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IMPACT OF THE LOCAL GEOLOGY ON THE SEISMIC VULNERABILITY OF THE METROPOLITAN ZONE OF GUADALAJARA, MEXICO

M CHAVEZ[1]

SUMMARY

A study about the impact of the local surficial geology on the seismic vulnerability of the Metropolitan Zone of Guadalajara (ZMG) is presented. The study includes Mercalli Modified Intensity (MMI) observations, as well as recordings obtained in the ZMG accelerographic network. Also, the available information on the surficial geology and on the statistics of the ZMG constructions were utilized. The spectral and Nakamura ratio techniques were applied to the accelerograms recorded from 1994 to 1998 in the ZMG, including the ones obtained for the earthquake of the 9th of october 1995 (Mw=8, depth=16Km,epicentral distance=240Km) which produced maximum MMI of 6 in the ZMG. The results of the application showed the existance of important site effects in the ZMG, particularly at sites in which the depths to rock, H, of their surficial soils are equal or larger than about 15m. Those results agree with the about 200 years of the ZMG historic MMI observations. From the analysis of those results, as well as from the processing of about 50 years of ZMG surficial geology information, a preliminar seismic microzonation of the ZMG in four subzones is proposed, as follows: I ($H \geq 5$m), II ($30 \geq H \geq 5$m), III ($50 \geq H \geq 30$m), IV ($H \geq 50$m). To analize the effects of the ZMG local geology on the seismic vulnerability of its c onstructions, the results mentioned above were combined with a plausible seismic hazard scenario for the ZMG (in which a maximum expected MMI of 6, 8, 8.5, and 9, were proposed for the subzones I, II, III, and IV, respectively) and with appropriate seismic empirical vulnerability functions . The main result of the study is that if the proposed seismic scenario occurred, from 9 to 90Km2, of the about 300Km2 of the ZMG construction stock would be seriously damaged. The spatial distribution of the potentially damaged constructions, depends on the subzone in which they are set. The incorporation of the proposed microzonation in the seismic code of the ZMG, as well as the upgrading of its construction stock, are strongly recommended in order to reduce the seismic vulnerability of its constructions.

INTRODUCTION

In this work a study is presented about the impact of the local surficial geology on the seismic vulnerability of the Metropolitan Zone of Guadalajara (ZMG). The study includes the following information about the ZMG: on its surficial geology, on the statistics of its construction stock, on its historic observations of Mercalli Modified Intensity (MMI) data, and strong ground motion records obtained in the ZMG accelerographic network for the period of 1994 to 1998. Also, a plausible seismic hazard scenario for the ZMG was considered, combined with appropriate seismic empirical vulnerability functions.

In chapter 2 a discussion is presented about the main features of the ZMG surficial geology. The presentation of a plausible seismic hazard scenario for the ZMG is the subject of chapter 3. In chapter 4 a study on the effects of surface geology on the seismic motions observed in the ZMG is presented. The consequence of those effects on the seismic vulnerability of the construction stock of the ZMG is discussed in chapter 5. The conclusions of the study are presented in chapter 6.

[1] *Inst de Ingenieria, UNAM, , and Inst deInvestigaciones para la Ingenieria, Guadalajara, Mexico;chavez@servidor.unam.mx*

SURFICIAL GEOLOGY OF THE ZMG

The ZMG is set in the so-called Guadalajara plain [Campos and Alatorre, 1998] which is located in the western part of the Transmexican Volcanic Belt (TMVB). This region of the TMVB is mainly covered by Tertiary and Quaternary igneous rocks. In particular the more recent rocks found in the Guadalajara plain are made of Quaternary pyroclastic flows and rhyolitic tuffs, also, there are recent alluvial and lacustrine deposits filling the geomorphic and tectonic depressions found in its vicinity [Campos and Alatorre, 1998]. Based on Bouguer anomaly data, as well as on borehole data of the region of interest, these authors proposed the shallow crustal structure in the vicinity of the ZMG shown in Figure 1. From this figure it can be concluded that the basement of the proposed structure is located at about 2Km depth and is made of granite. The basement is overlied by a layer of basaltic-andesite of about 1Km of thickness, and another layer of tuff and rhyolite of the same thickness than the former. Notice that the mentioned layers form a depression under the ZMG, Figure 1

The layer of tuff and rhyolite mentioned above is covered by a layer of a pumitic pyroclastic and alluvial material made of sands and gravels. This layer has a varying thickness, as it is shown in Figure 2. This figure is based on about 150 borehole data of the ZMG gathered in the last 45 years. From the processing of this data it was found that the pumitic layer is uniformly distributed under the ZMG. In particular, from Figure 2 it can be concluded that the depth to rock of the pumitic layer increases from about 1m to 100m, in the east to west direction, i.e. sites TON and GRAN, respectively [Chavez, 1997].

A SEISMIC HAZARD SCENARIO FOR THE ZMG

The high seismic potential of the region in which the ZMG is located has been shown for (at least) several centuries by the occurrence of large and destructive earthquakes in the region. For example, the 27th of december of 1568 an event with an estimated Richter magnitude, Ms, of 7, depth of 10 to 15 Km, and epicentral distance of about 70Km, occurred at the south-west of Guadalajara [Suarez et al., 1995]; also, the 14th of april of 1845 an earthquake with an estimated Ms of 7, surficial depth and epicenter in the Pacific Ocean, produced an IMM of 7 in the ZMG (notice that in its surroundings the IMM was only of 3), as it is shown in Figure 3; another event occurred the 11th of february of 1875, with an estimated Ms of 7, depth of 10 to 15 Km, and epicentral distance of about 30Km north-west of Guadalajara, this event produced a maximum MMI of 9-10 in the ZMG [Figueroa, 1987]. Other examples of large earthquakes that occurred in the vicinity of the ZMG are: the ones of the 3rd and 18th of june 1932, with an Ms of 8.2 and 8, respectively; as well as the one of the 9th of october of 1995, with an Ms of 7.4; the 3 events have depths of 15 to 20Km. The location and rupture areas of these events are presented in Figure 4. Notice that the three events have epicentral distances of about 200Km from rhe ZMG.

The seismic events mentioned above are associated with the subduction of the Rivera and Cocos plates under the North-american plate (mostly inverse mechanisms type of events, as the ones ocurred in 1845, 1932, and 1995); or to the surficial cortical activity of Quaternary structures located in the western part of the TMVB (mainly normal mechanism type of events, as the ones ocurred in 1568 and 1875).

The earthquake of 1995 is the only one (up to date) recorded in all of the 11 free field surface and 2 downhole stations of the ZMG accelerographic network, ZMGAN, which started operating in early 1992, and was completed by the end of 1993 [Chavez, 1993]. Other earthquakes have been recorded from 1994 to 1998 only at the station COL of the ZMGAN (Figure 2) which can be trigguered by ground motion accelerations of 0.5cm/s2, compared with larger values for the other stations. The free surface stations of the ZMGAN are set at sites with depths to rock of their soils that varies from 1 to 100m, as shown in Figure 2. The two downhole stations are at station COL, one at 9m soil depth and the second on rock at a depth of 35m. The free field and downhole stations of the ZMGAN are equiped with SSA2 and FDH13 accelerographs of Kinemetrics.

An example of the type of records obtained in the ZMGAN for the 1995 event are presented in figure 5. In this figure the W-E components of the recorded ground motions are presented. From figures 2 and 5 it can be concluded that: the maximum recorded accelerations, which vary from about 15 to 25cm/s2, correspond to stations with soil depths, H, equal or larger than about 15m; that the maximum accelerations for the rock motions were of about 6cm/s2 (recorded at TON and at the H =35m downhole station of COL), compared with the 15 to 25cm/s2 for the surface stations of COL, ROT, SUR, ARC, GRAN, OBR, and OBL; that the ground motions recorded at MIR, RAF and PLA stations are similar to the ground motions observed at TON station; that the longer record durations were observed at the COL station (about 180s). Similar conclusions can be drawn for the N-S and vertical (with smaller amplitudes) components, as shown elsewhere [Chavez, 1997].

From the information presented above, it can be concluded that the ZMG can be affected by surficial normal mechanism type of earthquakes, with an Ms of about 7 and epicentral distances of tens of kilometers; and also that it can be hit by inverse mechanism type of events with an Ms larger than 8, and epicentral distances of about 200Km (Figure 4). It can also be concluded that the ZMG available data on ground motion records is rather scarce, nevertheless, the records of the 1995 earthquake clearly showed that the ZMG surficial geology has the capacity of amplifying, significatively the ground motions recorded on rock, as the comparison of the records on the rock (H = 35m) and at the surfice (H = 0m) of the station COL showed (Figure 5). Incidently, this behavior has been previously observed in historical earthquakes, as the one occurred un 1845 in which an MMI of 7 was observed in ZMG, compared with an MMI of 3 in its vicinity , Figure 3, [Chavez, 1993]. It is also important to remark that the maximum MMI that has been reported for the ZMG is of 9-10 for the 1875 earthquake mentioned above.

Taking all this into consideration, in this work it was decided to assume, as a plausible seismic hazard scenario for the ZMG, one in which with a high probability, an earthquake could occur in the near future in its vicinity; the event could have the appropriate characteristics (i.e. with an Ms, a depth, and an epicentral distance) to generate a maximum MMI of 9 in the ZMG.

SURFICIAL GEOLOGY EFFECTS ON THE SEISMIC MOTIONS OF THE ZMG

In order to study the potential site effects that the ZMG surficial geology could have, the spectral and the Nakamura ratio techniques were applied to the ground motions recorded in the ZMGAN from 1994 to 1998. As mentioned in chapter 3, only the 9th of october 1995 event has been recorded in all the station of the network, therefore, as an example of the type of results obtained with the mentioned techniques, the ratios yielded by the spectral ratio technique applied to the Fourier amplitude spectra of the accelerograms of Figure 5 are presented in Figure 6 (similar results were obtained for the N-S components and also from the application of the Nakamura technique). For the application, the reference station was TON, that it is the only station of the ZMGAN with an H of about 1m, i.e. a station that can be assumed to be set on rock (Figures 2 and 5).

From Figure 6 it can be concluded that: the maximum values of the ratios for the stations MIR, RAF, and PLA are of about 2 or 3 times for frequencies above 1Hz; the ratios for the stations COL, ROT, ARC, SUR, GRAN, OBR, and OBL, vary from about 10 to 20 times, for frequencies from 1 to 10Hz; for several of the stations the larger ratios occur in a band of frequencies, i.e. GRAN, SUR, OBL, MIR, RAF,PLA; for stations COL, ROT, OBR and ARC, one or more peak ratios (in some cases of similar amplitudes) can be identified; the amplitude of the ratios seems to be an increasing function of the depth to the rock of the soils in which they are set (Figures 2 and 6). Another result, not included here for lack of space, is that the spectral ratios obtained in COL station with the record obtained at H = 35m as a reference station, are very similar to the presented in Figure 6 [Chavez and Ramirez, 1998].

By taking into account the results mentioned above, as well as the ones of chapter 2, the preliminar seismic microzonation of the ZMG included in Figure 7 is proposed, as follows: I (H≥ 5m), II (30≥ H ≥ 5m), III (50≥ H ≥30m), and IV (H≥ 50m).

LOCAL GEOLOGY EFFECTS ON THE SEISMIC VULNERABILITY OF THE ZMG

The estimation of the seismic vulnerability of the construction stock of the ZMG included in Figure 7 (i.e. the estimation of the level of damage expected for those constructions, for an earthquake with a probability of exceeding a given intensity for a selected lapse) was carried out by combining the seismic hazard scenario proposed in chapter 3, the preliminar seismic microzonation proposed in chapter 4 (Figure 7), the statistics of the ZMG construction stock, and a modified version of the Mean Damage Ratio Index (D) proposed by Cochrane and Schaad [1992]. The decision to use the later was taken by considering that there is not information available about the seismic vulnerability of the construction stock of the ZMG, and also by the fact that the D values proposed by those authors, included actual construction damage information for earthquakes occurred in Popayan, Colombia (1983), Chile (1985), and Mexico (1985), which have construction practices and use materials similar to the ones found in the ZMG [Garcia-Rubio, 1994; Chavez, 1997].

As mentioned above, for the estimation of the seismic vulnerability of the construction stock of the ZMG, it is necessary to define an earthquake with a probability of exceeding a given intensity for a lapse time, in this study, the selected event is the corresponding to the seismic hazard scenario proposed for the ZMG in chapter 3. The scenario assumed that with a high probability, in the near future, an earthquake could occur with the appropriate characteristics, as to generate a maximum MMI of 9 in the ZMG. From the conclusions of chapter 3 about the strong ground motions recorded in the ZMGAN for the 1995 earthquake, and taking into account the seismic microzonation proposed for the ZMG in chapter 4, it is considered here that the MMI of 9 could occur in subzone IV (Figure 7), and that for the subzones I, II, and III, a maximum MMI of 6, 8, and 8.5, could respectively, to be generated by the same event.

The statistics of the ZMG were obtained by considering: the construction type and average age ,and also the depth to rock of the surficial soils in which they are set. The synthesis of those statistics are presented in Figure 7 and the data set identified by Aij in Table 1. Notice that the C. Types A,B, and C, correspond to constructions made up of : Reinforced Concrete (RC) frames and masonry, masonry made of unreinforced brick, and masonry made of hollow blocks, respectively. Also notice that the C. Ages E1, E2, and E3, were associated with their average age, as follows: less or equal to 15 years, between 15 and 30 years, and larger than 40 years. Finally, that the depth to the soils in which the ZMG constructions are set correspond to the seismic subzones I to IV, of

Figure 7. From Table 1 it can be concluded that the total construction stock of the ZMG is of about 300Km2. The summary of a particular type of construction, its average age, and the subzone of soil in which it is set, can be found in the part of the table identified by Aij (i = C. Type, j =microzonation subzone).

To estimate the seismic vulnerability of the ZMG construction stock (Figure 7 and Table 1) the following assumptions were made: that the D index for the construction stock of the ZMG have the basic form shown in Figure 8, which corresponds to the soils of subzone II and an average age of 30 years; that a specific Dij (i = C. type, j = microzonation subzone) is uniformly distributed per unit of surface, the Dij are presented in the middle part of Table 1; that Dij can be associated to the expected fraction of the surface of C. Type i, damaged by an earthquake with the MMI corresponding to the j subzone, herewith called Sij; that Sij can be computed by the product Aij x Dij.

The results of the computation of Sij are shown in the lower part of Table 1. Among other results that can be drawn from this part of Table 1, the main one is that if the seismic hazard scenario proposed in this study occurred, about a 30%, i.e about 89Km2, of the 280Km2 built surface of the ZMG would be badly damaged. From the 38, 120, 56, and 64Km2 of the ZMG constructions located in subzones I, II, III, and IV, respectively, the damaged surfaces would be of 0.4, 33, 22, and 32Km2, respectively. With relation to the percentages of the type of constructions that would be damaged, 34, 36 and 19Km2 would correspond to construction types A, B , and C (as defined in Figure 8), respectively. In terms of the average ages of the constructions of the ZMG which are 130, 77 and 71Km2 of ages E1, E2, and E3 (as defined in Fig 7), respectively; the corresponding Sij statistics would be 32, 25, and 32Km2, for E1, E2, and E3, respectively. If it is considered that the quoted results were overestimated by a factor of 10 (mainly associated to the adopted Dij) the total damaged surface would be of about 9Km2.

CONCLUSIONS

The main result of the study is that if a large earthquake (one with: Ms = 7, depth = 10 to 15Km and epicentral distance = tens of Km.; or one with: Ms = 8 or larger, depth = 15 to 20Km, epicentral distance = 200Km) ocurred in the vicinity of the ZMG in the near future , from 9Km2 (optimistic scenario) to 90Km2 (pesimistic scenario), of the about 300Km2 of the ZMG construction stock would be seriously damaged. The spatial distribution of the potentially damaged constructions, would depends on the ZMG proposed seismic microzone in which they are set. The incorporation of the microzonation proposed herewith in the seismic code of the ZMG, as well as the upgrading of its construction stock, are strongly recommended in order to reduce the seismic vulnerability of its constructions.

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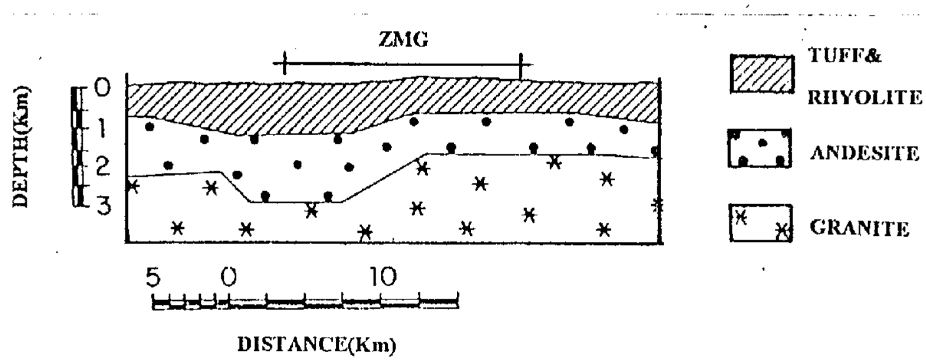

Figure 1: Shallow crustal structure in the vicinity of the Metropolitan Zone of Guadalajara (ZMG) (modified from Campos and Alatorre, 1998)

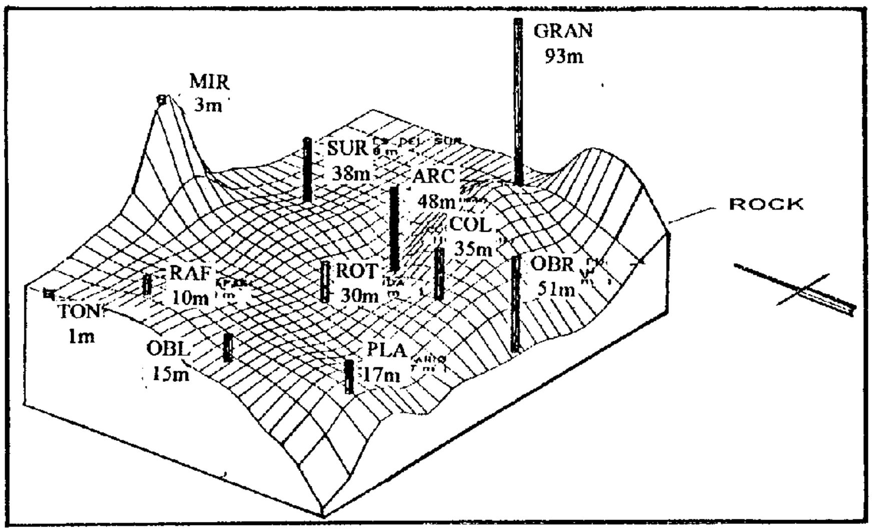

Figure 2: Depth to rock of the surficial soils of the ZMG at the stations of the accelerographic network of the ZMG (Chavez, 1997)

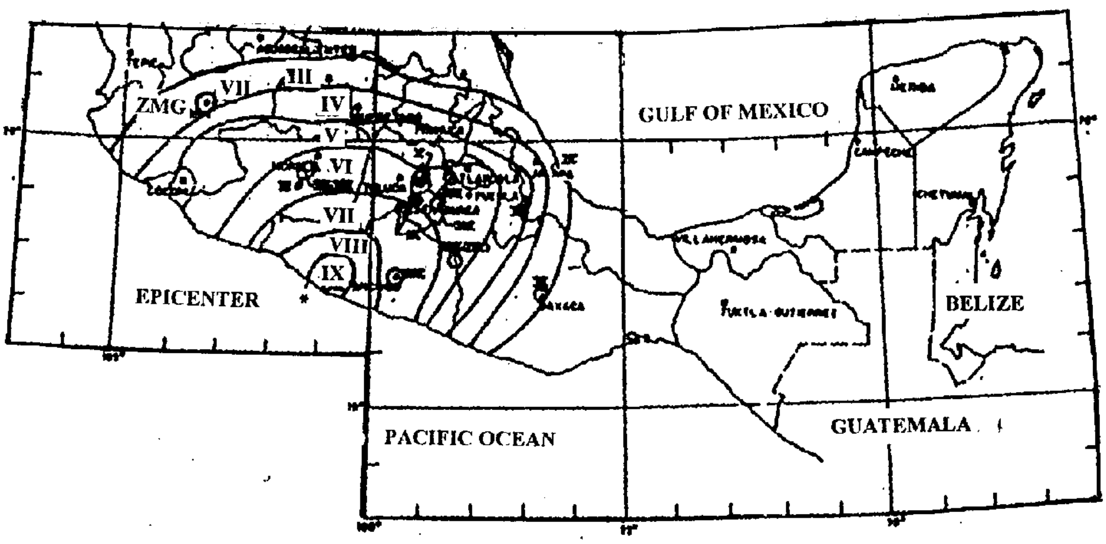

Figure 3: Isoeists of the 1845 earthquake M = 7 (modified from Figueroa, 1987)

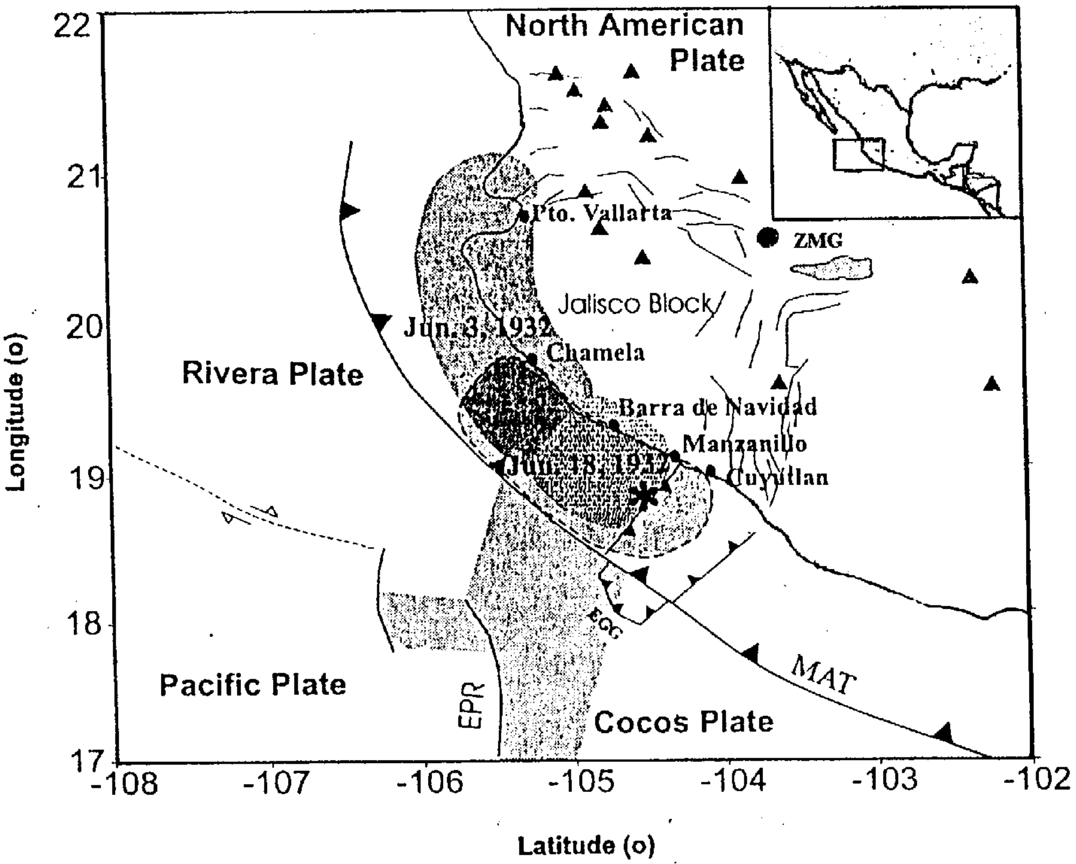

Figure 4: Rupture areas of the earthquakes of june 3rd and 18th, 1932; and of october 9th, 1995 (dashed line) and the epicenter of the last one. Triangles: volcanoes, EPR: East Pacific Rise, EGG: El Gordo Graben (modified from Ortiz et al., in preparation)

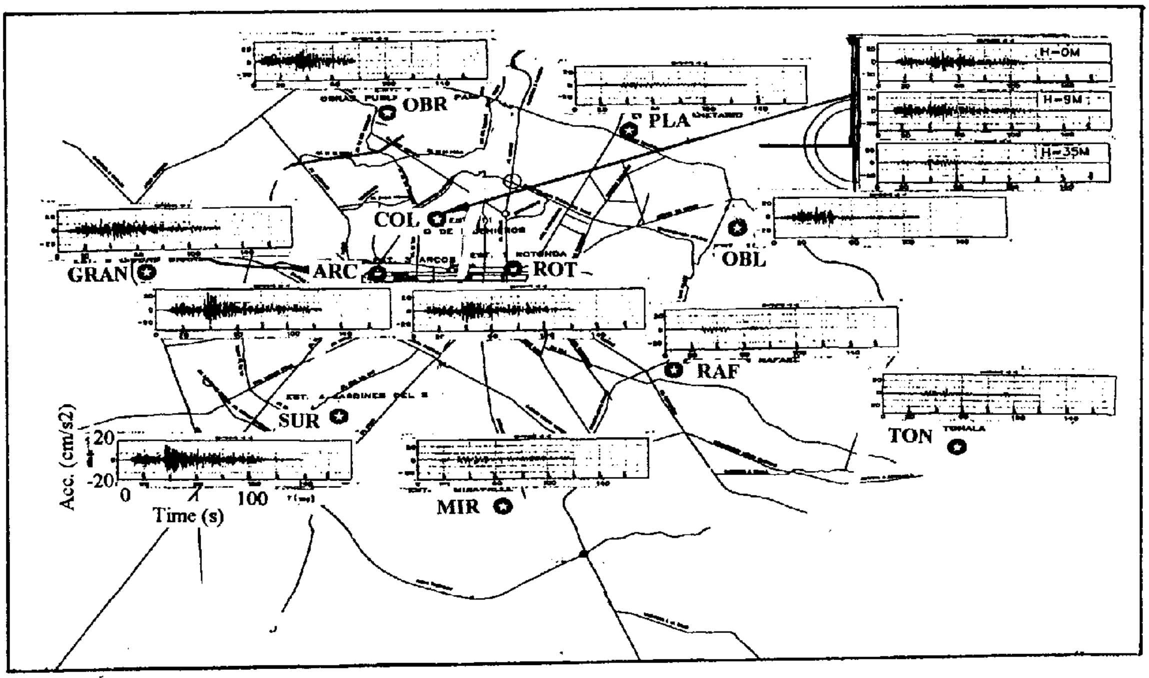

Figure 5: Accelerograms recorded in the Metropolitan Zone of Guadalajara in the W-E direction during the 9th of october 1995 earthquake

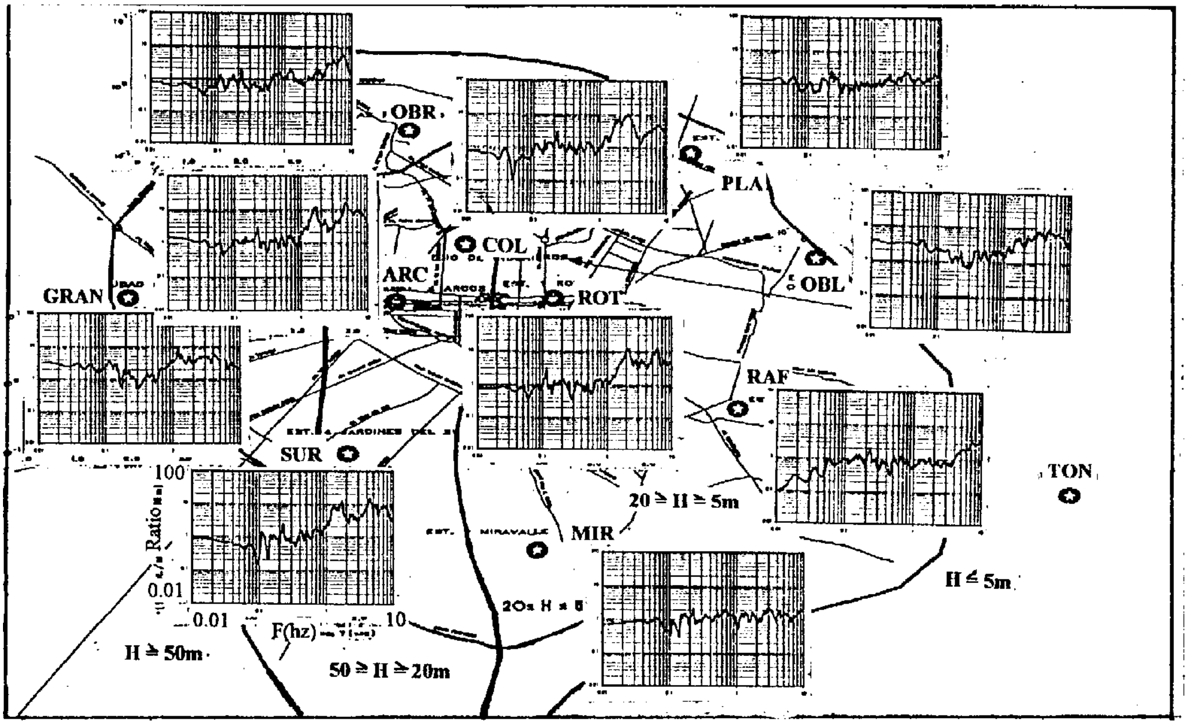

Figure 6: Fourier spectral ratios of the accelerograms of figure 5. The reference station is TON

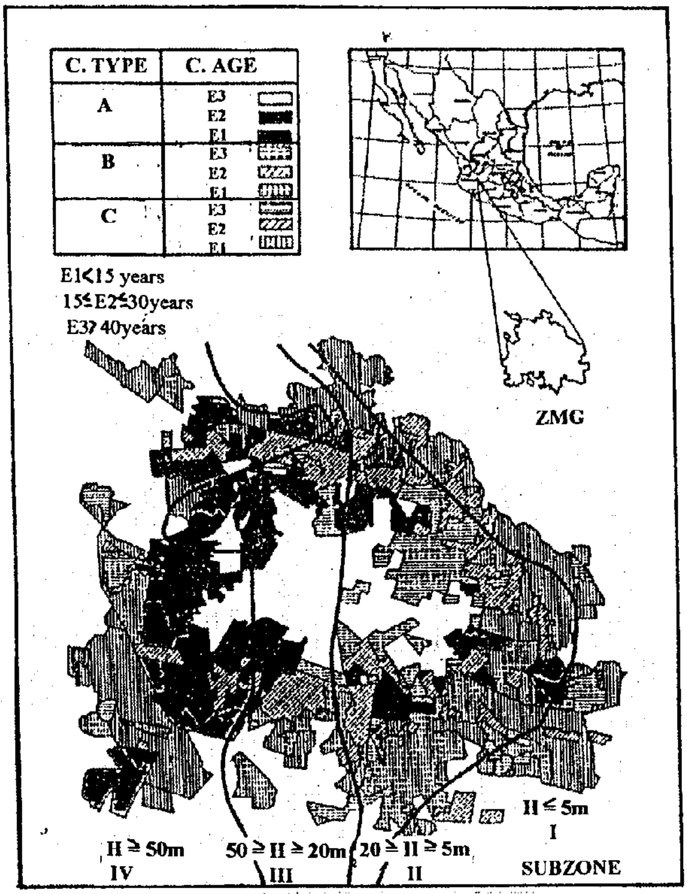

Figure 7: Preliminar seismic microzonation proposed for the Metropolitan Zone of Guadalajara, and distribution of its constructions by type and material, age, and depth to rock of its soils

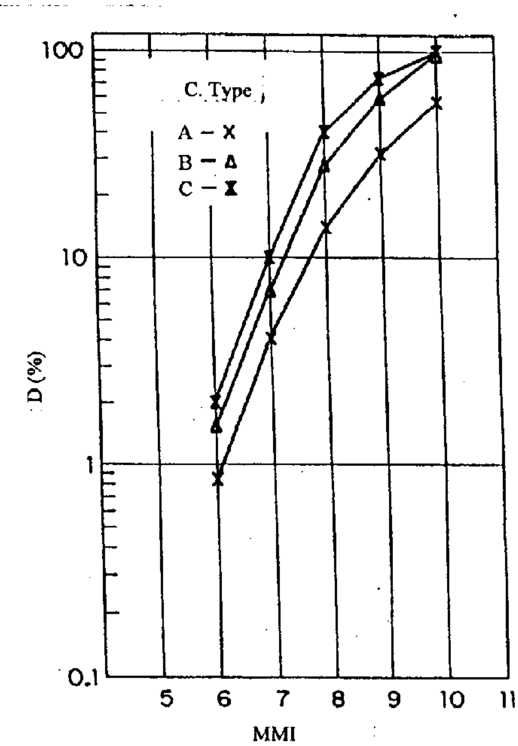

Figure 8: Mean damage ratio (D) vs Mercalli Modified Intensity (MMI) for construction types: A = made of RC frames and masonry; B =masonry made of unreinforced brick; C= masonry made of hollow blocks (adapted from Cochrane and Schaad, 1992)

Table 1: Expected seismic vulnerability for the constructions of the Metropolitan Zone of Guadalajara assuming the ocurrence of an earthquake which could generate MMI of 6, 8, 8.5, and 9 in the subzones I, II, III, and IV, respectively

Aij (km2) (Built surface)

SUBZONE

C. Type	I(IMM=6)			II(IMM=8)			III(IMM=8.5)			IV(IMM=9)			Σ
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	
A	0.68	0.27	0.14	3.16	8.35	18.83	0.57	14.50	19.44	7.66	20.10	5.50	99.2
B	10.77	3.55	2.73	48.13	14.04	16.62	4.89	6.35	3.88	5.45	6.26	1.81	124.5
C	17.82	0.65	1.15	9.50	1.64		6.14	0.42		15.52	0.89	1.34	55.08
Σ		37.76			119.50			55.56			64.54		278.7

Dij (Mean damage ratio) %

SUBZONE

C. Type	I(IMM=6)			II(IMM=8)			III(IMM=8.5)			IV(IMM=9)		
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3
A	0.34	0.85	2.55	4.20	14.00	42.00	7.00	20.00	52.00	12.80	32.00	70.40
B	0.60	1.50	3.00	21.60	27.00	42.50	34.00	40.00	58.00	54.00	60.00	84.00
C	0.80	2.00	4.00	32.00	40.00	60.00	46.75	55.00	79.75	67.50	75.00	100.00

Sij(km2) (Expected built surface damaged)

SUBZONE

C. Type	I(IMM=6)			II(IMM=8)			III(IMM=8.5)			IV(IMM=9)			Σ	Σ(%)
	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3	E_1	E_2	E_3		
A	0.002	0.002	0.004	0.133	1.169	7.581	0.039	2.899	9.781	0.981	6.430	3.873	33.560	0.336
B	0.065	0.053	0.082	10.390	3.791	6.733	1.662	2.538	2.249	2.946	3.754	1.522	35.790	0.287
C	0.143	0.013	0.046	3.040	3.695		2.872	0.229		10.470	0.667	1.343	19.480	0.353
Σ		0.409			33.420			22.270			32.010		88.760	0.318