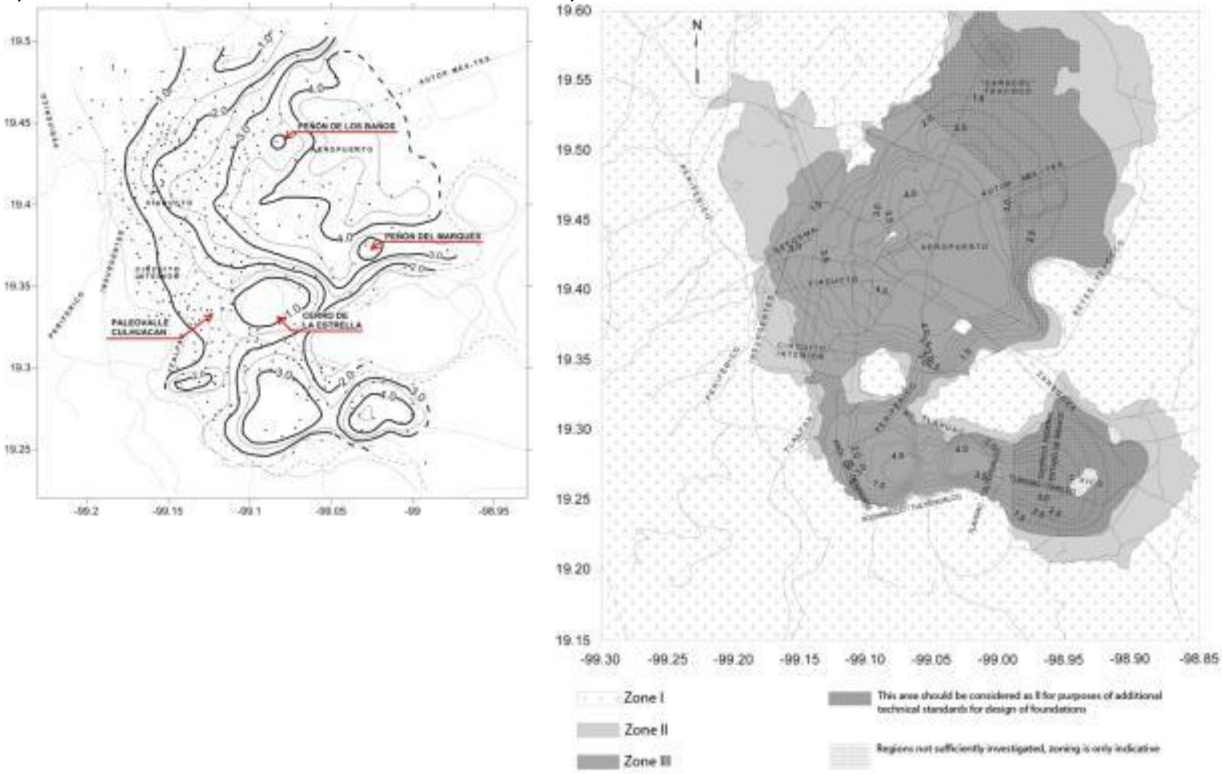

Figure 1.1 a) Map proposed by Lermo *et al.* (1994) for Mexico City, each dot indicates a measurement. b) Isoperiod Map for the Federal District in Complementary Technical Annex for Seismic Design (NTCDS, 2004).

Note however, that these maps have some differences that require a comment. The NTCDS' map displays isoperiod curves (Ts=3.0 and Ts=4.0s) that cross the well-known Peñón de los Baños and Peñón del Marqués topographic features. On the other hand, the Lermo and Chávez-García (1994) maps clearly depict the isoperiod contours with values smaller than Ts=3.0s around these two geological structures.

On the other hand, the map of Fig. 1.1 a) shows with dashed line Ts=0.5s as indicative at the west side while the contours for Ts=0.5 and Ts=1.0s at the east were inferred. This is because data quantity was small or null to provide reliable estimates. A similar situation was observed for the north and south. However, the NTCDS map gives a sharp limit for zones I and II, probably based upon geotechnical information. The west of the city has the larger concentration of measurements while in other parts there is not enough information to trustworthy establish these limits.

Regarding the right map in Fig. 1.1 b) clearly shows that the region at the east of cerro de la Estrella is usually regarded as transition (zone II) due to the lack of data. This zone, known as the Culhuacan paleo-valley (Mooser, 1990), was part of an old hydrological system from north to south until the volcanic activity that originated the Chichinautzin mountain range. This geological event filled the chanel and significant clay deposits may be found there. This area is considered as zone II in the NTCDS. Perhaps it should be considered instead as zone III.

Another aspect to consider is the effect of regional subsidence that has been presented in the last 100 years. The overuse of water has caused the generation of cracks, reduction of piezometric levels, which leads to the consolidation and compaction of the clays, changing the dynamic properties of the soil. To date, in some areas of the city it is well documented accumulated subsidence of up to 11 meters in the time referred to. However, between the years 2000-2005 there was an increase in the speed of sinking of 30-35 cm/year (Méndez et al., 2008). Using direct and indirect approaches several authors have confirmed a generalized subsidence of the old lake zone (Ovando et al., 2007; Aguilar, 2008; López-Quiroz et al., 2009; Avilés y Pérez-Rocha, 2010; Cabral-Cano et al., 2010; Arroyo et al., 2012). These studies agree that Nezahualcoyotl City, a settlement there, is the area with the maximum subsidence. Despite the magnitude of this problem, very few studies have analyzed the variation in the seismic response of the soil by the effect of regional sagging.

This work describes perhaps the latest seismic ambient vibration measurements in the area as well as a new assessment of the dominant period using also the records of 12 earthquakes felt in the Valley of Mexico (from 2004 to 2012) and recorded in 85 accelerometric stations of the MCAN that currently operate within the basin of Mexico (see Fig. 1.2 and Table 3.1). We used the standard spectral ratio (SSR) with the aims of updating maps of predominant periods of the soil (Ts) and the zoning map of the seismic design, that are currently in the NTCDS (2004) of the RCDF. In summary, these maps require their update for two main reasons: 1) by inconsistencies in origin and, 2) changes in its value by regional effects of the sinking of the basin.

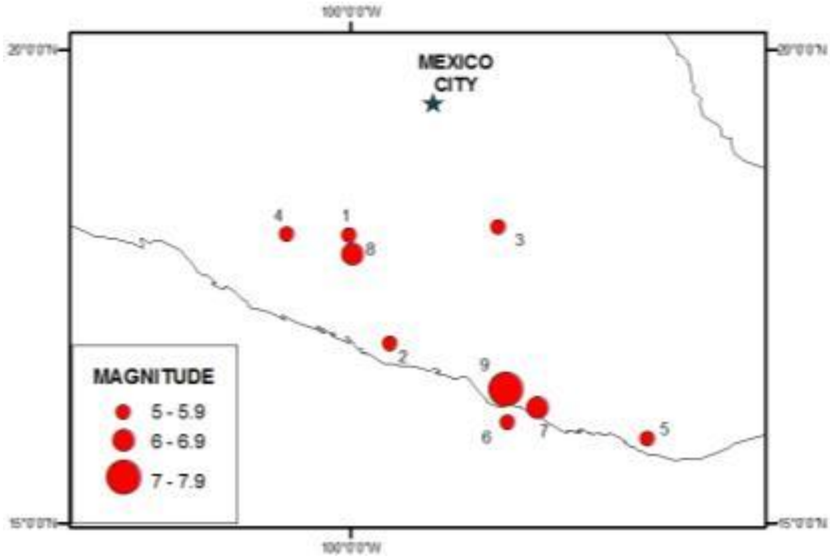

Figure 1.2. Location of the studied earthquakes between 2001 and 2012

2. MEASUREMENTS OF MICROTREMORS IN THE VALLEY OF MEXICO

Since 2009 several campaigns of microtremor measurements were developed around Peñón del Marqués, Peñón de los Baños, the Culhuacan paleo-valley and in various locations of Mexico City as well. The aim was to assess predominant periods in 810 new points using the H/V spectral or Nakamura ratio (HVNR). Measurements were made using the K2 Kinemetrics accelerometers.

The area at the east of cerro de la Estrella (the Culhuacan paleo-valley) was studied during May 2010 with 5 profiles along the principal streets in the area that run north-south and east-west (see Fig. 2.1). Approximately 150 measurements were taken. This information is complementary of the one gathered by Lermo and Chávez-García (1994). Transfer functions (TF) in this zone display peaks in periods between 0.6s and 1.4s and amplifications of more than 10 times. On the other hand, in the neighborhood there are 5 accelerometric stations of the Center of Seismic Instrumentation and Recording (CIRES) that also belong to the MCAN. From data of recent earthquakes the TF was obtained using the SSR with a reference site in the UNAM's main campus University City (CU). Also the H/V spectral ratio with earthquakes (HVSR) was obtained. Figure 2.2 shows a comparison of the average TF with SSR and the values of HVSR and HVNR. Results are displayed for two stations

(IB22 and JC54), out of the five mentioned, at the Culhuacan paleo-valley and for other 13 stations scattered in the Lake, Transition and Hill zones as well.

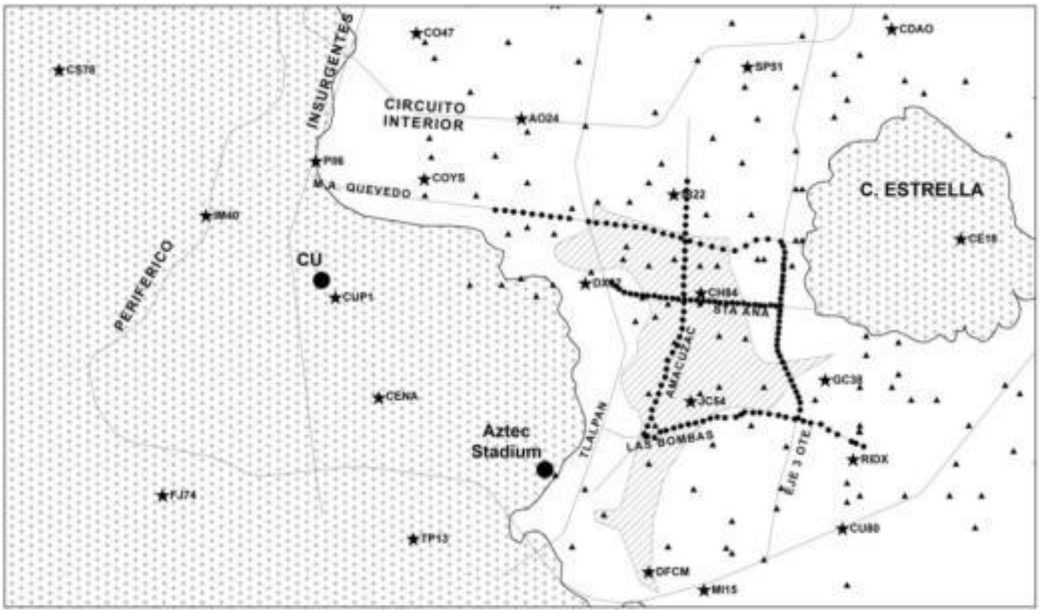

Figure 2.1. Distribution of measurement points in the Culhuacán paleo-valley area (dashed). Measurement points of 1992 within the area are marked with triangles while accelerometres are marked with stars.

Figure 2.2 depicts the Transfer Function (SSR) with red line, the HVNR of microtremors with continuous black line, and the HVSR of earthquakes with blue line. This comparison shows striking results and validate our microtremor measurements in 790 measured points (150 in this zone and 640 within the DF). In fact, the H/V of microtremors mimics both the H/V for earthquakes and, very important, the standard transfer function SSR in the peak frequency and amplitude. The contribution of the soil fundamental mode is preserved in contrast with higher modes that microtremor measurements do not capture in most cases. This behavior of HVNR can be explained in terms of the model that emerges from the diffusive character of noise (see Sánchez-Sesma et al., 2011). This deficit in the higher modes also show up in other Lake zone sites but is less evident in sites of Transition and Hill zones. The maps of isoperiods and the zonation maps of DF are then reliable.

A question that arises from Fig. 2.2 is why the HVNR gives amplitudes close to those of the transfer function at the peak frequency. Typically it is reported that H/V of microtremors systematically under-estimate the spectral amplification for earthquakes (Hagshenas et al., 2008). The good agreement here reported is due to the fact that our microtremor measurements are conducted continuously along 24 hours or more. Results are relatively independent of window size. Here we used windows of 80s without any smoothing.

In March 2011 data were collected around Peñón de los Baños and Peñón del Marqués. In those sites 59 and 78 registros were obtained, respectively. These measurements allowed to set properly the limits of the Hill zone (zone I), Transition zone (zone II) and the Lake zone (zone III) as shown in Fig. 2.3.

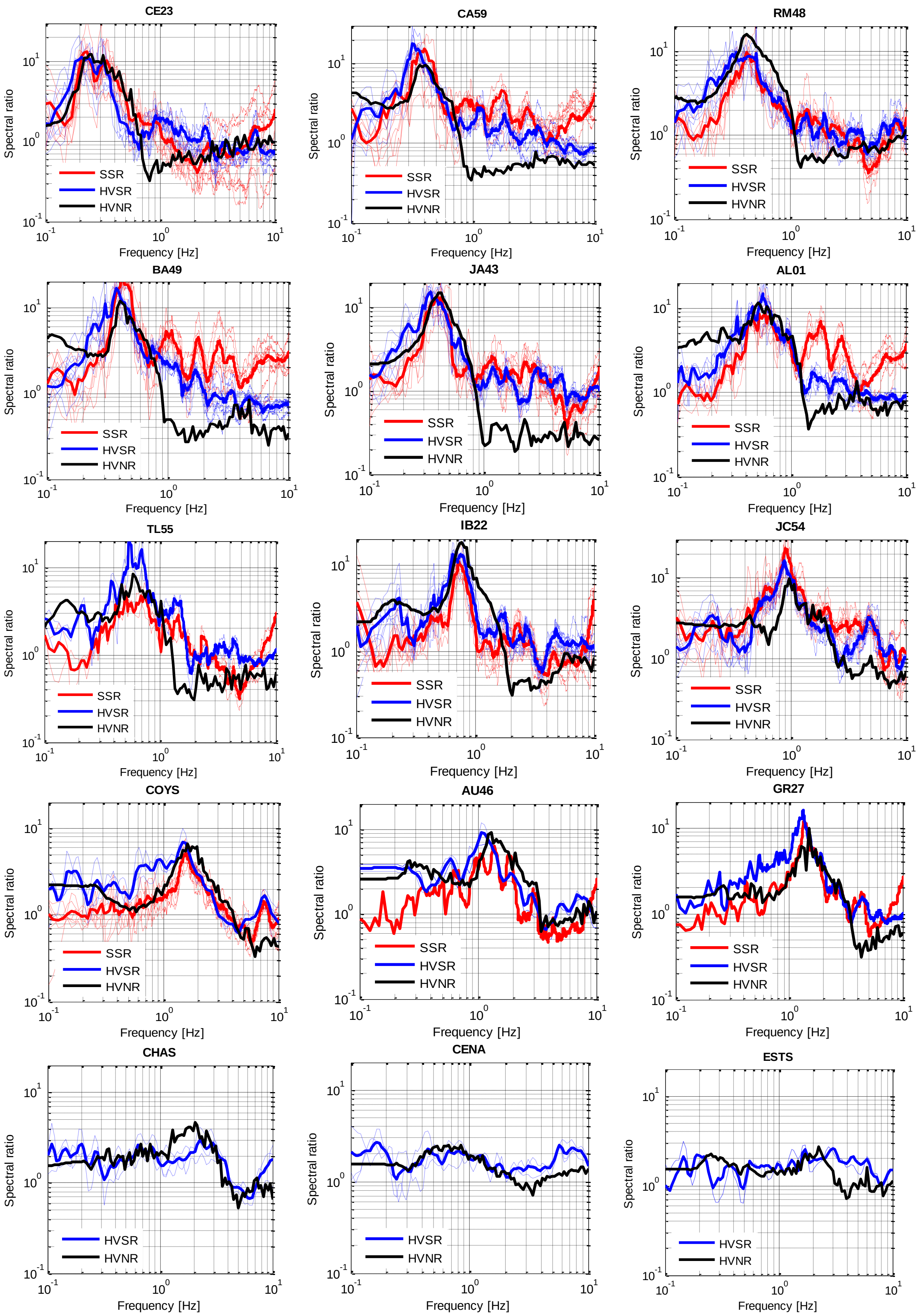

Figure 2.2. Comparison of TF from earthquake (SSR, in red, and HVSR, in blue) and the microtremor HVNR. Results for two stations in the Culhuacan paleo-valley.

Figure 2.3. Yellow lines give the zonification for Peñón de los Baños (left) and Peñón del Marqués (right). Red dots indicate measurement points. Values in contours correspond to period in seconds.

In a second campaign, broadband Guralp 6TD seismographs were used to set the limits between zones I and II. These measurements correspond to several hours of recording. The H/V spectrum allows to establish the predominant period (or frequency) as discussed by Sánchez-Sesma et al. (2011). Measurements were performed along the contour Ts=0.5s of NTCDS and 0.7s was found instead. This period enlargement suggests increase of thickness or shear velocity reduction. To clarify the issue measurements in higher locations were made.

3. ANALYSIS OF PERIOD CHANGE DUE TO REGIONAL SUBSIDENCE

The comparison of dominant period obtained 20 years ago and recent measurements of earthquake and noise at the same locations, is shown in the regression depicted in Fig, 3.1. This allowed updating the 409 values recorded then. This plot presents the comparison of periods for 102 sites in a variety of locations. Two tendencies are observed: the first curve in red shows the best fitting for 0.4s to 1.1s for which the change is null. The second part covers the rest of data (1.2s up to 5.2s). Therefore, we have:

$$T_1 = 0.87T_0 - 0.05 \tag{3.1}$$

where T_0 = period for 1990, T_1 = updated period for 2012. The standard deviation is 0.5s.

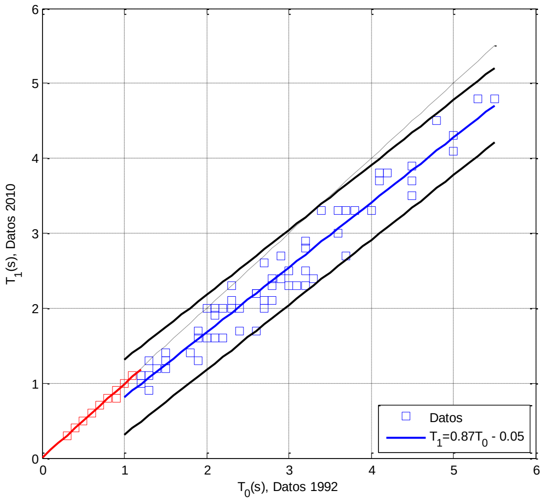

Figure 3.1. Comparison periods from 1992 and 2012 in 102 locations of México City

Fig. 3.2 shows the comparison of two H/V spectral ratios for microtremors. Spectral ratio of 1990 is drawn in black lines (Lermo *et al.*, 1994) blue lines depict the spectra for 2010. A shifting towards larger frequencies is evident. For the CDAO site the change is 0.05 Hz while in SCT it is 0.1 Hz.

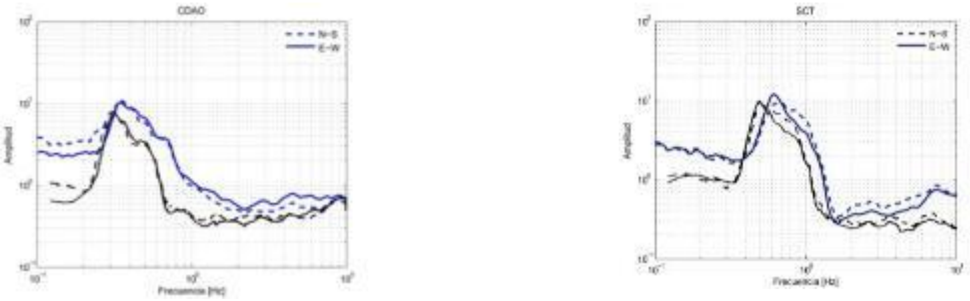

Figure 3.2. HVNR of 1992 (black) vs HVNR of 2010 (blue) at two sites of zone III.

Fig. 3.3 shows location of accelerometric stations and the observed variation of periods associated with subsidence of the last 20 years. Blue dots represent negligible variation (0-0.1s), green dots correspond to small variations (0.2-0.3s) and red dots reveal critical changes (0.4-0.9s). This clearly shows that the largest changes occurred within the Lake zone, where the clay thickness is larger, mainly at the airport south-east (Nezahualcóyotl city) with a change of 0.7s and Chalco with 0.9s.

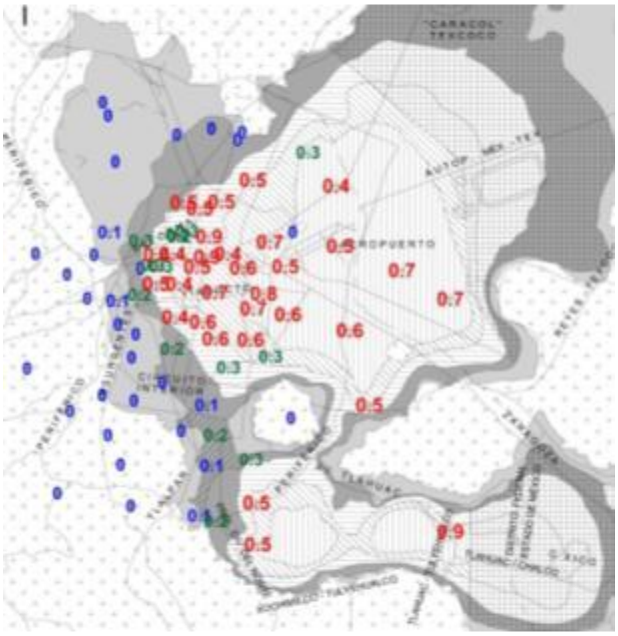

Figure 3.3. Location of estimated period variations. Annotated over the zonation of NTCDS (2004), in seconds.

After these measurements 1300 measurement points have been gathered (see Fig. 3.4). Using this information we propose to update the seismic zonation to consider the present conditions of Mexico City soils. The most significant changes are presented within zone IIId, for which we estimated a reduction of 45.8% of its original surface (157.1 km^2). Zona II increased his surface in 73.6 km^2 as a consequence of changing the limit Ts=0.5s.

In face of the subsidence problem it is convenient to perform microtremor measurements and a thorough analysis of acceleration records at a given time lapse, thus revising and modifying the zonation maps.

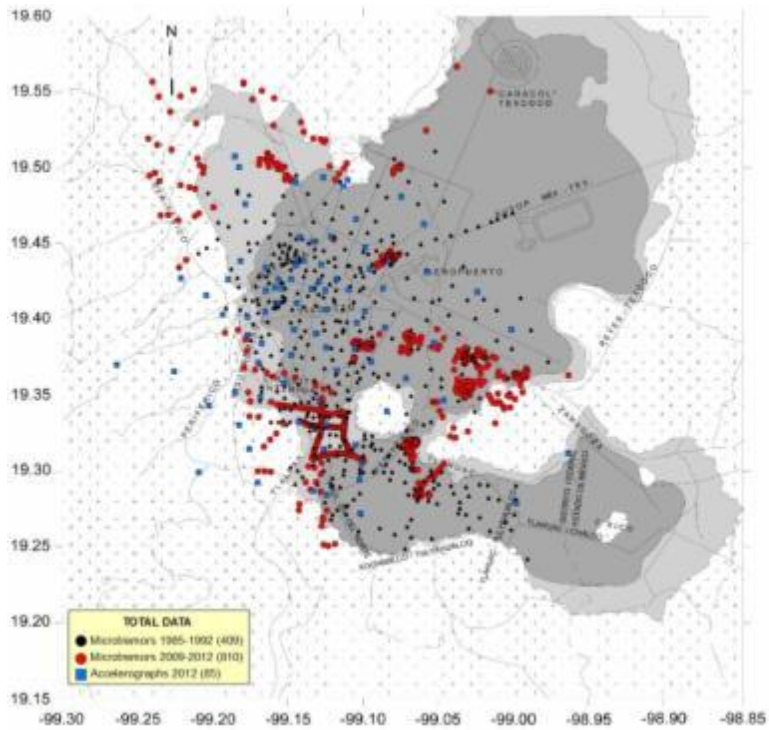

Figure 3.4. Location of all mesurements in the Valley of Mexico

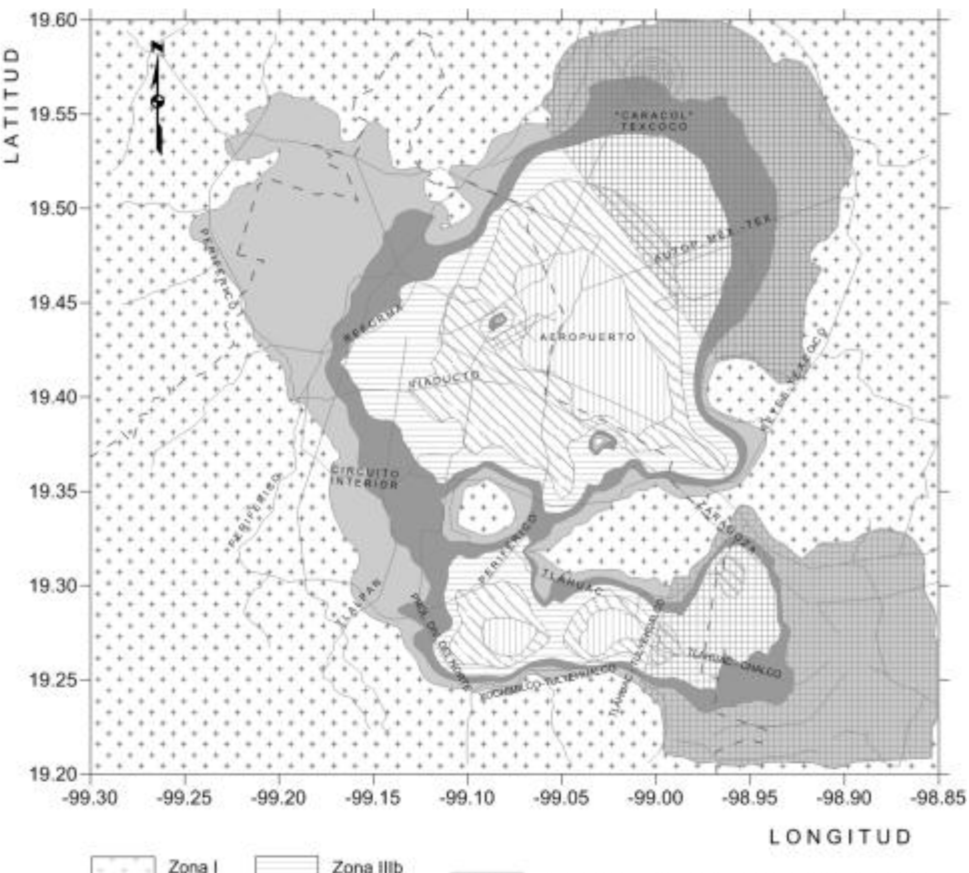

Figure 3.5. Proposal of seismic zonation map for the Valley of Mexico

Table 3.1. Earthquakes studied in this work

Event	Lat.	Long.	Depth (km)	Mag.	Data
1	18.05	-100.01	52	5.6	28.04.2008
2	16.90	-99.58	7	5.7	27.04.2009
3	18.13	-98.44	45	5.7	22.05.2009
4	18.06	-100.67	55	5.4	15.08.2009
5	15.90	-96.86	37	5.8	09.02.2010
6	16.07	-98.34	5	5.0	20.04.2010
7	16.22	-98.03	8	6.0	30.09.2010
8	17.84	-99.98	58	6.5	10.12.2011
9	16.42	-98.36	15	7.4	20.03.2012

4. CONCLUSIONS

As a result of new measurement points (1304) and the recent earthquake records we update the various maps of soil dominant period at Mexico City. The most salient characteristic of the sites are (see Figs. 3.3 y 3.5):

1. A large number of measurements were conducted and analyzed at the Culhuacan paleo-valley, at Peñón Viejo hill, at Peñón del Marqués hill and the basaltic flow of Cerro San Nicolas. All measurements can be grouped in Transition and Lake zones (zones II and IIIa, respectively).
2. Given the changes of dominant periods, the proposed new zones: II, IIIa y IIIb are more extense as compared with 2004 zonation.
3. The Transition zone (zona II) has no change in dominant period in the last 20 years.
4. Period variations during the last 20 years in zone IIIa are less than 0.3s.
5. Within the Lake zone (IIIb, IIIc and IIId) variations of 0.3s to 0.9s of dominant period have been observed during the last 20 years. Some reductions appeared for zone IIId.
6. For Lake subzones (IIIb, IIIc and IIId) with large period variation, the use of microtremors seems to be convenient for an annual checking, given their validity for period assessment.
7. It seems convenient to continue recording campaigns of microtremors and earthquakes in the south and west of Mexico City and the State of Mexico.

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