

# Modeling of Broadband Strong Ground Motions Observed for the 09/10/95, Mw=8 Colima-Jalisco Earthquake

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## Abstract

**We compute broadband synthetic accelerograms at stations located in the near (Manzanillo, MZ), intermediate (Ciudad Guzman, CG) and far fields (Guadalajara, COL) by combining low-frequency (<0.5 Hz) finite-difference and high-frequency (>0.5 Hz) Empirical Green Function simulations for the Mw 8 09/10/95 Colima-Jalisco (CJ) earthquake. The synthetics show a good spectral fit to the observed accelerograms for the entire modeled bandwidth, including local soil effects for COL. Our hybrid method allows the generation of more reliable estimates of the seismic hazard in regions such as the CJ.**

## Introduction

The high seismic potential of the Colima-Jalisco (CJ) region in Mexico has been demonstrated over the last several centuries. Recently, large shallow thrust subduction earthquakes occurred the 3rd and 18th of June 1932, with Ms of 8.2 and 8, respectively, as well as on the 9th of October of 1995 (Mw 8, Ms 7.4, Fig. 1). It is therefore important to estimate the seismic hazard in the CJ region for future large events. Due to limited availability of empirical ground motion observations, theoretical simulations constitute the best method to provide such information. For example, Olsen (2000[9]) computed the long-period (>2s) 3D response of the Los Angeles basin for nine different earthquake scenarios. Although the simulation of the 1994 Northridge earthquake reproduced the recorded particle velocities relatively well, the results were limited by the upper frequency limit of 0.5 Hz. A significant part of the seismic hazard for large earthquakes is due to the ground motion at higher frequencies.

In order to obtain better estimates of the seismic hazard at both long and short periods at sites of the CJ region we use a hybrid technique to generate broadband synthetics for the 09/10/1995 earthquake. The technique combines low-frequency simulations incorporating a 2.5D model of the crustal structure with higher-frequency synthetics computed from smaller, recorded accelerograms. Our broadband synthetics are validated by comparisons with high-quality free-field and downhole strong motion data for the the 9th of October of

1995 event at stations Manzanillo (MZ), Ciudad Guzman (CG), and Guadalajara (COL), with epicentral distances to the mainshock in the near (35 km), intermediate (140 km) and far (240 km) fields, respectively. 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 deployed (Chavez, 1993[2], 2000[3]) and in the second largest town of the state of Jalisco (Ciudad Guzman).

The paper is divided into four parts. In the first 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 are presented in the second part, in the third part a brief discussion of the broadband modelling technique is included, and the modeling data and results are presented in the fourth part.

## **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. 1. The age of the Rivera plate varies between 10 and 15 Ma 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. This pattern is supported by the observation that in the 20th century, 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. In contrast, the most recent known Giant earthquake in the Cascadian subduction zone was in 1700.

Fig. 1 shows 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 event are very similar to the average mechanism of the mainshock, 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.

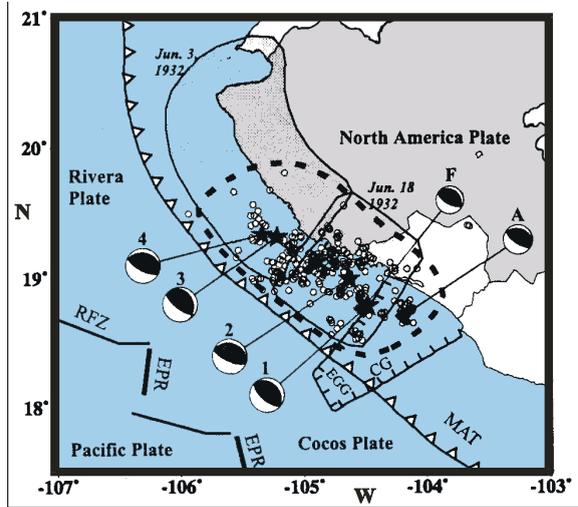


Fig. 1 Rupture area for June 3 and June 18 1932 earthquakes, epicentral locations and focal mechanisms for the Oct 9 1995 mainshock (1), the foreshock F (Oct 6), the largest aftershock A (Oct 12), the outline of the aftershock zone (dashed), as well as 4 subevents (1-4) interpreted as the source for 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., GRL, 1998[4]).

Based on gravity observations, constrained by seismicity data, Bandy et al. (1999[1]) proposed a model of the geological structure of the subducting and continental plates in the CJ region (Fig 2). Among other findings, they proposed that the thickness of the continental crust averages 38 km and thickens gradually up to 44 km towards the continent. They also concluded that the density of the upper part of the subducting plate increases below a depth of 30 km, probably reflecting a phase transition of basalt to eclogite.

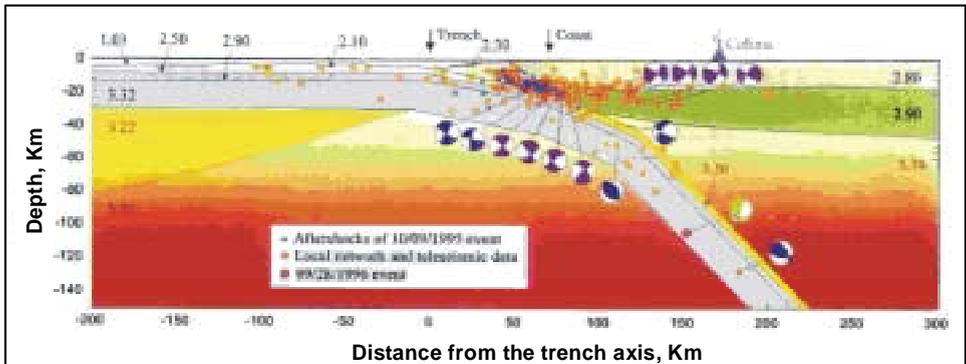


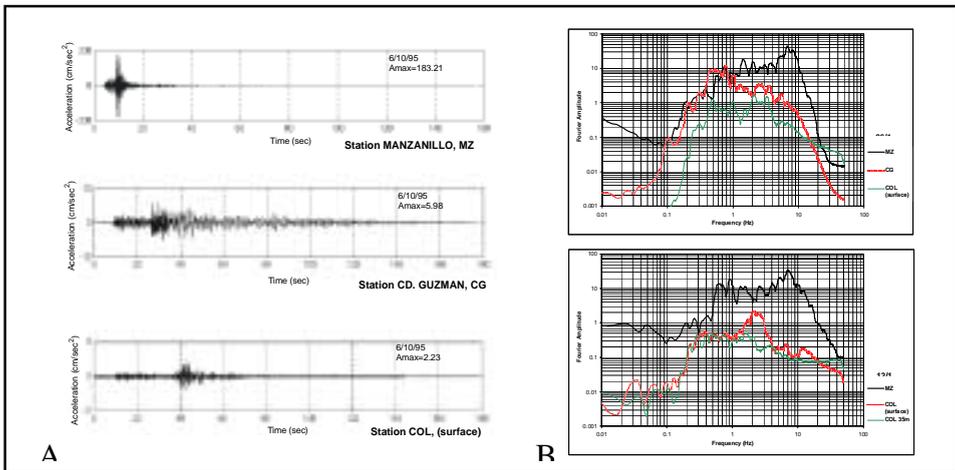
Fig. 2 Recent seismicity and the geometry and densities (in g/cm<sup>3</sup>) of the subducting and continental plates for a 500 km profile in the region of interest. The location of the profile is shown in Fig. 4 A. (Modified from Bandy et al., Geofisica Int., 1999[1]).

Fig. 2 shows that the dip of the subducting slab varies from 90 (surface) to 160 (20 km depth), gradually increasing to about 500 at depths below 50 km. The continental crust consists of an upper layer with a density of 2.8 g/cm<sup>3</sup>, a lower layer with a density of 2.9 g/cm<sup>3</sup>, and a thin sedimentary layer with a density of 2.3 g/cm<sup>3</sup> in the continental slope zone. Bandy et al. (1999[1]) modeled the Rivera plate as consisting of three layers with densities of 2.5, 2.9 and 3.32 g/cm<sup>3</sup>, and the upper mantle with a density of 3.3 g/cm<sup>3</sup>.

## 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. 3). The three stations are on top of soil layers and the downhole accelerograph is in basaltic rock at 35 m depth.

In Fig. 3 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. Note the attenuation with distance from the epicenter of the recorded signals, MZ (35 km), CG (140 km) and COL (240 km). Also note the large amplitudes and high frequency content of the MZ signal, compared with the ones at CG and COL, and the site effect between 2 and 3 Hz for the aftershock records in COL (Chavez, 2000[3]).



Figs. 3.(A) Accelerograms observed in the West-East (W-E) direction at stations MZ, CG and COL (surface) for the 6/10/95 earthquake. (B) Fourier Amplitude spectra of acceleration for the 6/10/95 event stations MZ, CG and COL (surface), and for the 12/10/95 event stations MZ, COL (surface) and COL (downhole).

## Broadband modeling procedure

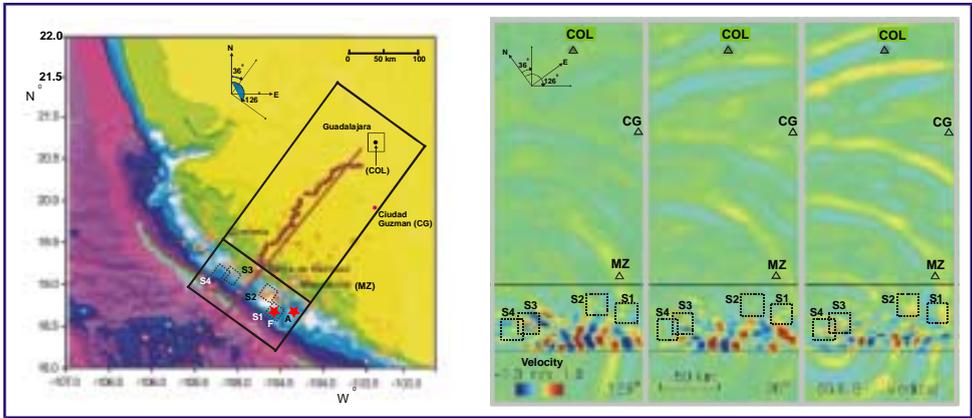
A hybrid procedure combining long period and high frequency simulations was developed for the computation of broadband synthetics of the accelerograms observed at stations MZ, CG and COL for the 09/10/1995 Mw 8 earthquake. The long period ( $<0.5$  Hz) wave field was simulated using a fourth-order staggered-grid finite-difference method (Olsen (1994[8])). The earthquake source is implemented in the finite-difference grid by adding  $-M_{ij}/V$  to  $S_{ij}$ , where  $M_{ij}$  is the  $ij$ th component of the moment tensor for the earthquake,  $V$  is the cell volume, and  $S_{ij}$  is the  $ij$ th component of the stress tensor on the fault at time  $t$ .

The high frequency ( $\geq 0.5$  Hz) synthetics were generated with the Empirical Green function (EGF) method (Irikura, 1986[7]). 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 assumption of the EGF method is that large and small events follow the  $\omega^2$  model and generate a constant stress drop, implying that the source displacement spectrum has a flat level at low frequencies and an omega-square decay at high frequencies beyond the corner frequency.

We follow the suggestion of Frankel (1995[5]) as well as Hartzell et al. (1996[6]) 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 are combined using matched filters.

## Modeling data and results

Long-period ( $>2$  s) wave propagation in a 2.5-D model of the subduction zone constrained by gravity and seismicity data (Fig. 2) have been simulated using a four sub-event 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.1,4A, Table 1B) and the W-E records at MZ, CG and COL (Fig. 3) of events F and A. The area of the elementary source ( $a$ ) was computed by the expression:  $a = (m_0/M_0)^{2/3} A$ , where  $m_0$ ,  $M_0$  and  $A$  are the seismic moments of the EGF event, of the subevent and the area of the latter, respectively. The low- and high-frequency synthetics were combined using matched filters. Figs. 5 and 6 show a comparison of the observed and synthetic accelerograms and of their corresponding Fourier Amplitude spectra for the W-E components of the 09/10/95 earthquake. The comparison is satisfactory.



Figs. 4. (A) 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. (B) Snapshot of the velocity wavefield propagation, for  $f = 0.5$  Hz, in the surface of the domain of interest. Two horizontal and the vertical ground motions are presented.

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 <sup>3</sup> ).	1000
Number of grid points 126° direction.	273
Number of grid points 36° direction.	591
Number of grid points vertical direction.	272
Number of time steps.	1428
Simulation time (sec).	250

A

Event	Depth (km)	Strike (°)	Dip (°)	Rake (°)	Mo (Nm)	Mw
Foreshock	18	314	29	104	$4.28 \times 10^{17}$	5.75
Mainshock	24	306	26	94	$1.84 \times 10^{19}$	7.50
Aftershock	21	290	25	76	$7.75 \times 10^{17}$	5.92
Subevent 1	28	320	28	98	$4.39 \times 10^{18}$	
Subevent 2	31	286	25	84	$4.92 \times 10^{18}$	
Subevent 3	19	338	25	119	$4.13 \times 10^{18}$	
Subevent 4	20	282	26	75	$5.00 \times 10^{18}$	

B

Table 1. (A) Parameters for the 2.5D model. (B) 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]).

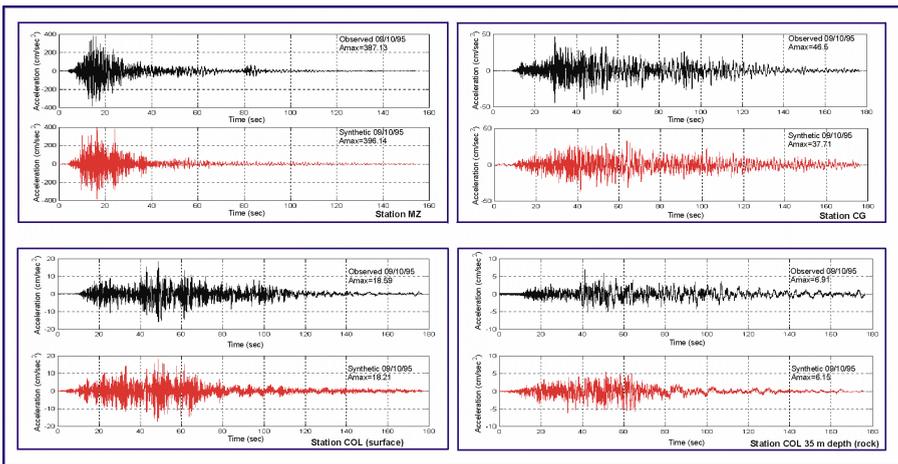


Fig. 5 Comparison of observed and synthetic accelerograms in the W-E direction at MZ, CG and COL's surface and downhole stations, for the 09/10/95 earthquake.

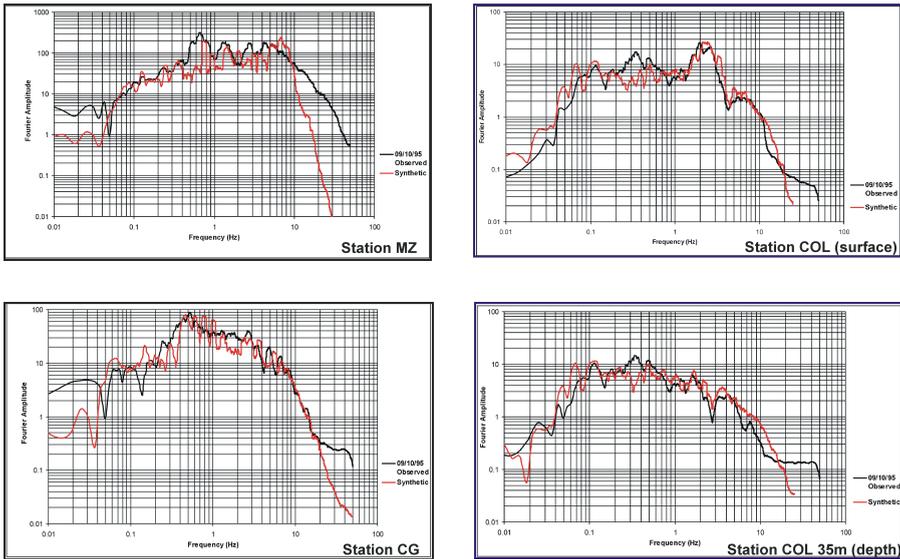


Fig. 6 Comparison of the Fourier Amplitude spectra for the observed and the synthetic accelerograms of Fig. 5.

## Conclusions

We have computed broadband synthetic accelerograms at stations Manzanillo (MZ), Ciudad Guzman (CG) and Guadalajara (COL) by combining low-frequency (<0.5 Hz) finite-difference and high-frequency (>0.5 Hz) Empirical Green Function simulations for the  $M_w$  8 09/10/95 Colima-Jalisco earthquake. The synthetics show a good spectral fit to the observed accelerograms for the entire modeled bandwidth, including local soil effects for COL. Our hybrid method allows the generation of improved estimates of seismic hazard in regions such as the Colima-Jalisco.

## Acknowledgments

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