OBSERVATIONS AND MODELING OF EXTREME SUBDUCTION EARTHQUAKES

M. Chavez[1,2], E. Cabrera[3], N. Perea[1]

[1] *Institute of Engineering, UNAM, C.U., 04510, Mexico DF, Mexico*
[2] *Laboratoire de Géologie CNRS-ENS, 24 Rue Lhomond, Paris, France*
[3] *DGSCA, UNAM, C.U., 04510, Mexico DF, Mexico*

ABSTRACT

The 19/09/1985 a Ms 8.1 thrust mechanism subduction superficial (TSS) earthquake occurred in the Mexican Pacific ocean coast with an epicentral distance of 380 km from Mexico City (MC). The estimates of the human and economical losses related to this large event, were of about 30,000 people and more than 6 billion US dollars, the largest share of these were in MC. The largest, Ms 8.2, instrumentally observed TSS earthquake in Mexico, occurred in the Colima-Jalisco region the 3/06/1932, with epicentral distance of about 200 km from Guadalajara (G) in northwestern Mexico. The estimated frequency of occurrence, in Mexico, of these types of events varies from decades to about 100 years and their upper Ms bound are still under discussion. By applying a hybrid method, previously validated for the 19/09/1985 and for the 09/10/1995 Ms 7.6 Colima-Jalisco earthquakes, we generated broadband synthetic accelerograms, expected in MC stiff and compressive soils, and in G sandy soils, associated to extreme seismic scenarios for TSS Mw 8.5 earthquakes. Based on an acceptable risk criteria, in order to minimize the probability of exceedance associated to an expected economical loss of 6.22 Billion US dollars, for the proposed Mw 8.5 MC earthquake scenario, a compressible soil design spectra Sa(5%) ordinate of 1.4g (g=981 cm/s2), seems appropriate (for the 19/09/1985 earthquake the observed Samax(5%) was equal to about 1g). From the information of the construction stock of G, the economical loss, associated to the Mw 8.5 earthquake scenario analyzed amounts to 19 billion US$ dollars.

KEYWORDS: Observations, hybrid synthetics, subduction, extreme earthquakes, economics.

1. INTRODUCTION

The 19/09/1985 a Ms 8.1 thrust mechanism subduction superficial (TSS) earthquake occurred in the Mexican Pacific ocean coast with an epicentral distance of 380 km from Mexico City (MC). The estimates of the human and economical losses related to this large event, were of about 30,000 people and about 6 billion US dollars, the largest share of these were in MC. The largest, Ms 8.2, instrumentally observed TSS earthquake in Mexico, occurred in the Colima-Jalisco region the 3/06/1932, with epicentral distance of about 200 km from Guadalajara (G) in northwestern Mexico. The estimated frequency of occurrence, in Mexico, of these types of events varies from decades to about 100 years and their upper Ms bound are still under discussion. The importance of obtaining reliable estimates of the seismic hazard and of its economical consequences, associated with the possible occurrence of extreme earthquakes in those regions of Mexico are the objectives of this work. By applying a hybrid method, previously validated for the 19/09/1985 and for the 09/10/1995 Ms 7.6 Colima-Jalisco earthquakes (Chavez et al. 2004) we generated broadband synthetic accelerograms, expected in MC stiff and compressive soils, and in G sandy soils, associated to extreme seismic scenarios for TSS Mw 8.5 earthquakes. The economic impact of the scenarios is also analyzed.

The paper is divided in 6 parts. In the 2nd we briefly discuss the main seismotectonic features of the Mexican subduction zone, a synthesis of the hybrid broadband modeling procedure used to generate synthetic accelerograms is presented in part 3, the comparison of the recordings obtained for the 19/09/1985 Ms 8.1 Michoacan and the 9/10/1995 Ms 7.6 Colima-Jalisco earthquakes are presented in the 4th, the results of the modeling for the Mw 8.5 scenario earthquakes, as well as of their economic impacts on MC and G are presented in the 5th part. Finally the main conclusions of the work are presented.

2. SEISMOTECTONIC FEATURES OF THE MEXICAN SUBDUCTION ZONE

The seismotectonic of the Mexican subduction region is associated with the dynamics of the Cocos, Rivera, Caribean and Northamerican plates (Fig. 1A). The Cocos and the Rivera plates are subducting the Northamerican one and had generated the most recent, largest surficial thrust earthquakes in the region, such as the Jalisco 3/06/1932 Ms 8.2, the Ms 7.6 (Mw 8) Colima-Jalisco 9/10/1995 and the 19/09/1985 Ms 8.1(Mw 8.01) Michoacan earthquakes (Fig. 1A). The geometry and some geophysical properties of the mentioned interacting plates are shown in Figs. 1B and 1F, respectively. The rupture area and the kinematic slip distribution of the Michoacan earthquake is shown in Fig. 1C; and the rupture area and the location of the four subevents of the Colima-Jalisco earthquake are presented in Fig. 1E.

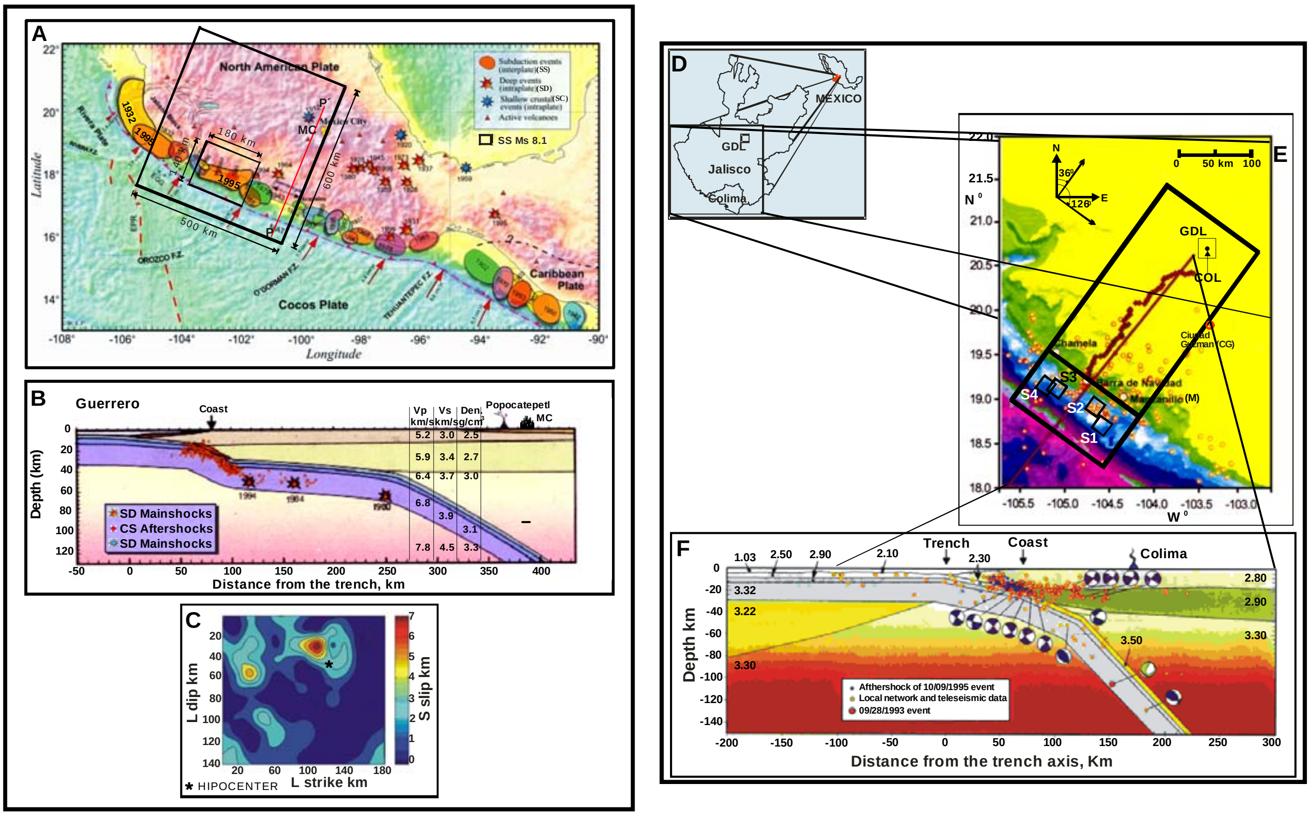


Fig. 1. A) Outer rectangle is the surface projection of the 500x600x124 km^3 earth crust volume 3D discretization, inner rectangle is the rupture area of the 19/09/1985 Ms 8.1 earthquake; B) profile P-P′; C) Kinematic slip distribution of the rupture of the 1985 earthquake (Mod. Mendoza and Hartzell, 1989); D) Location of the Colima –Jalisco region; E) surface projection of the 160x390x180 km^3 earth crust volume 3D discretization, inner rectangle (160x90 km^2) rupture area of the 1995 earthquake, the 4 smaller rectangles represent the four (S1 to S4) subevents of the 1995 earthquake (Escobedo et al, 1998); F) Profile from the coast to Guadalajara which includes the densities of the layers. (Bandy et al., 1999)

3. BROADBAND MODELING PROCEDURE

A hybrid procedure (Fig. 2), combining long period and high frequency simulations (Chavez et al., 2004) was utilized for the computation of broadband synthetics accelerograms for the Ms 8.1 (Mw 8.01) Michoacan 1985 and the Ms 7.6 (Mw 8) Jalisco-Colima 1995 earthquakes, as well as for extreme Mw 8.5 earthquake scenarios for Mexico City and Guadalajara. The long period (< 0.3 Hz) wave field was simulated using a recently optimized 3D seismic wave propagation parallel finite difference code, that uses 2nd order operators in time and 4th order differences in space (Cabrera and Chavez et al, 2007). The high frequency (≥ 0.3Hz) synthetics were generated with the Empirical Green function (EGF) method, Irikura (1986). In this method the ground motion of a large event is expressed as the superposition of the records of small events (elementary sources). Finally, the low and high frequency synthetics are combined using matched filters (Chavez et al., 2004).

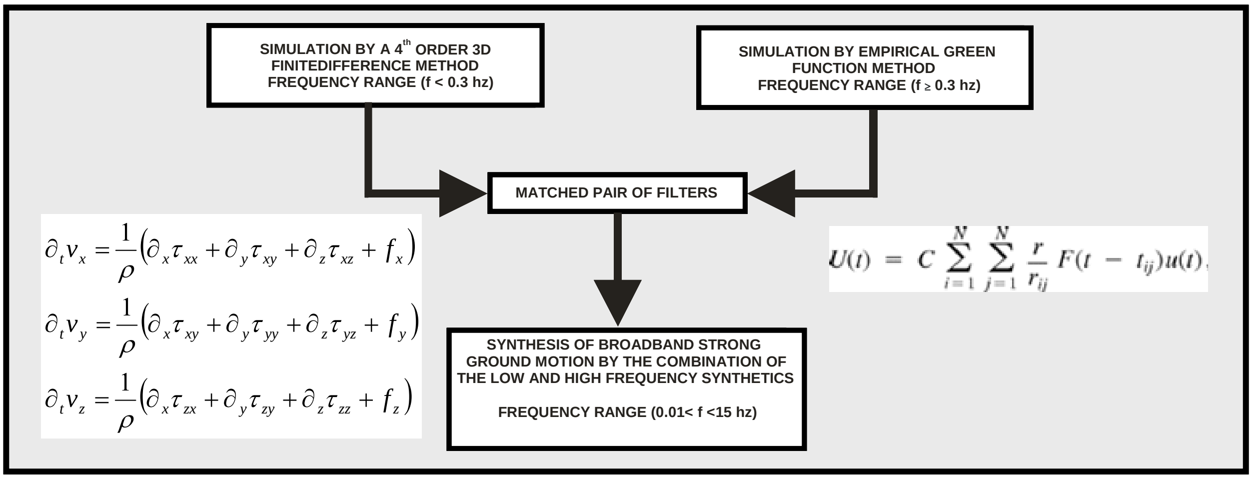


Fig. 2 Hybrid procedure combining long period and high frequency simulations (Chavez et al., 2004)

4. OBSERVATIONS AND MODELING OF THE 19/09/1985 Ms 8.1 MICHOACAN AND THE 9/10/1995 Ms 7.6 COLIMA-JALISCO EARTHQUAKES

The broadband hybrid modeling procedure synthesized in Fig. 3, was utilized to generate synthetic accelerograms to compare them with the ground motions recorded at stations SCT (located on a 40 m layer of compressible soils of MC) and Colegio (located on a 35 m layer of sandy soils overlying rock in Guadalajara) for the Ms 8.1 Michoacan and the Ms 7.6 Colima-Jalisco earthquakes, respectively. For the low frequency modeling of the 1985 Michoacan event, a 500 x 600 x 124(depth) km^3 volume was used, spatial and temporal discretizations of 0.25 km and 0.01s, respectively, and the geophysical parameters shown in Fig. 1 (Cabrera and Chavez et al. 2007) were utilized. For the high frequencies modeling of the 1985 event, recordings of the 14/03/1997 Ms 7.3, 21/09/1985 Ms 7.6 and 14/09/1995 Ms 7.4 subduction earthquakes were utilized (Chavez et al, in preparation). For the low frequency modeling of the 1995 Colima-Jalisco earthquake, a volume of 160 x 350 x 180 (depth) km^3 was utilized, and for the high frequency, the recordings of their 6/10/1995 Ms 5.8 and 12/10/1995 Ms 5.9 for and after shocks were used (Chavez et al. 2004). In Figs. 3 and 4, the synthetic accelerograms and their associated Fourier amplitude spectra for the SCT site N-S direction 1985 Michoacan earthquake and the Colegio (Guadalajara) site W-E 1995 Colima-Jalisco earthquake, respectively, are compared with their observations. Notice that the agreements between them are satisfactory in both cases, including the local soil effects at 0.5 and 2.0 Hz for stations SCT and Colegio, in MC and G, respectively.

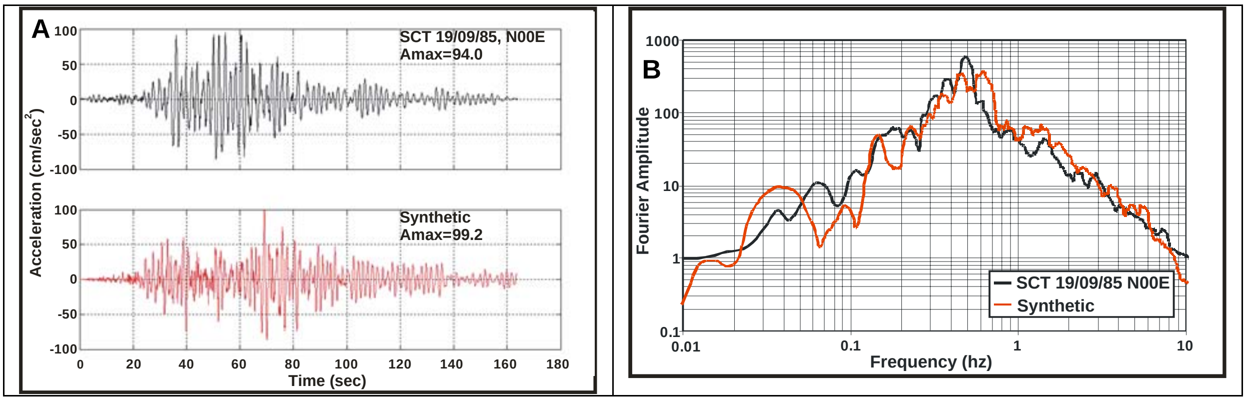


Fig. 3 A) Observed and synthetic accelerograms and B) their corresponding Fourier amplitude spectra in the N-S direction at station SCT (Mexico City) for the 19/09/1985 Michoacan earthquake.

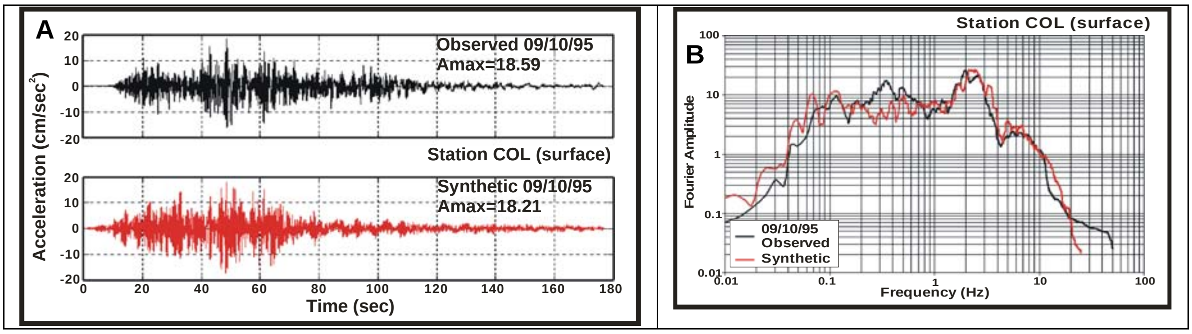


Fig. 4 A) Observed and synthetic accelerograms and B) their corresponding Fourier amplitude spectra in the W-E direction at station COL (Guadalajara) for the 09/10/95 Colima-Jalisco earthquake.

5. MODELING OF Mw 8.5 SUBDUCTION SURFICIAL EXTREME EARTHQUAKE SCENARIOS FOR MEXICO CITY AND GUADALAJARA AND THEIR ECONOMICAL CONSEQUENCES.

The importance of obtaining reliable estimates of the seismic hazard and of its economical consequences, associated with the posible occurrence of extreme earthquakes in regions of Mexico such as the Colima – Jalisco were in 1932 a Ms 8.2 earthquake occurred (Fig. 1) and Guerrero where a Ms 8.1$^+$ is expected (in the so-called Guerero seismic gap), could be hardly overstated, particularly if the Ms 8.1, 1985 Michoacan earthquake (Fig.1) destructive effects on MC are taken into account (about 30,000 deaths and more than 6 billion dollars loss). Based on the satisfactory results obtained for the modeling of the 1985 Mw 8.01 and the 1995 Mw 8 events (Figs. 3 and 4), the hybrid method described in 3 was also utilized to generate synthetic accelerograms for the ground motions expected in MC and G for thrust subduction surficial (TSS) Mw 8.5 extreme earthquake scenarios.
For the computation of MC synthetics, in Fig. 5A the surface projection of the 500 x 600 x 124(depth) km^3 volume used for the low frequency modeling of the Mw 8.5 scenario is presented, the spatial and temporal discretizations as well as the geophysical parameters are the ones mentioned in part 4. The synthetic fractal slip distributions considered for the scenario ruptures are shown in Fig. 5B. For the high frequency modeling, the recordings mentioned above for the 1985 Ms 8.1 event were used, as well as the observations of the later. An example of the type of results obtained is shown in Figs. 6 B. Fig 6A shows MC distribution of the estimated maximum horizontal ground acceleration (Amax) and spectral acceleration Sa(5%) at 2 s for the Ms 8.1 1985 earthquake and Fig. 6B shows the corresponding distribution for the Ms 8.5 scenario earthquake. Notice that for the SCT site, for the scenario earthquake, Amax is equal to 274 cm/s^2 versus 168 cm/s^2 and for Sa(5%) 1390 cm/s^2 versus 973 cm/s^2 . Also notice, that the Mexico City zones were Sa(5%) $\geq$ 700 cm/s^2 increases considerable with respect to the ones estimated from the 1985 earthquake observations. The economical impact of the considered scenarios, analyzed by an acceptable risk criteria, is shown in Fig 7. Notice in this figure, that the previous 1985 earthquake (1976) and actual (2004) seismic recommendations of the MC Construction Code, as well as the 1985 observation, correspond to a Sa(5%) of 240, 450 and 960 cm/s^2 , respectively, and that they are in the so called unacceptable risk zone for the consequence cost of 6.22 US billion dollars (estimated for the 1985 earthquake). The Sa(5%) of 1400 cm/s^2 (obtained from statistics of the extreme earthquake scenarios considered, Chavez et al., in preparation) is in the so called transition risk zone for the same abscise.
For the modeling of the G synthetics, in Fig. 8A, the surface projection of the 288 x 300 x 160 (depth) km^3 volume used for the low frequency simulation of the Mw 8.5 earthquake scenario is presented (with a rupture area which includes large parts of the 1932 and the 1995 earthquakes, Fig. 1), the discretizations used to model the 1995 earthquake were also utilized. The distribution of the 12 subevents considered to represent the Mw 8.5 (each one with a seismic moment = Mo of the scenario earthquake /12) is also included in this figure. For the high frequency modeling, the recordings of the 1995 Ms 7.6 (Mw 8) event were used. Before showing examples of the modeling results obtained, let us briefly discuss about the population, geotechnical and construction characteristics of G shown in Fig. 8B (Chavez et al 2004). a) It has about 6 million inhabitants; b) 25%, 28% , and 47% of its construction stock (about 300Km^2) were built more than 40, between 15 to 40 and less than 15 years ago, respectively; c) From that construction stock only 14% has been built on firm soils or rock sites,

therefore, from the observations of the 9/10/1995 Mw 8, about 86% of that stock is on sandy soils in which the local site effects are guaranteed, as the observed at COL (Fig. 4); d) The actual construction code of Guadalajara does not recognize the seismic site effects.

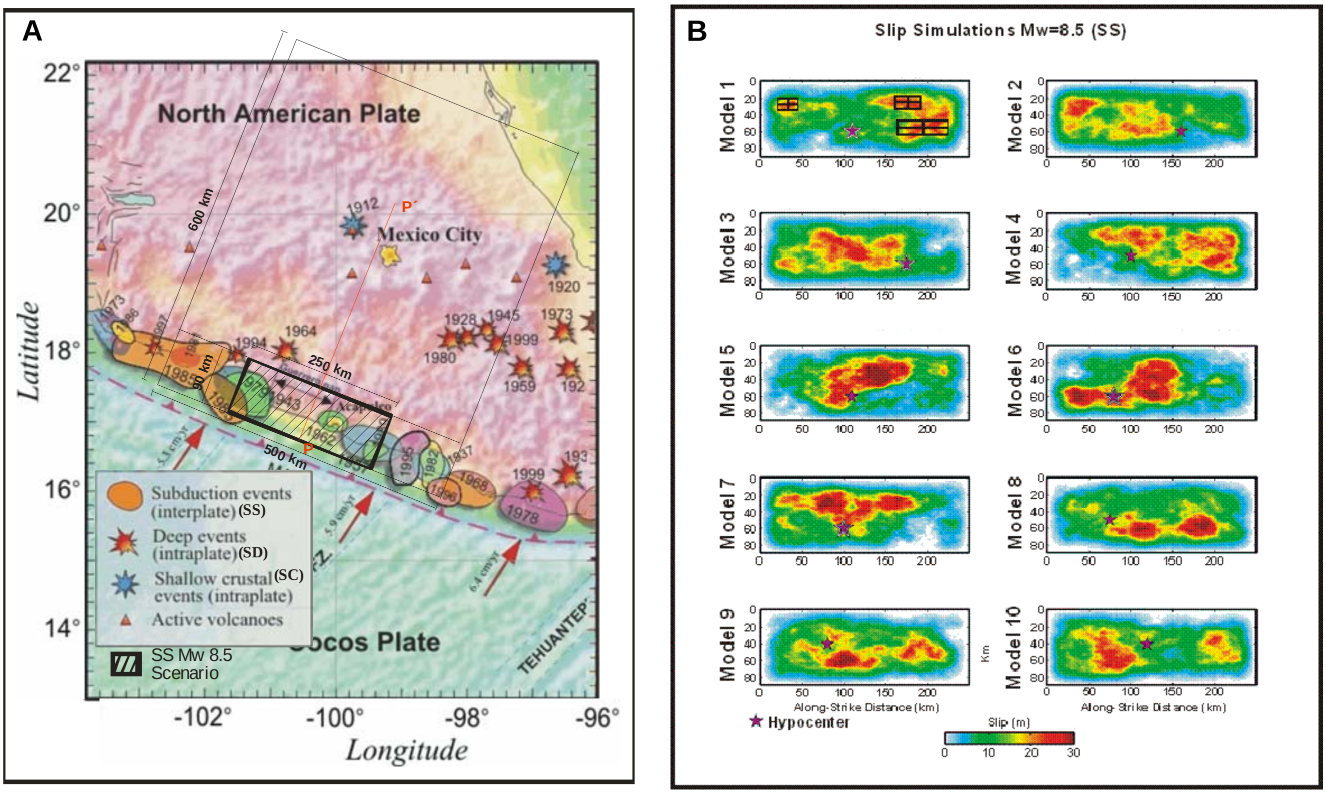
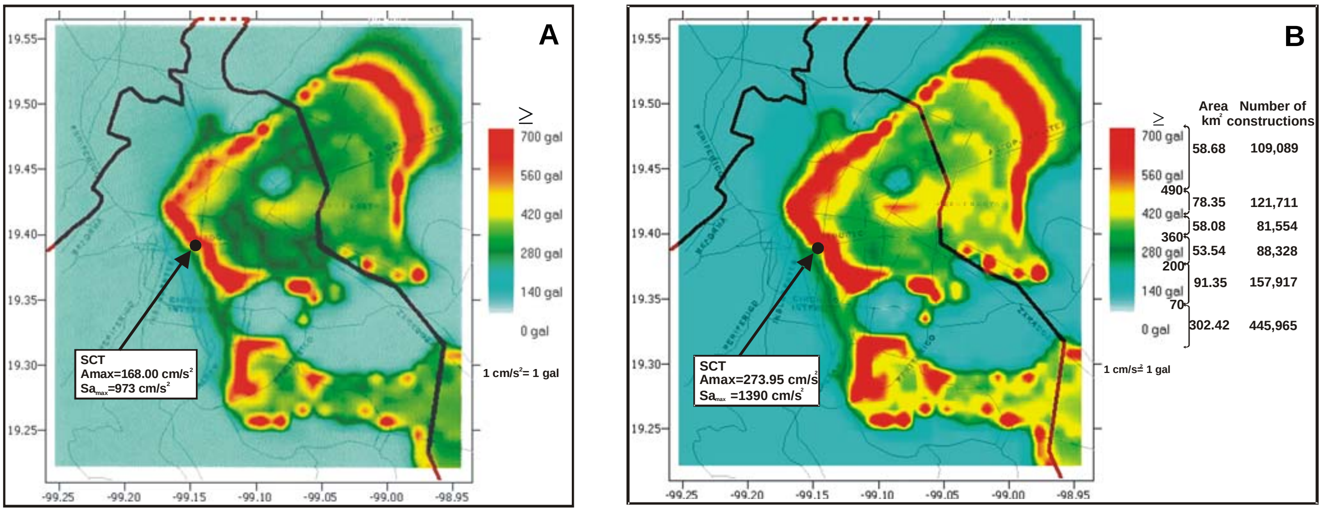


Fig. 5 A) Surface projection of the 3D volume (500 x 600 x 124 km) utilized in the low frequency modeling of the Mw 8.5 TSS earthquake scenarios. B) Fractal slip simulations (based on Mai and Beroza, 2002) used in the hybrid modeling of the Mw=8.5 Subduction Surficial earthquake Mexico City scenarios. The rectangles in model 1 are an example of the finite sources used for the high frequency Empirical Green Functions simulations.



SCT
Amax=168.00 cm/s²
Sa$_{max}$=973 cm/s²

SCT
Amax=273.95 cm/s²
Sa$_{max}$ =1390 cm/s²

≥	Area km²	Number of constructions
490–700 gal	58.68	109,089
420–490	78.35	121,711
360–420	58.08	81,554
200–360	53.54	88,328
70–200	91.35	157,917
0–70	302.42	445,965

Fig. 6 A) Mexico City distribution of the estimated horizontal spectral acceleration Sa (damping 5%) at 2 s for the Ms 8.1 1985 earthquake and B) the corresponding distribution for the Ms 8.5 scenario earthquake. The respective Amax and Sa(5%) values for the SCT site are also included. MC built area (km^2) and the number of constructions of one to three floors are also listed.

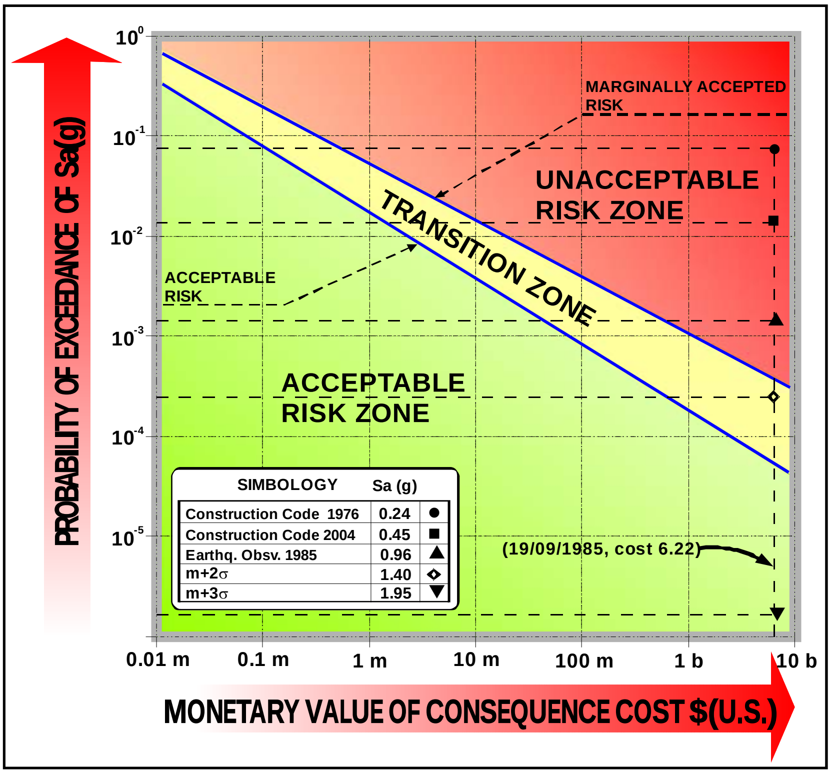


Fig. 7 Probability of exceedance for a time period of 50 years of several Sa(g) values, g=9.81 m/sec^2, for the Mw 8.5 scenario vs Consequence cost in \$ US, of the 19/09/1985 Ms 8.1 Michoacan earthquake.

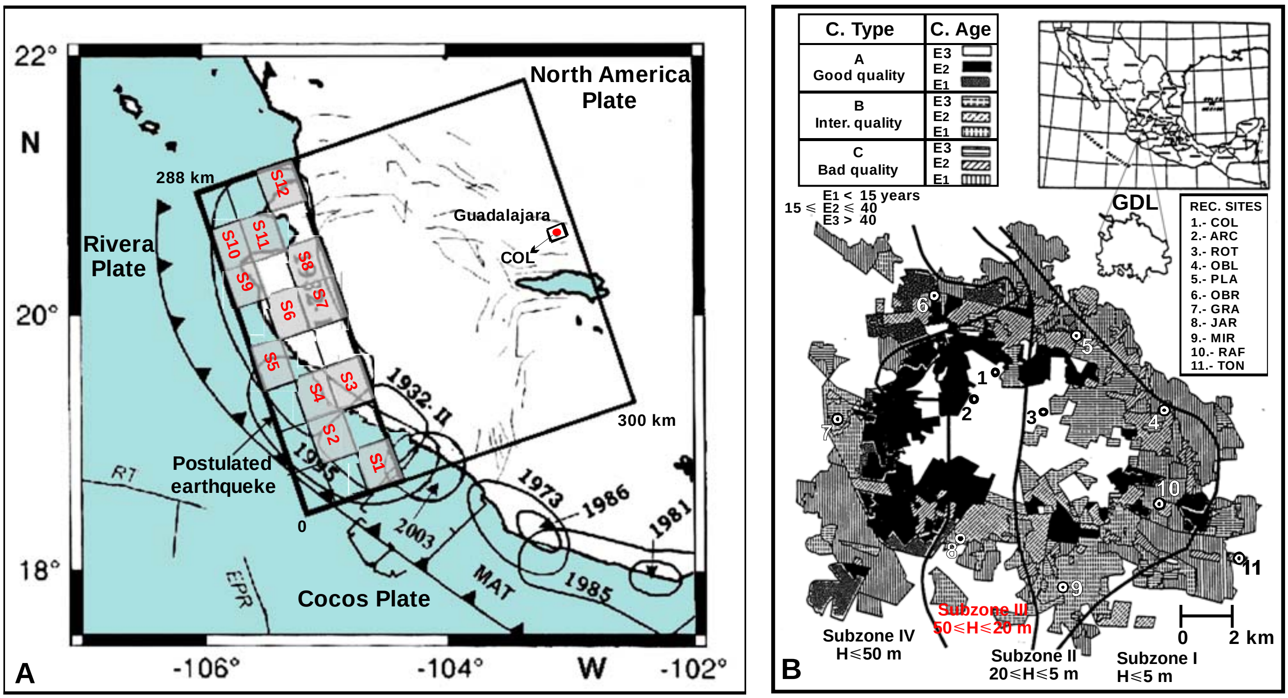


Fig. 8 A) Surface projection of the 288 x 300 x 180 km^3 volume used in the low frequency modeling, including the rupture area for the Mw=8.5 postulated earthquake. S1-S12 depict the location of its 12 assumed subevents. B) Distribution of Guadalajara´s construction stock and its four geothechnical subzones (H depth of rock under Guadalajara´s sandy soils). The encircled dots (1 to 11) identify the recording sites of the 09/10/1995 Ms 7.6 main shock and its 06/09/1995 and 12/09/1995 for and after shocks.

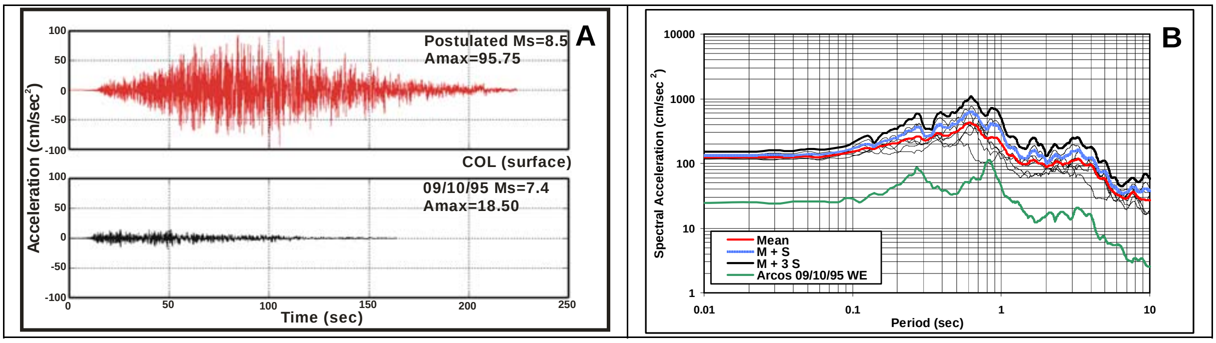


Fig. 9 A) Observed and synthetic accelerograms for Colegio site in Guadalajara for the 09/10/1995 Mw 8 (Ms 7.6) earthquake and the scenario Mw 8.5 extreme earthquake; B) Acceleration response spectra statistics for subzone III (Fig. 8B) of Guadalajara for the extreme scenario earthquake.

Table 1. Guadalajara´s built surface stock, Aij; Mean damage ratio, Dij; Expected built surface damage Sij

A_{ij} (km^2) (Built surface stock) i=A, B, C; j=E_1, E_2, E_3

SUBZONE

C. Type	I H ≦ 5m			II 5 ≦ H ≦ 20m			III 20 ≦ H ≦ 50m			IV H > 50			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	0.680	0.270	0.140	3.160	8.350	18.830	0.570	14.500	19.440	7.660	20.100	5.500	99.200
B	10.770	3.550	2.730	48.130	14.040	16.620	4.890	6.350	3.880	5.450	6.260	1.810	124.480
C	17.820	0.650	1.150	9.500	1.640		6.140	0.420		15.520	0.890	1.340	55.070
Σ	29.270	4.470	4.020	60.790	24.030	35.450	11.600	21.270	23.320	28.630	27.250	8.650	278.750

H=depth to rock of soil; $E_1 \leqq 15$ years, $15 \leqq E_2 \leqq 40$ years, $E_3 > 40$ years; A=Good quality, B=Intermediate quality, C=Bad quality

D_{ij} (Mean damage ratio) %

SUBZONE (IMM)

C. Type	I (7.0)			II (7.5)			III (8.5)			IV (9.0)		
	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	1.60	4.00	12.00	2.13	7.10	21.30	7.00	20.00	52.00	12.80	32.00	70.40
B	2.72	6.80	13.60	10.80	13.50	21.25	34.00	40.00	58.00	54.00	60.00	84.00
C	4.40	11.00	22.00	16.00	20.00	30.00	46.75	55.00	79.75	67.50	75.00	100.00

S_{ij} (km^2) (Expected built surface damage) = A_{ij} x D_{ij}

SUBZONE (IMM) [(Amax + 3σ) cm/s^2]

C. Type	I (7.0) [67]			II (7.5) [83]			III (8.5) [151]			IV (9.0) [172]			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	0.011	0.011	0.017	0.067	0.593	4.011	0.039	2.899	10.109	0.981	6.430	3.873	29.040
B	0.293	0.241	0.371	5.198	1.895	3.532	1.662	2.538	2.250	2.946	3.756	1.522	26.205
C	0.784	0.072	0.253	1.520	0.328		2.872	0.229		10.470	0.667	1.343	18.538
Σ	1.088	0.324	0.641	6.785	2.816	7.542	4.573	5.666	12.359	14.397	10.853	6.738	73.783

Table 2. Economical impact of the Mw 8.5 scenario earthquake in Guadalajara built stock

C_{ij} / km^2

Cost x 10^6 US$

C. Type	I (7.0) [67]			II (7.5) [83]			III (8.5) [151]			IV (9.0) [172]		
	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	25	50	100	50	100	175	550	385	275	550	385	275
B	50	75	125	100	125	150	400	280	200	400	280	200
C	100	125	75	125	150	100	275	200	140	275	200	140

$C_{ij} = S_{ij}$ x C_{ij} / km^2

Total cost x 10^6 US$

C. Type	I (7.0) [67]			II (7.5) [83]			III (8.5) [151]			IV (9.0) [172]			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	0.3	0.5	1.7	3.4	59.3	701.9	21.5	1,116.1	2,780.0	539.6	2,475.6	1,065.1	8,765.1
B	14.7	18.1	46.4	519.8	236.9	529.8	664.8	710.6	450.0	1,178.4	1,051.7	304.4	5,725.6
C	78.4	9.0	19.0	190.0	49.2		789.8	45.8		2,879.3	133.4	188.0	4,381.9
Σ	93.4	27.6	67.1	713.2	345.4	1,231.7	1,476.1	1,872.6	3,230.0	4,597.3	3,660.7	1,557.5	18,872.6

The scenarios analyzed, included that the epicenter of the Mw 8.5 earthquake could occur at S1, S12 and S7. An example of the type of synthetic accelerograms obtained for the Colegio site (subzone III of Fig. 8B) is shown in Fig. 9A, which also includes the observation of the 1995 Mw 8 event. Notice that the Amax = 96 cm/s^2 for the

Mw 8.5 scenario, compared to 18.5 cm/s^2 for the Mw 8 1995 event. In Fig. 9B the statistics of the Sa(5%) for the subzone III are shown. Similar graphs were obtained for the other subzones of G.
The economical impact of the extreme earthquake scenarios analyzed is synthesized in Tables 1 and 2. Table 1 includes the statistics of Guadalajara´s built surface stock, Aij; the seismic vulnerability of its construction stock, expressed by the mean damage ratio, Dij (as a function of the Mercalli Modified Intensity and the corresponding Amax obtained from the statistics of the extreme earthquake scenarios, as the one shown in Fig. 9B) for each geotechnical subzone; the expected built surface damage Sij (equal to the product Aij x Dij) associated to the Mw 8.5 scenario. The economical consequences of the extreme Mw 8.5 scenario considered, estimated as the product of the actual cost, Cij (of the different types of Guadalajara´s Aij) by Sij, are presented in Table 2. Notice that its total amount is of about 19 Billion US dollars.

6. CONCLUSIONS

By applying a hybrid method, previously validated for the Ms 8.1 19/09/1985 and for the 09/10/1995 Ms 7.6 Colima-Jalisco earthquakes, we generated broadband synthetic accelerograms, expected in Mexico City stiff and compressive soils, and in Guadalajara sandy soils, associated to extreme seismic scenarios for thrust subduction surficial Mw 8.5 earthquakes. Based on an acceptable risk criteria, in order to minimize the probability of exceedance associated to an expected economical loss of 6.22 billion US dollars (observed in 1985), for the proposed Mw 8.5 earthquake scenario, a Samax(5%) ordinate of 1.4g (g=981 cm/s2), seems appropriate (for the 19/09/1985 Ms 8.1 earthquake the observed Samax(5%) was equal to about 1g). From the information of the construction stock of Guadalajara, the economical loss, associated to the possible occurrence of the Mw 8.5 earthquake scenario analyzed amounts to 19 billion US$ dollars.

REFERENCES

Bandy W, V. Kostoglodov, H. Hurtado-Díaz , M. Mena, (1999). Structure of the southern Jalisco subduction zone Mexico, as inferred from gravity and seismicity. Geofisica Int., **38**, 3, 127-136.

Cabrera E., M. Chavez, R. Madariaga, N. Perea, M. Frisenda, (2007). 3D parallel elastodynamic modeling of large subduction earthquakes. F. Capello et al. (eds): Euro PVM/MPI 2007, LNCS 4757, pp. 373-380, Springer-Verlag Berlin Heidelberg.

Chavez M., K. Olsen, E. Cabrera, (2004). Broadband modeling of strong ground motions for prediction purposes for subduction earthquakes occurring in the Colima-Jalisco region of Mexico. 13WCEE, Vancouver, B.C., Canada, August 1-6, Paper No 1653.

Escobedo D, J.F. Pacheco, G. Suarez, (1998). Teleseismic body-wave analysis of the 9 october, 1995 (Mw=8.0), Colima-Jalisco, Mexico earthquake, and its largest foreshock and aftershock. Geophysical Research Letters, **25**, 4, 547-550.

Mai M. and G.C. Beroza, (2002). A spatial random filed model to characterize complexity in earthquake slip. J. Geophysical Res., Vol **107**, No B11, 2308.

Mendoza C, S. Hartzell, (1989). Slip distribution of the 19 september 1985 Michoacan, Mexico, earthquake: near source and telesismic constrains, Bull. Seismol. Soc. Amer., **79**, pp 655-699.

Irikura K., (1986). Prediction of strong acceleration motion using empirical Green´s function. Proc. 7th JEES, 151-156.

ACKNOWLEDGMENTS

We would like to thank the support of J.L. Gordillo, the Supercomputing staff and M. Ambriz and Leonardo Alcantara, of DGSCA, and the Institute of Engineering, UNAM, respectively.We also acknowledge the support of R. Madariaga and M. Mai of the ENS, Paris and ETH, Zurich, respectively. We acknowledge DGSCA, UNAM for the support to use KanBalam, as well as the STFC Daresbury Laboratory to use HECToR Supercomputers.The authors also acknowledge support from the Scientific Computing Advanced Training (SCAT) project through Europe Aid contract II-0537-FC-FA (http://www.scat-alfa.eu).