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BROADBAND MODELING OF STRONG GROUND MOTIONS FOR PREDICTION PURPOSES FOR SUBDUCTION EARTHQUAKES OCCURRING IN THE COLIMA-JALISCO REGION OF MEXICO

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SUMMARY

The high seismic potential of the Colima-Jalisco (CJ) region in northwestern Mexico has been shown over the last several centuries. For example, recent destructive large shallow thrust subduction earthquakes occurred the 3^{rd} and 18^{th} of June 1932 with Ms of 8.2 and 8, respectively, the 30^{th} of January 1973 (Mw 7.6, Ms 7.3) and also on the 9^{th} of October 1995 (Mw 8, Ms 7.4) and the 22^{nd} of January 2003 (Mw 7.4, Ms 7.3). The frequent occurrence of large events calls for reliable seismic hazard estimates for the CJ region.

In the first part of this study, we present broadband synthetics generated by a hybrid model combining long period and high frequency simulations and compare them with the accelerograms recorded in Manzanillo (MZ), Ciudad Guzman (CG), and at the Colegio station of Guadalajara (G), which are located at 35, 140, and 240 km, from the epicenter of the 1995 earthquake, respectively. The low frequency (< 1Hz) synthetics were simulated by using a fourth order finite difference method (Olsen, 1994) including a finite-fault description of the source with four asperities in a 2.5D model constrained by gravity and seismological data. The high frequencies (> 1Hz) were modeled by the empirical Green function technique (Irikura, Procc. 7^{th} JEES, 1986), the four-asperity source model, and the recordings of the fore- and aftershocks of the Mw 8 1995 event. The comparisons of the synthetics with the observed strong ground motions for the 1995 earthquake in the near field (MZ), intermediate field (CG), and the far field (G) are satisfactory for the entire modeled bandwidth (0.04 – 20Hz), including the local soil effects at CG and G.

In the second part of the study we present the results we obtained, by applying the proposed hybrid model, for the computation of the expected strong ground motions at G (free field soil site and at 35m rock depth) for a hypothetical Mw 8.5 (Ms 8.2) earthquake, similar to the 03/06/1932 event. Three rupture propagation scenarios were analyzed, the same 2.5D model was used, and the finite source was modeled with 12 asperities; for the high frequencies (> 1Hz) the same 12 asperity model and the recordings of the 1995 main shock were utilized.

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Among other results we can mention that for the Mw 8.5 earthquake scenario, the expected maximum accelerations at the surface and at 35m rock depth at station Colegio of Guadalajara are of 108 and 40cm/s^2, compared with 19 and 7cm/s^2, respectively observed, for the 1995 Mw 8 earthquake.
Based on the results of the study, we believe that our hybrid method allows the generation of more reliable estimates of the seismic hazard in regions such as the Colima-Jalisco.

INTRODUCTION

The high seismic potential of the Colima-Jalisco (CJ) region in Mexico has been demonstrated over the last several centuries. For example, in the period from about 1800 to 1900 the following large earthquakes occurred in the region: the 25th of March 1806 (Ms 7.5), the 31st of May 1818 (Ms 7.7), 20th of January and 16th of May 1900 (Ms 7.6 and 7.1), Nishenko and Singh [1]. Recently, other large shallow thrust subduction earthquakes occurred the 3rd and 18th of June 1932, with Ms of 8.2 and 8, respectively, the 30th of January of 1973 (Mw 7.6, Ms 7.3), as well as on the 9th of October of 1995 (Mw 8, Ms 7.4), and on the 22nd of January of 2003 (Mw 7.4, Ms 7.3), Fig. 1. The seismic data in the CJ region has lead to the conclusion that the best recurrence time estimates for earthquakes such as the Ms 8.2 1932 event range from 77 to 126 years, Nishenko and Singh [1].

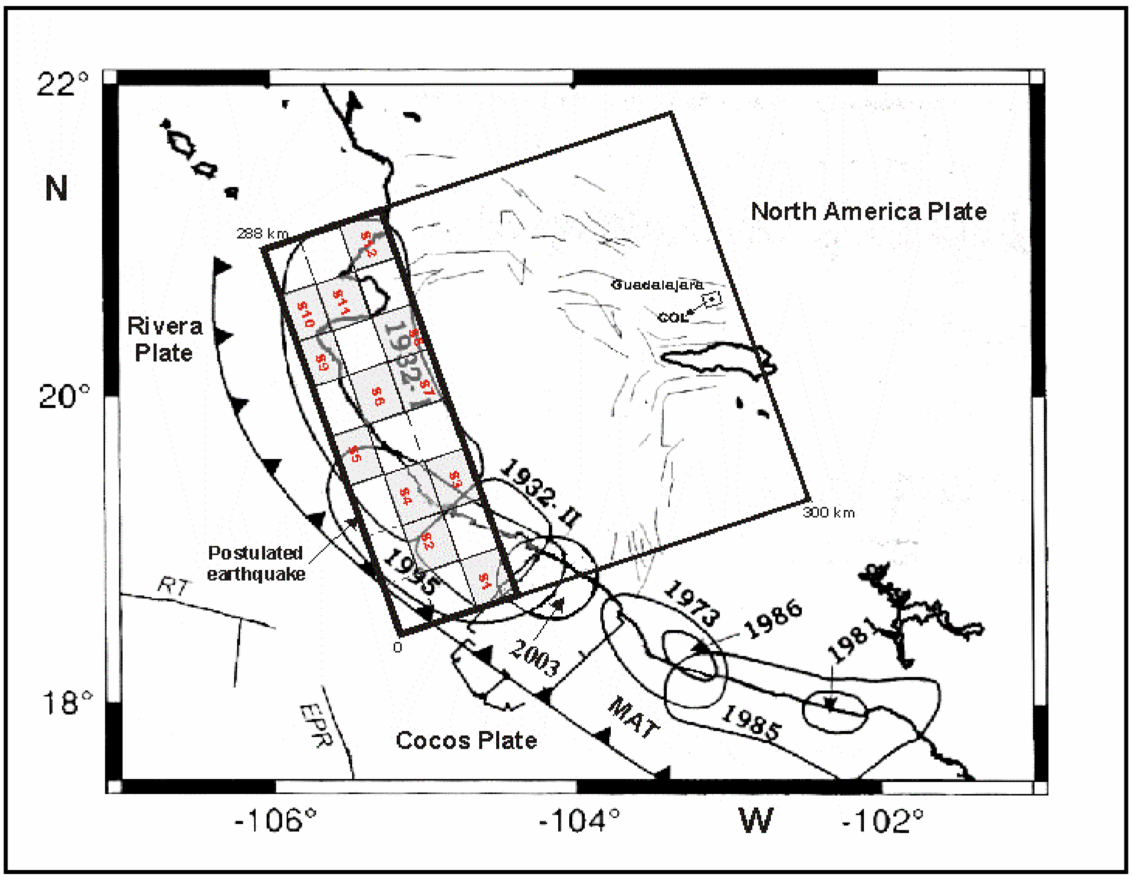


Fig. 1 Rupture areas for the: June 3 (1932-I) and 18 1932 (1932-II), January 31 1973, October 9 1995, January 22 2003 and September 19 1985, earthquakes. Also shown are the rupture areas of the Mw=8.5 postulated earthquake and the model area for the 2.5-D multiple-subevent finite-difference simulation. S1-S12 depict the location of the subevents (Modified from Singh et al., [12])

For the 1995 earthquake (and for its largest foreshock 6/10/95 Ms 5.8 and aftershock 12/10/95 Ms 5.9) good quality, free field, accelerographic records were obtained at stations Manzanillo (MZ), Ciudad Guzman (CG), and Guadalajara (COL), with epicentral distances to the mainshock in the near (35km), intermediate (140km) and far fields (240km), respectively, Fig. 4A. The intermediate and far field stations are part of an accelerographic network installed in 1992-1993 in the state of Jalisco, to monitor the strong ground motions in the second largest city of Mexico (Guadalajara) where 11 free field and two downhole stations were set, Chavez [2,3] and in the second largest town of the state of Jalisco (Ciudad Guzman).

In order to obtain better estimates of the seismic hazard at sites of the CJ region, there is a need to generate synthetics associated to plausible seismic scenarios; towards this objective, here we present the results of a hybrid technique to generate synthetics in the near (MZ), intermediate (CG) and far (G) fields for the 09/10/1995 earthquake, as well as the estimated strong ground motions at G, for an earthquake similar to the 03/06/1932 event.

The paper is divided in 6 parts. In the 1st part we discuss the main features of the seismotectonics of the CJ region, the characteristics of some of the recordings obtained for the largest fore and aftershocks of the 1995 event are presented in the 2nd part. In the 3rd part a brief discussion of the broadband modeling technique is included, and the data and numerical results for the 1995 earthquake are presented in the 4th part. In the 5th part we present the results of the modeling for an Mw 8.5 earthquake scenario occurring in the CJ region. Finally the main conclusions of the work are presented.

SEISMOTECTONICS OF THE COLIMA- JALISCO REGION

The seismotectonics of the CJ region is mainly associated with the subduction of the Rivera plate beneath the North-American plate (NOAM) in the Jalisco-Colima zone, in the northern part of the Middle American Trench in western Mexico. The main tectonic features of the region of interest are shown in Fig. 2, Escobedo et al [4].

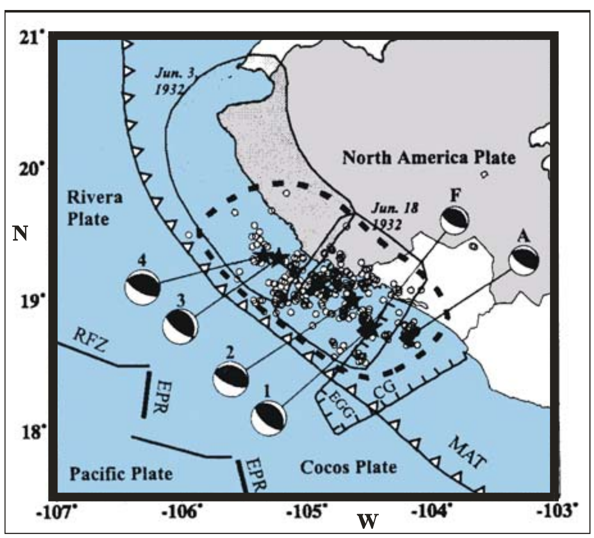


Fig. 2 Rupture area for June 3 and June 18 1932 earthquakes, epicentral locations and focal mechanisms for the Oct 9 1995 mainshock 1, the foreshock F (Oct 6), the largest aftershock A (Oct 12), the outline of the aftershock zone (dashed), as well as 4 subevents (1-4) interpreted as the source for the main event. RFZ: Rivera Fracture Zone; EPR: East Pacific Rise: EGG: El Gordo Graben; CG: Colima Graben; MAT: Middle American Trench (Modified from Escobedo et al., [4]).

The age of the Rivera plate varies between 10 and 15 My and its rate of subduction below the NOAM is estimated to be from 2 to 5 cm/year. Regardless of this slow convergence rate, the periods of interseismic activity between large earthquakes in this region appear to be shorter than in similar tectonic regions as, for example, the Cascadian subduction zone. For example, between 1932 and 2003, the subduction process of the Rivera-NOAM plates has generated the three large and destructive earthquakes mentioned above: the two of 1932 and the one of 1995.

From Figs. 1 and 2 it can be observed that the rupture area of the 9/10/1995 earthquake included about 40% and 100% of the rupture areas of the 3rd and 18th of June 1932 earthquakes, respectively. It can also be observed that the source mechanisms of the largest fore and aftershocks of the 1995 mainshock are very similar to the average mechanism of the latter, i.e. the three events are shallow-dipping, thrust-fault earthquakes, in agreement with the relative plate motions for the Rivera-NOAM and the Cocos-NOAM plate boundaries.

Based on gravity observations, constrained by seismicity data, Bandy et al. [5] proposed a model of the geological structure of the subducting and continental plates in the CJ region, Fig 3. Among other findings, they proposed that the thickness of the continental crust averages 38 km and thickens, gradually, towards the continent up to 44 km. They also concluded that the density of the upper part of the subducting plate increases at a depth of 30 km, probably reflecting a phase transition of basalt to eclogite.

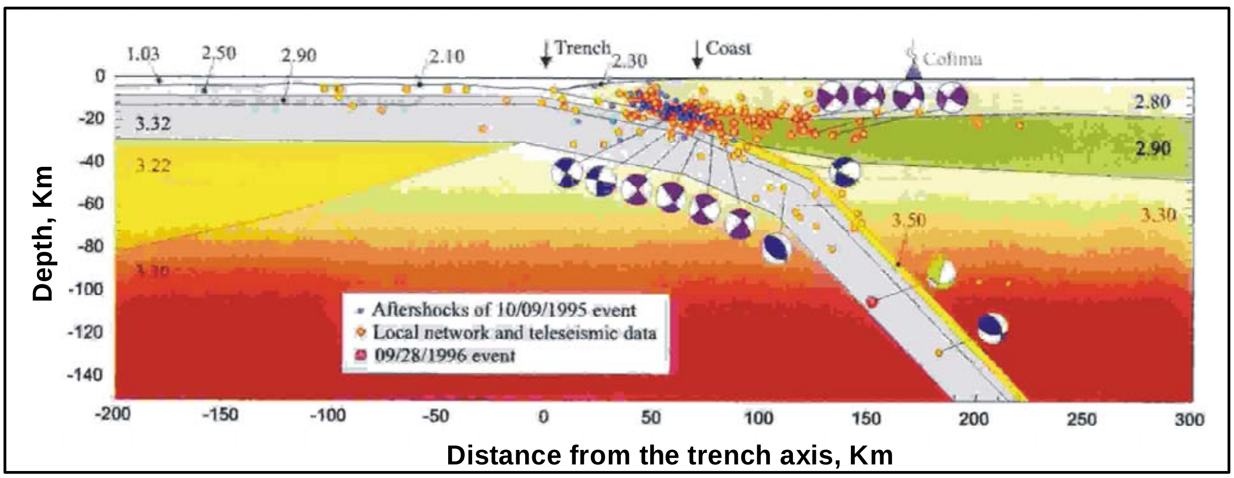


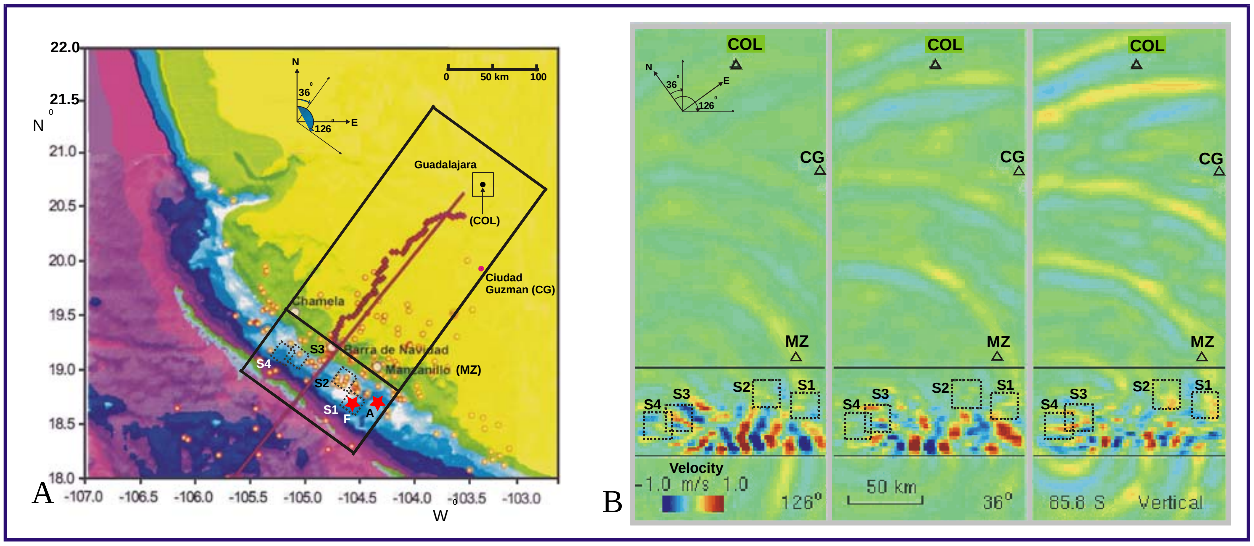
Fig. 3 Recent seismicity and the geometry and densities (in g/cm^3) of the subducting and continental plates for a 500km profile in the region of interest. The location of the profile is shown in Fig. 4 A. (Modified from Bandy et al., [5]).

From Fig. 3 it can be observed that the subducting slab initially dips at an angle which varies from 9^0 to 16^0 down to a depth of about 20 km, and then the dipping angle of the slab gradually increases to about 50^0 at depths below 50 km. The continental crust is made of an upper layer with a density of 2.8 g/cm^3, a lower crustal layer with a density of 2.9 g/cm^3, and a thin sedimentary layer with a density of 2.3 g/cm^3 in the continental slope zone. In relation to the Rivera plate, Bandy et al. [5] modeled it as consisting of three layers with densities of 2.5, 2.9 and 3.32 g/cm^3, and the upper mantle beneath it with a density of 3.3 g/ cm^3, as under the continental crust.

RECORDINGS OF THE 6TH AND 12TH OCTOBER 1995 FORE AND AFTERSHOCKS

Three-component strong ground motion records were obtained for the 09/10/1995 mainshock as well as for the 6/10/1995 Ms 5.8 foreshock and 12/10/1995 Ms 5.9 largest aftershock, at the free-field accelerographic stations of Manzanillo (MZ), Ciudad Guzman (CG) and in Guadalajara´s COL surface and downhole instruments, Fig. 4A. The three stations are on top of soil layers and the downhole accelerograph is on a basaltic rock at 35 m depth.

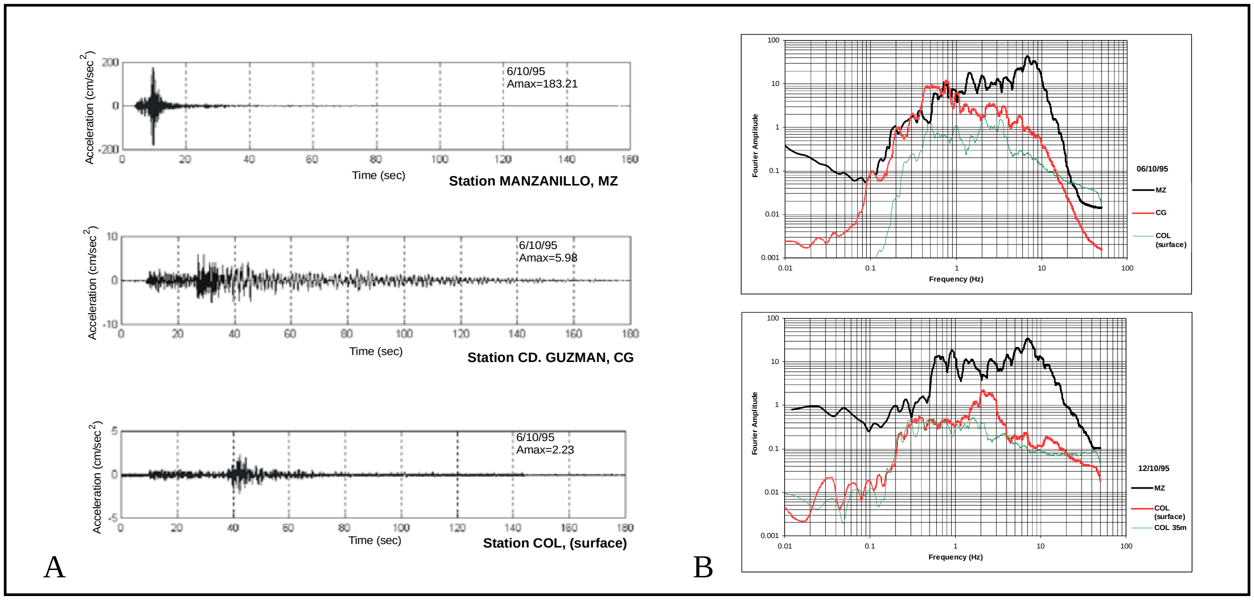
In Fig. 5 A and B we show examples of the recorded accelerograms for the largest fore and aftershocks (W-E components) and of their associated Fourier amplitude spectra, respectively. Notice the attenuation with distance from the epicenter of the recorded signals, MZ (35 km), CG (140 km) and COL (240 km). Also notice the large amplitudes and high frequency content of the MZ signal, compared with the ones at CG and COL and lastly, that for the aftershock records in COL, it is important to remark the site effect between 2 and 3 Hz Chavez [2, 3].



Figs. 4A Model area for the 2.5-D multiple-subevent finite-difference simulation. S1-S4 depict the location of the subevents, F is the foreshock, and A is the largest aftershock. 4B Snapshot of the three component wavefield propagation, for f≤0.5 Hz.

BROADBAND MODELING PROCEDURE

A hybrid procedure combining long period and high frequency simulations was developed for the computation of broadband synthetics of the accelerograms observed at stations MZ, CG and COL for the 09/10/1995 Mw 8 earthquake. The long period (<1 Hz) wave field was simulated using a method that consists of a staggered-grid finite-difference scheme, to solve the 3D elastic equation of motion to a level of accuracy that is fourth order in space and second order in time, as implemented by Olsen [6]. The earthquake source is implemented in the finite-difference grid by adding –Mij/V to Sij, where Mij is the ijth component of the moment tensor for the earthquake, V is the cell volume, and Sij is the ijth component of the stress tensor on the fault at time t, Olsen et al. [7].



Figs. 5A Accelerograms observed in the West-East (W-E) direction at stations MZ, CG and COL (surface) for the 6/10/95 earthquake. 5B Fourier Amplitude spectra of acceleration for the 6/10/95 event at stations MZ, CG and COL (surface), and for the 12/10/95 event at stations MZ, COL (surface) and COL (downhole).

The high frequency (≥1Hz) synthetics were generated with the Empirical Green function (EGF) method, Irikura [8]. In this method the ground motion from a large event is expressed as a superposition of the records of small events (elementary sources). The number of the elementary sources is controlled by scaling relations between the large and the small earthquakes. An important hypothesis of the EGF method is that large and small events follow the ω^2 model and a constant stress drop; this implies that the source displacement spectrum has a flat level at low frequencies and an omega-square decay at high frequencies beyond a corner frequency. We follow the suggestion of Frankel [9] as well as Hartzell et al. [10] when expressing the elementary source area as the ratio of the seismic moments of the small and large events to the 2/3 power multiplied by the large event rupture area. Finally, the low and high frequency synthetics were combined using matched filters.

RESULTS FOR THE 9TH OF OCTOBER 1995 MW 8 COLIMA-JALISCO EARTHQUAKE

Long-period (>2 s) wave propagation in a 2.5-D model of the subduction zone constrained by gravity and seismicity data (Fig. 3) have been simulated using a four-subevent source model (Fig. 4A and Table 1A). The dimensions of the model are 350 km by 140 km by 180 km (depth). Figure 4B shows a snapshot of the long-period velocity. Notice in Fig. 4B the waves trapped in the accretionary prism (depicted by the horizontal lines). To generate the EGF's we used the source information of the four subevents, the foreshock (F), the largest aftershock (A) (Figs.2, 4A, Table 1B) and the W-E records at MZ, CG and COL (Fig. 5) of the events F and A.

Tables. 1A Parameters for the 2.5D Modeling (f≤1 Hz). 1B Source parameters of the foreshock, largest aftershock and the four subevents of the earthquake of the 09/10/95 (Modified from Escobedo et al., 1998[4]).

Parameters	Value
Spatial discretization (km).	0.6
Temporal discretization (sec).	0.35
P wave minimum velocity (km/sec) (water).	1.5
S wave minimum velocity (km/sec) (water).	0
Minimum density (kg/m^3).	1000
Number of grid points 126^o direction.	273
Number of grid points 36^o direction.	591
Number of grid ponts vertical direction.	272
Number of time steps.	1428
Simulation time (sec).	250

A

Event	Depth (km)	Strike (^{o})	Dip (^{o})	Rake (^{o})	Mo (Nm)	Mw
Foreshock	18	314	29	104	$4.28x10^{17}$	5.75
Mainshock	24	306	26	94	$1.84x10^{20}$	7.50
Aftershock	21	290	25	76	$7.75x10^{17}$	5.92
Subevent 1	28	320	28	98	$4.39x10^{19}$	
Subevent 2	31	286	25	84	$4.92x10^{19}$	
Subevent 3	19	338	25	119	$4.13x10^{19}$	
Subevent 4	20	282	26	75	$5.00x10^{19}$	

B

In Fig. 6 we present the observed and the synthetic accelerograms for the W-E components of the 09/10/95 earthquake associated to the MZ, CG, and G (COL) stations. From this figure it can be concluded that as a whole, the wave forms of the computed synthetics are similar to the observed ones, particularly for the lapses of the larger amplitudes, and that the maximum accelerations values of the former are close to the values of the latter.

The Fourier Amplitude spectra of the accelerograms of Fig. 6 are shown in Fig.7. In this figure we observe that the agreement between the observed and the computed synthetic spectra is as a whole satisfactory for the frequency band analyzed (0.04 to 20Hz). Notice that for the low and high frequencies the Fourier amplitudes are very close, and that for the intermediate low frequencies the results could still be improved. Notice that for the station COL (surface) of G, the local site effect, reported by Chavez [3], which occurs from 1.5 to 4Hz, is reproduced by the synthetic (Fig. 7).

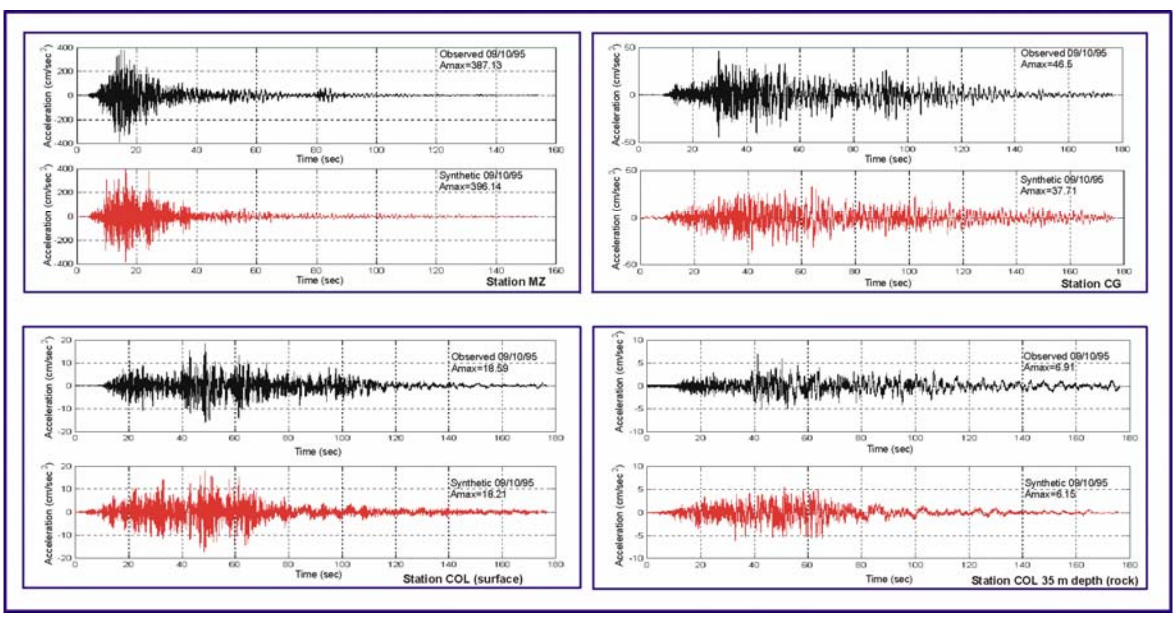


Fig. 6 Comparison of the observed and synthetic accelerograms in the W-E direction at stations MZ, CG and COL´s surface and downhole, for the 09/10/95 earthquake.

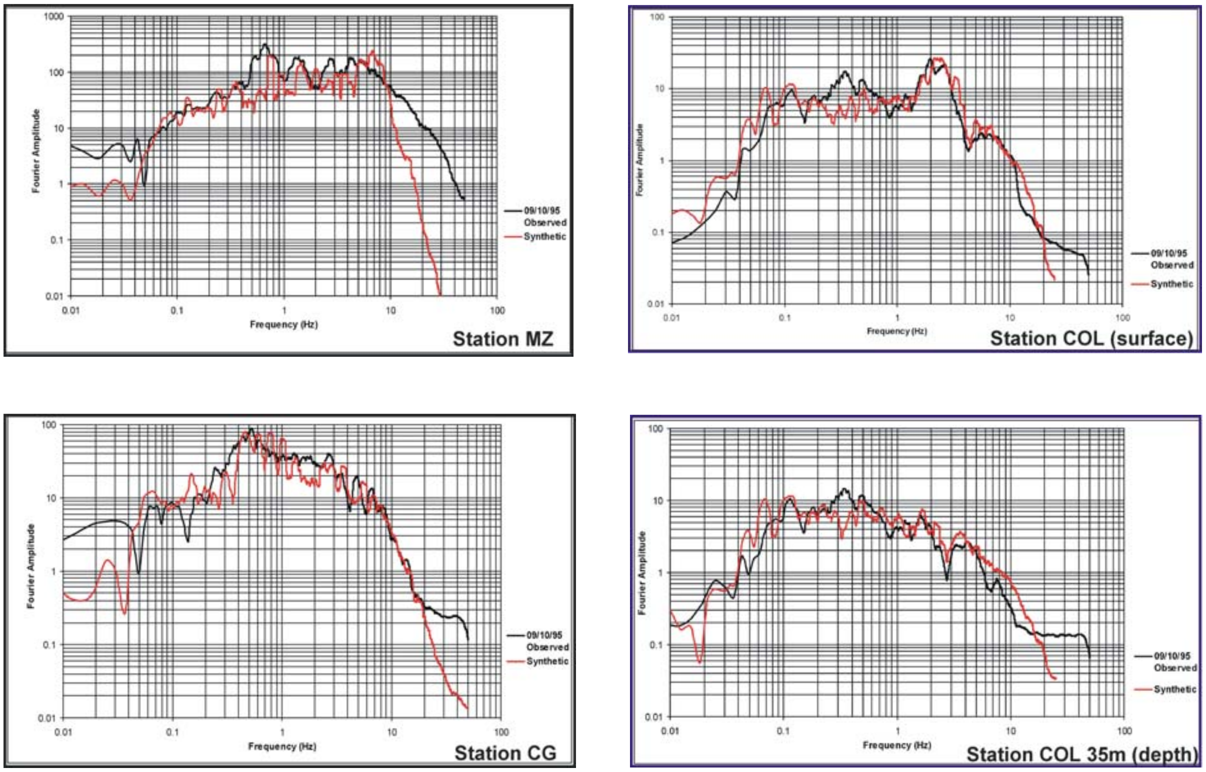


Fig. 7 Comparison of the Fourier Amplitude spectra for the observed and the synthetic accelerograms of Fig. 6.

MODELING DATA AND RESULTS FOR A MW 8.5 EARTHQUAKE SCENARIO OCCURRING IN THE COLIMA-JALISCO REGION

The importance of obtaining reliable estimates of the seismic hazard in regions such as the CJ, in which events as the one of the 3rd of June 1932 Ms 8.2 have occurred, is critical, particularly if the Ms 8.1, 1985 Michoacan earthquake (Fig.1) destructive effects on Mexico City are taken into account (about 30,000 deaths and 4 billion dollars loss). The setting is the following: a) Approximately 25%, 28% , and 47% of the actual construction stock (about 300 km^2) of the metropolitan zone of Guadalajara (about 6 million inhabitants) were built more than 50 years, between 20 to 50 years and less than 20 years ago, respectively, Chavez [11]. b) 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 data at COL surface (Figs. 6 and 7), Chavez [3, 11]. c) The construction code in force in Guadalajara does not recognize the site effects [13]. d) The recurrence time of a 1932 Ms 8.2 type of earthquake proposed by Nishenko and Singh [1], is of 77 to 126 years (i.e. the next large event is expected between the years 2009 and 2058).

As a first approximation to obtain synthetics at G associated with a 1932 Ms 8.2 type of earthquake, we assumed a scenario of a Mw 8.5 (Mo 6.92 x 10^{21} Nm) earthquake with a rupture area which includes those of the two of 1932, and parts of the ones of 1995 and 2003, Fig. 1 (notice that the 1985 earthquake overlaps the 1981, and parts of the 1986 and 1973 events, Fig. 1).

Based on the satisfactory results obtained for the modeling of the 1995 Mw 8 event, for the low frequency (<1Hz) wave propagation of the Mw 8.5 hypothetical event, we basically adopted the same modeling data discussed above, which are included in Fig. 3 and Tables 1A-B. However, in this case we used the 12 subevent source model shown in Fig. 1. The subevents had an average Mo of 5.77 x 10^{20} Nm, and a strike, dip and rake source mechanism of 340°, 17° and 90° (these values are based on Fig. 3 and on the corresponding parameters included in Table 1B).The dimensions of the model are 300 km by 288 km by 180 km (depth), Fig 1. We also considered the three rupture scenarios shown in Fig. 8 for the postulated earthquake, i.e. starting the rupture at subevents S1 (southern), at subevent S7 (central), and at subevent S12 (northern). For the EGF high frequencies (>1 Hz) modeling we used the same 12 subevent source model, the source information of the mainshock 1995 data included in Table 1B, and also the North-South (N-S) recordings obtained for this earthquake, at the surface and at 35m rock depth at COL station of Guadalajara, Fig. 9A.

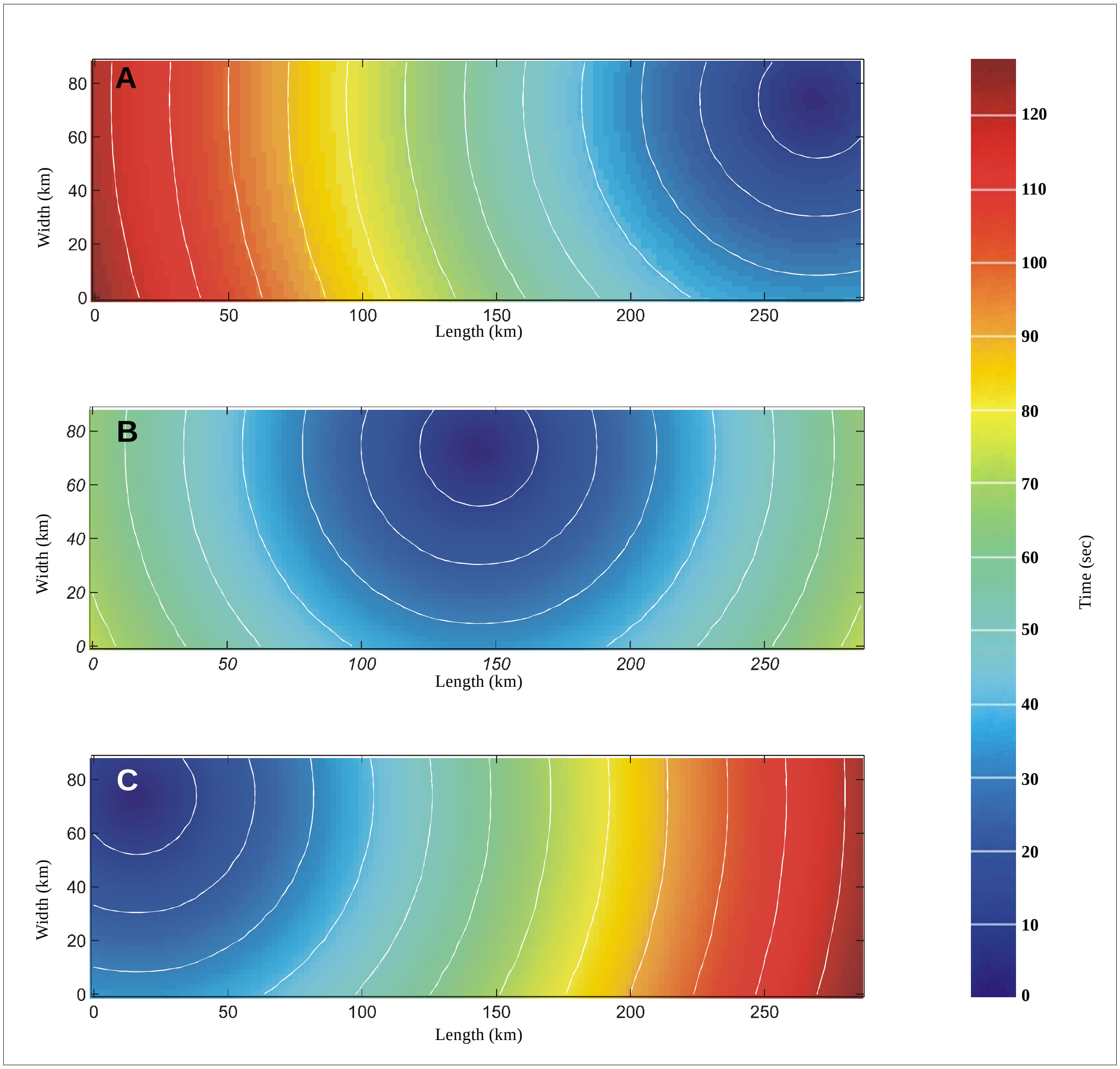


Fig. 8 Rupture area considered for the Mw=8.5 hypothetical earthquake A, B, C, the southern, central and northern rupture scenarios included in the study.

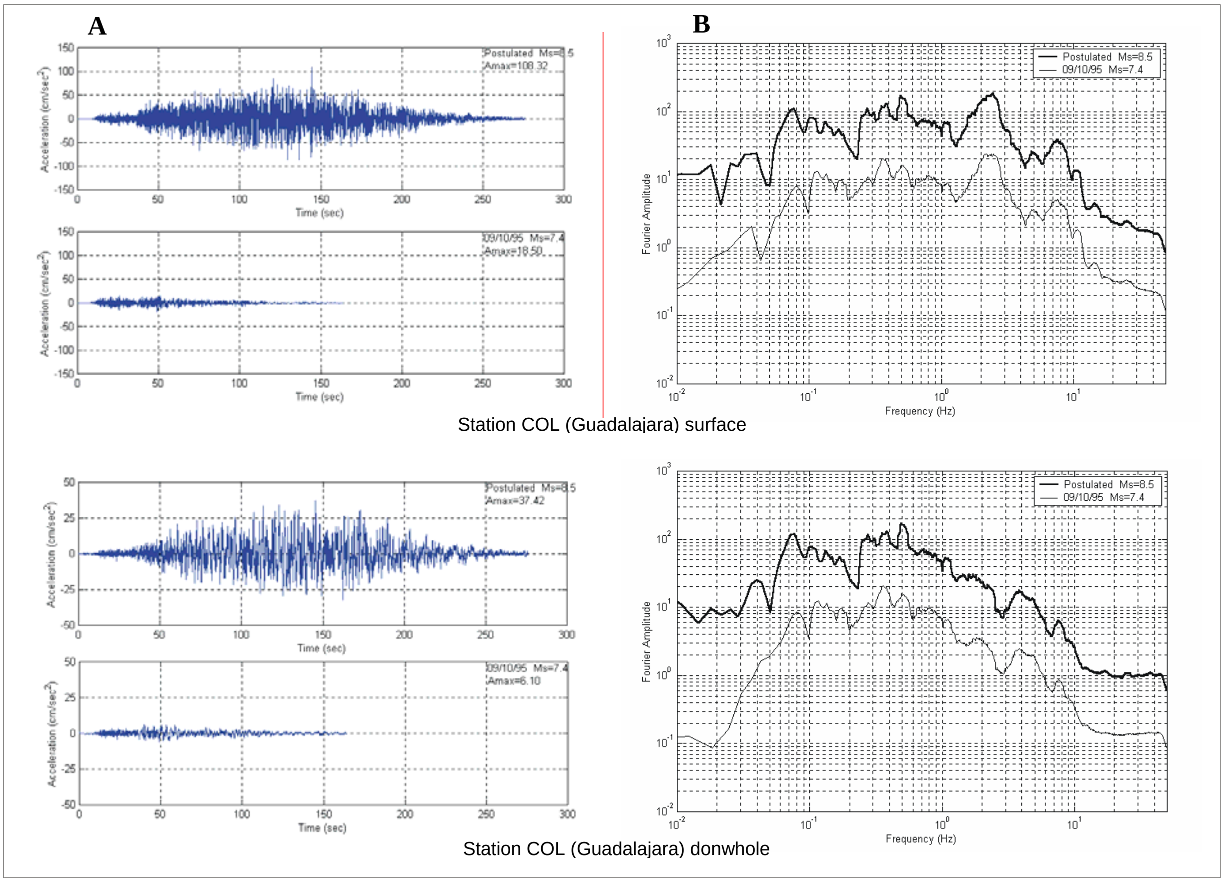


Fig. 9A Accelerograms observed (09/10/95) and synthetic (Mw=8.5 hypothetical earthquake southern rupture scenario) in the North-South direction at station COL (Guadalajara) surface and downhole. 9B Fourier Amplitude Spectra of 9A.

In Figs. 9, 10 and 11 A we present the observed and the synthetic accelerograms for the N-S components of the 09/10/95 and the hypothetical earthquakes (southern, central and northern rupture scenarios) for the surface and 35m rock depth of COL Guadalajara station. From these figures it can be concluded that as expected the duration and amplitudes of the postulated Mw 8.5 events are larger than the observed for the 1995 event. For example, total durations of about 225s (central rupture scenario) to 275s (southern and northern rupture scenarios) for the postulated earthquakes, versus 170s for the 1995 earthquake. Notice the large durations (tens of seconds) of the intense parts of the ground motions synthetics.

The maximum accelerations at COL surface are 108, 96, and 84cm/s^2 for the southern, central and northern rupture scenarios analyzed (Fig. 8), about 5 times the observed for the 1995 earthquake. The corresponding values for the COL 35m rock depth are 37, 42, and 36cm/s^2, respectively, about 6 times the observed for the 1995 event.

The Fourier Amplitude spectra of the accelerograms of Fig. 9, 10, 11 A are shown in Figs. 9, 10, 11 B. In these figures it can be observed (as expected) the large amplitudes of the Fourier spectra for the frequency range 0.05 – 1Hz, and also, the large amplitudes for the spectra of the surface synthetics for the frequencies between 2 and 3 Hz, corresponding to the local site effects, already observed for the 1995 earthquake.

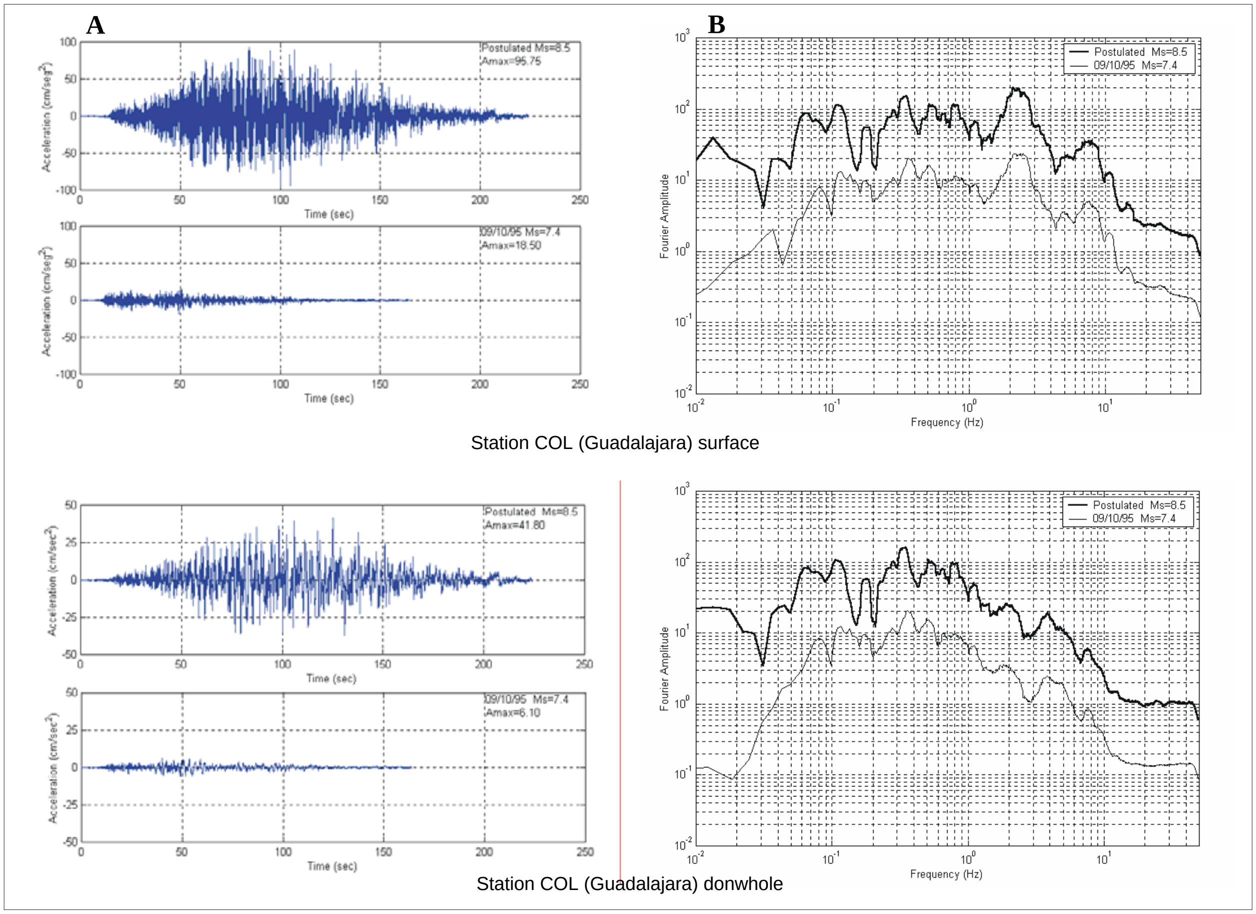


Fig. 10A Accelerograms observed (09/10/95) and synthetic (Mw=8.5 hypothetical earthquake central rupture scenario) in the North-South direction at station COL (Guadalajara) surface and downhole. 10B. Fourier Amplitude Spectra of 10A.

In Fig. 12 the comparison of the Fourier amplitude spectra of the synthetic accelerograms at COL surface for the three rupture scenarios are shown. From this comparison it can be concluded that the main differences among the spectra occur for frequencies of less than 1Hz, which are associated with the postulated earthquakes ruptures, whose effect is heavily reduced for the higher frequencies as shown by the agreement of the Fourier amplitudes from 1.3 Hz onwards. Similar comments apply for the comparison of the Fourier amplitude spectra of the synthetic accelerograms at COL 35m rock depth which are shown Fig. 13.

In Figs. 14 and 15 the comparison of the acceleration response spectra of the synthetic accelerograms at COL surface and 35m rock depth for the three rupture scenarios are presented. From Fig. 14 it can be concluded that for COL surface, the spectral acceleration at low periods fluctuates from about 80 to 110cm/s^2, that for a period of about 0.12s the central scenario reaches a value of about 300cm/s^2, while for the northern and southern are of only 200cm/s^2, that for a period of about 0.4s the three response spectra reach a value of about 450cm/s^2 , for higher periods and up to 3s the corresponding values are smaller than 200cm/s^2.

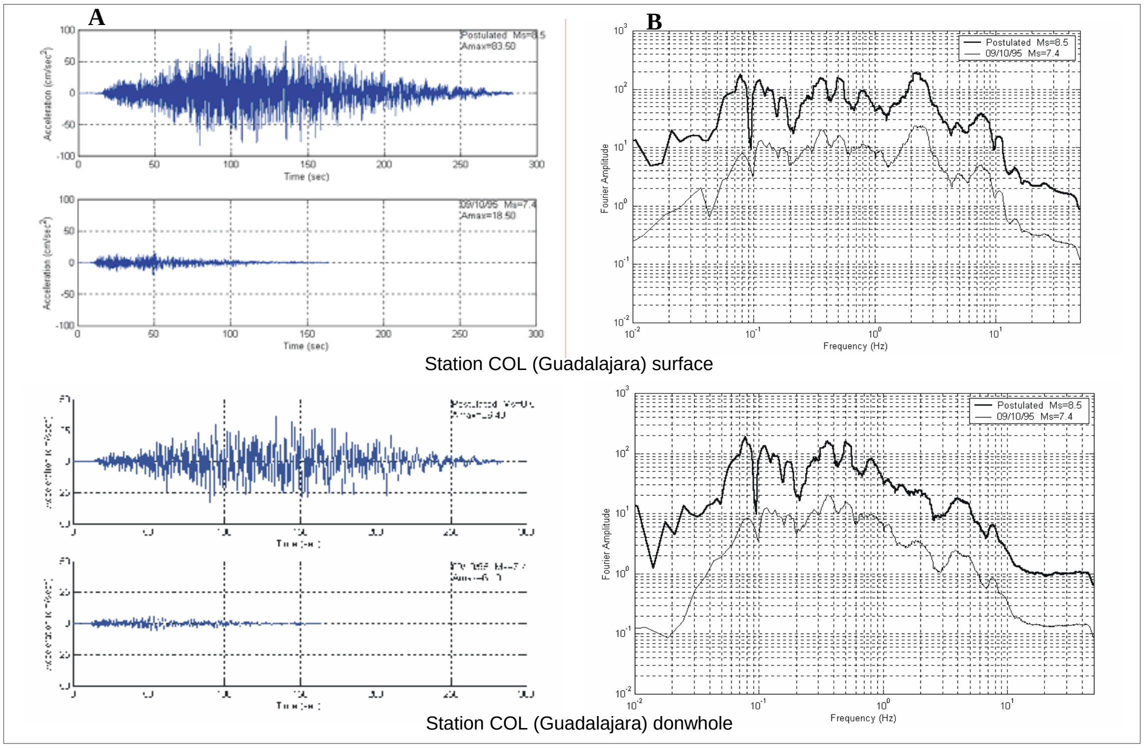


Fig. 11A Accelerograms observed (09/10/95) and synthetic (Mw=8.5 hypothetical earthquake northern rupture scenario) in the North-South direction at station COL (Guadalajara) surface and downhole. 11B Fourier Amplitude Spectra of 11A.

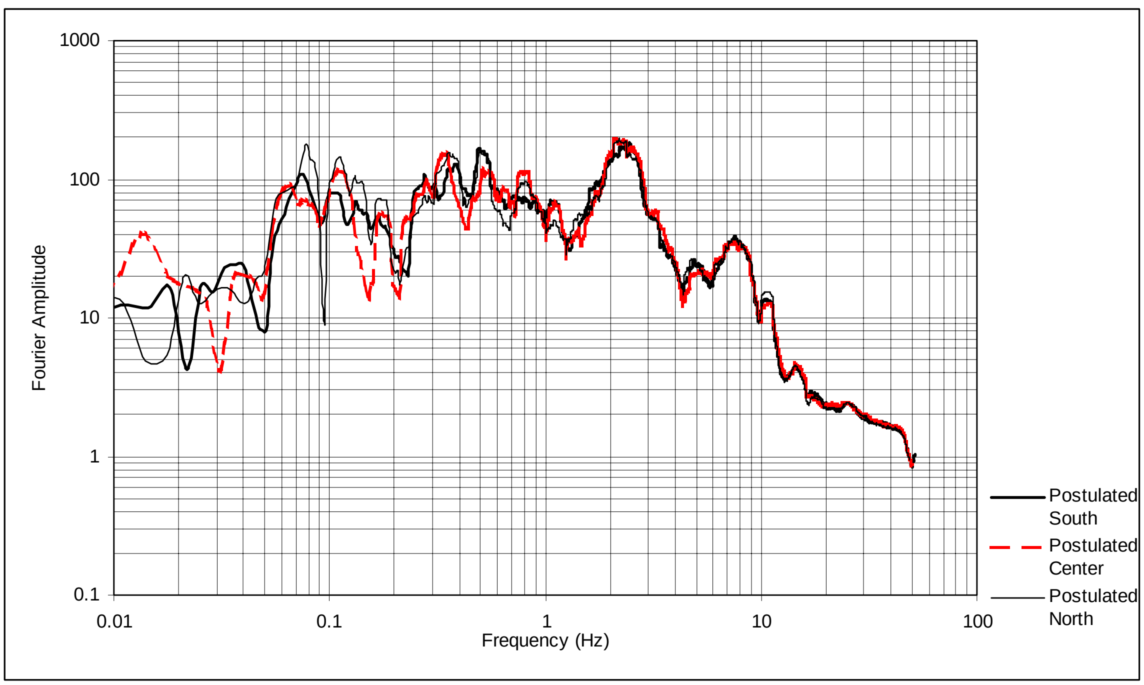


Fig. 12 Fourier amplitude spectra of the synthetic accelerogram at station COL (Guadalajara) surface hypothetical southern, central, and northern Mw=8.5 earthquake scenarios

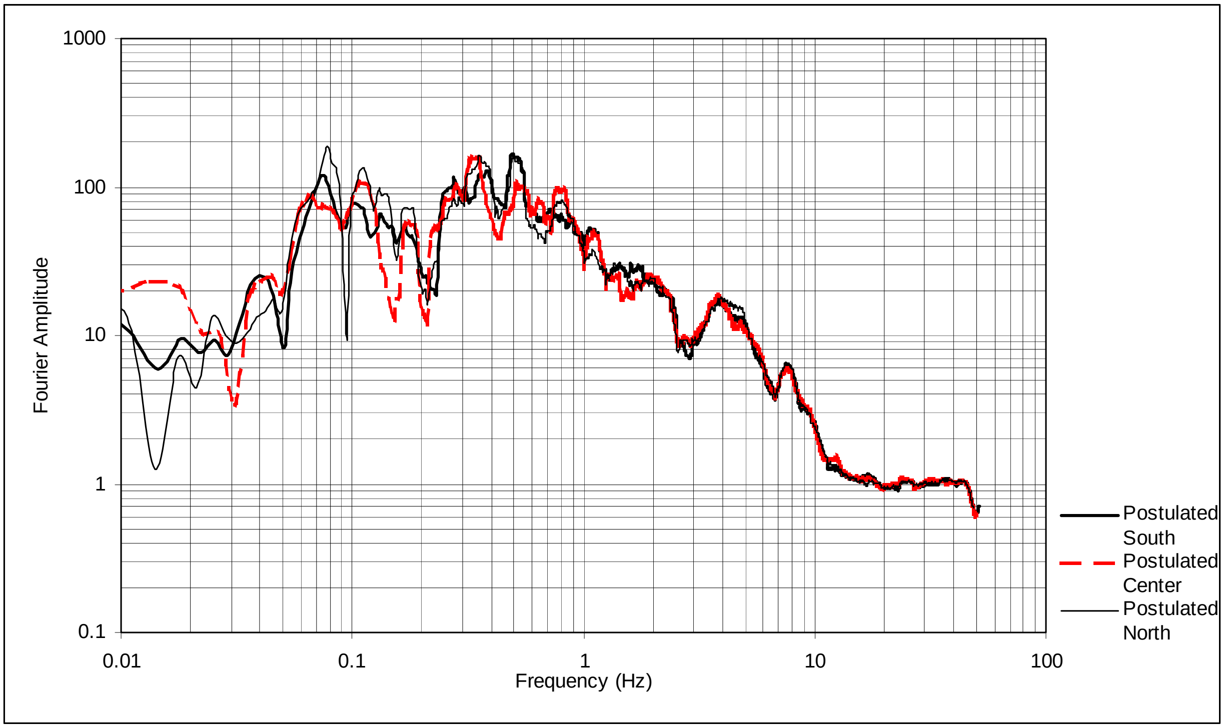


Fig. 13 Fourier amplitude spectra of the synthetic accelerogram station COL (Guadalajara) downhole hypothetical southern, central, and northern Mw=8.5 earthquake scenarios

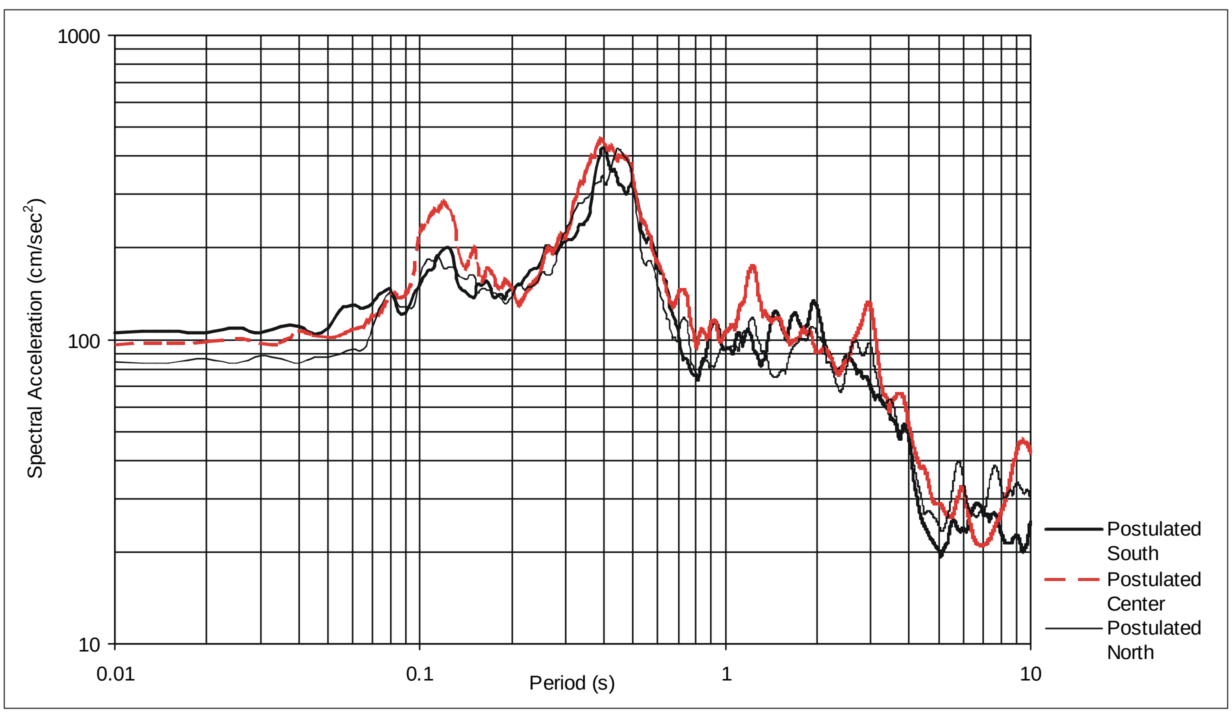


Fig. 14 Response spectra of the synthetic accelerogram station COL (Guadalajara) surface hypothetical southern, central, and northern Mw=8.5 earthquake scenarios

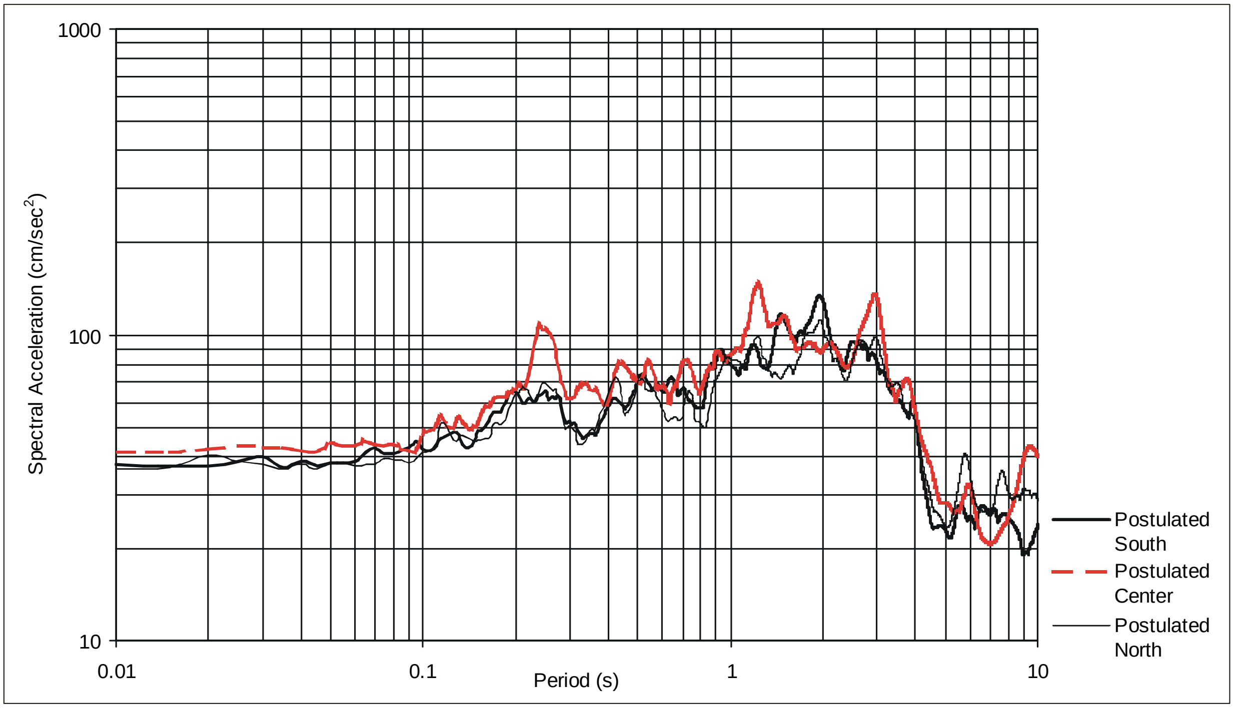


Fig. 15 Response spectra of the synthetic accelerogram station COL (Guadalajara) downhole hypothetical southern, central, and northern Mw=8.5 earthquake scenarios

From Fig. 15 it can be concluded that for COL 35m rock depth, the spectral acceleration at low periods fluctuates from about 36 to 42cm/s^2, that for a period of about 0.25s the central scenario reaches a value of about 100cm/s^2, while for the northern and southern scenarios are of only 70cm/s^2 . For periods between 1 and 3s the three response spectra reach a value of about 150cm/s^2, for higher periods the corresponding values are smaller than 70cm/s^2.

CONCLUSIONS

From the computation of the broadband synthetic accelerograms at stations Manzanillo (MZ), Ciudad Guzman (CG) and Guadalajara (COL), by combining low-frequency (<1 Hz) finite-difference and high-frequency (>1 Hz) Empirical Green Function simulations, for the Mw 8 09/10/95 Colima-Jalisco earthquake, it can be concluded that the synthetics show a good spectral fit to the observed accelerograms for the entire modeled bandwidth, including local soil effects for COL. The proposed hybrid method was also applied to obtain synthetics at Guadalajara (COL) at the surface and at 35m rock depth, for a postulated Mw 8.5 earthquake, similar to the Ms 8.2 3rd of June 1932 earthquake. Three rupture scenarios were analyzed. The maximum computed accelerations were of about 100cm/s^2 and 40cm/s^2 for the surface and 35m rock depth, respectively, and the corresponding maximum response spectra accelerations were of 450cm/s^2 and 150cm/s^2. From those results we conclude that our hybrid method allows the generation of more reliable estimates of seismic hazard in regions such as the Colima-Jalisco.

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