# Calibration of Strong-Motion Models for Central America Region

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**ABSTRACT :**

We present the results of a study aimed at choosing the more suitable strong-motion models for seismic hazard analysis in the Central America (CA) Region. After a careful revision of the state of the art, different models developed for subduction and volcanic crustal zones, in tectonic environment similar to those of CA, were selected. These models were calibrated with accelerograms recorded in Costa Rica, Nicaragua and El Salvador. The peak ground acceleration PGA and Spectral Acceleration SA (T) derived from the records were compared with the ones predicted by the models in similar conditions of magnitude, distance and soil. The type of magnitude ($M_s$, $M_b$, $M_w$), distance ($R_{hyp}$, $R_{rup}$, etc) and ground motion parameter (maximum horizontal component, medium, etc ) was taken into account in the comparison with the real data. As results of the analysis, the models which present a best fit with the local data were identified. These models have been applied for carrying out seismic hazard analysis in the region, in the frame of the RESIS II project financed for the Norway Cooperation Agency (NORAD). .

**KEYWORDS:** Central America, accelerograms, ground motion, spectral acceleration, seismic hazard

## 1. INTRODUCTION

Central America is located in the western limit of the Caribbean plate. This plate is surrounded by the North American, Cocos, Nazca and South American plates. The Cocos-Caribbean contact is convergent or of subduction. Nazca and Caribbean plates are limited by the Southern Panama Deformed Belt (SPDB). The transcurrent faults of Polochic-Motagua-Chamelecón (PMCHF), Panama Fracture Zone (PFZ), and the Atrato Suture Zone (ASZ) form the limits of the North American-Caribbean plates, Cocos-Nazca plates and Caribbean-South America plates, respectively (figure 1). Other important tectonic units are: the Hess Scarp, Nicaragua Depression and the southern Panama Fault Zone. Recently, it has been proposed that the southern half of Costa Rica, Panama and Northwest Colombia constitute an individual microplate named Panama microplate. In this region, relative plate motions vary between 2 and 9 cm/year are accompanied by active volcanism and high shallow and intermediate seismicity. Regarding the attenuation of ground motion, we can distinguish three tectonic environments: crustal zones, subduction interface and subduction inslab zones, since the effects of the wave propagation led to different attenuation of energy with distance in the three sources.

During the last 500 years, numerous destructive earthquakes have occurred. These events presented large and moderate magnitudes ($5.5 \geq M \geq 8.0$) and were related to Interplate and Intraplate sources. This intense regional seismic and tectonic activity has led to the installation of strong-motion stations since the middle XX century. Although the operation periods of local networks differ, they can be considered stable from the 80s in Costa Rica and El Salvador and from the 90s in the rest of Central American countries. The operation of these networks has facilitated the recording of a significant amount of ground-motion data and the development of several strong-motion models in terms of peak ground accelerations and spectral accelerations (Climent et al., 2007), which have been used for seismic hazard studies in the region. However, any spectral model for the three environments have not been developed at present.

In a worldwide context, the expansion of strong-motion networks lead to an increase of the amount of strong-motion records available, both in number and in quality. Consequently, it has been possible to develop more complete and refined strong-motion models. These worldwide models are usually used in areas were no attenuation models exist or in ones where its own models have some deficiencies due to limitations in the data base.

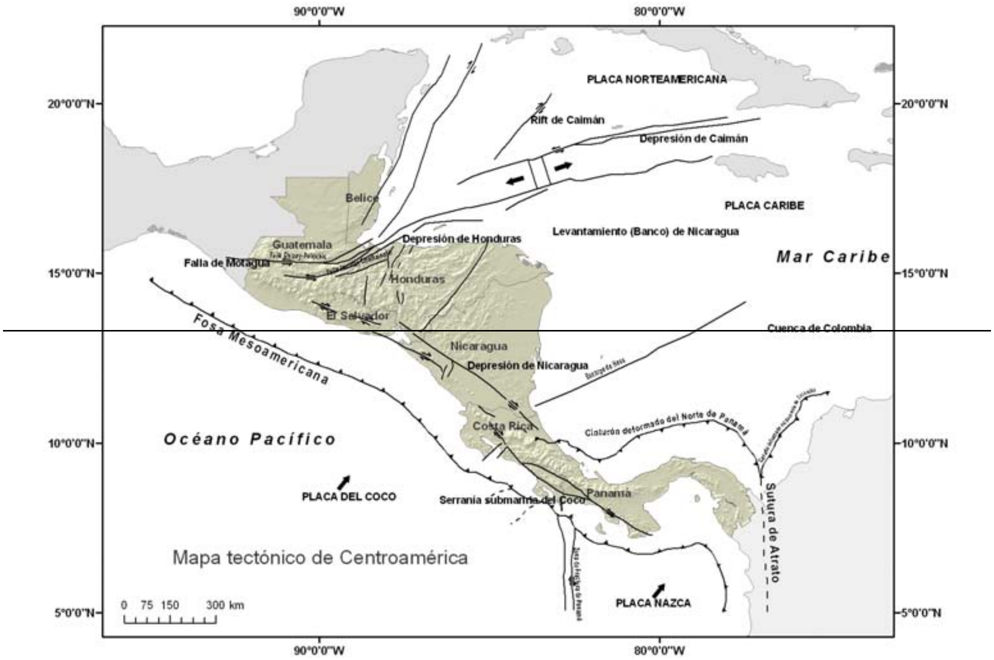


Figure 1 Seismotectonic framework of Central America.

Given the availability of these models, it would be interesting to select some of them which have some tectonic affinity with the study area and check whether they adjust to existing attenuation patterns in Central America. The selected models could complement the available regional in future seismic hazard assessment studies.

Selecting ground-motion models that reflect realistically the attenuation in Central America, according to instrumental observations, is particularly important in hazard evaluations because the attenuation is the factor that presents the highest impact in hazard results (higher than seismic parameters and sources geometry), as derived from sensibility studies.

The selection of a ground motion model must consider the influence of tectonics, because the expected attenuation in crustal zones differs greatly from subduction zones, and within the later ones, between interface and inslab zones. According to this procedure, three sets of extraneous ground-motion models (crustal, inslab and interface) are considered and contrasted with instrumental data classified in the same manner. The strong-motion database complied for this work contains data from El Salvador, Costa Rica and Nicaragua.

The methodology followed is based on the direct comparison between PGA and SA values extracted from actual records with the corresponding acceleration values predicted by the selected ground-motion models for similar magnitude, distance and soil conditions. Residuals between observed and predicted values for PGA, SA(0.3sec) and SA(1sec) are calculated. These residuals are plotted as a function of distance and magnitude analyzing their deviation from the mean value.

Theoretically, if one model fits finely the data, the associated residuals should present zero mean ($\mu$) and constant variance ($\sigma^2$). This is the main criterion for determining the goodness of a model fit, together with the percent of observations lying within the confidence intervals $\mu \pm 1\sigma$ y $\mu \pm 2\sigma$.

## 2. MODELS DEVELOPED IN CENTRAL AMERICA

As Costa Rica and El Salvador are the countries with the more stable strong-motion networks during the last 30 years in Central America, they already have local strong-motion models and they supply the largest amount of data for the development of ground-motion models at regional scale (Climent et al., 2007).

By the end of the 80s, when strong-motion data from the Ms 5.4 1986 San Salvador was available, Algermissen et al. (1988) and Alfaro et al. (1990) proposed the first PGA attenuation models for El Salvador. A new PGA model was developed by Singh et al. (1993) to be used in the seismic hazard analyses that served as basis for the new Salvadorian Seismic Code. Subsequently, Bommer et al. (1996) proposed a subduction atenuation model for spectral acclelerations using Salvadorian data. Recently, Cepeda et al. (2004) used the records of the 2001 events of El Salvador to develop PGA and SA attenuation models for shallow faulting sources and inslab subduction sources.

In 1992, all the ground-motion information available in Central America was collected and put in uniform format by Taylor et al. (1992), who developed the first PGA attenuation model for the entire Central American region. This database was augmented and improved by Climent et al. (1994), who calculated the first ground-motion model including spectral ordinates for the entire area. This was slightly modified by Dahle et al. (1995). In both models, data from shallow sources and subduction sources were mixed. Later Schmidt et al. (1997) enlarged and improved this database and developed a spectral attenuation model for Costa Rica, separating subduction and shallow faulting sources. New efforts are under development to update the regional strong-motion database, and it is likely that new regional strong motion models become available soon.

## 3. MODELS USED IN THE ANALYSIS

In addition to local attenuation relations, a number of published ground-motion models are considered in our study because they apply to seismotectonic settings similar to those recognized in Central America, characterized by active plate convergence and periodic occurrence of destructive earthquakes in volcanic environments. For this study, only models predicting both PGA and SAs, that can be used for seismic hazard applications, are considered. Table 1 summarizes these models.

## 4. DATA BASE FOR MODELS CALIBRATION

The data base used for models calibration counts with data supplied by these strong motion networks: Servicio Nacional de Estudios Territoriales (SNET) from El Salvador, Instituto Nacional de Estudios Territoriales (INETER) from Nicaragua, Instituto Costarricense de Electricidad (ICE) from Costa Rica and Laboratorio de Ingeniería Sísmica (LIS-IINI-UCR) from Costa Rica University. This data base includes mainly digital records of seismic events occurred from 2000 to 2007 with $M_w$ magnitudes ranging between 4.0 and 7.7, epicentral distances between 1 and 480 km, and focal depths between 1 and 200 km. Some analogical records corresponding to strong events occurred in earlier years (El Salvador, years 82, 83, 87, 86, 88 and 89; Costa Rica, years 90 and 91) completed the data base. Figure 2 shows graphically the magnitude and distance ranges covered by the ground-motion data used in the analysis.

Table 1 Models used in the analysis

| Equation | Data Base | Dependent variable Component | Source type | Distance (km) | $M_w$ |
|---|---|---|---|---|---|
| Youngs *et al.* (1997) (YOUN97) | Worldwide | Geometric mean | Interface, Inslab | 10 - 500 | 5,0 - 8.2 |
| Atkinson and Boore 2003(AYB03) | Worldwide | Both horizontal (random) | Interface, Inslab | 10-400 | 5,0 - 8,3 |
| Garcia *et al.* (2005) (GAR05) | Mexico | Media cuadrática | Inslab | 4 - 400 | 5,2 – 7,4 |
| Cepeda *et al.*(2004) (CEP04) | El Salvador | Random<br>Geometric mean | Inslab<br>Crust | 10 – 400<br>0-100 | 5,0 – 8,3<br>5,1 – 7,2 |
| Climent *et al.* 1994 (CLI94) | Central America, Mexico | Largest horizontal | Interface, Shallow crust | 5 - 400 | 4,0 - 8,0 |
| Zhao *et al.* (2006) (ZH06) | Japan | Geometric mean | Interface, Inslab, shallow crust | 10-300 | 5,0 – 8,2 |
| Spudich *et al.* (1999) (SEA99) | Worldwide | Geometric mean | Shallow crust | 0 - 100 | 5,1 – 7,2 |
| Schmidt *et al.* (1997) (SCH97) | Costa Rica | Largest horizontal | Shallow crust | 6 - 200 | 3,7 – 7,6 |

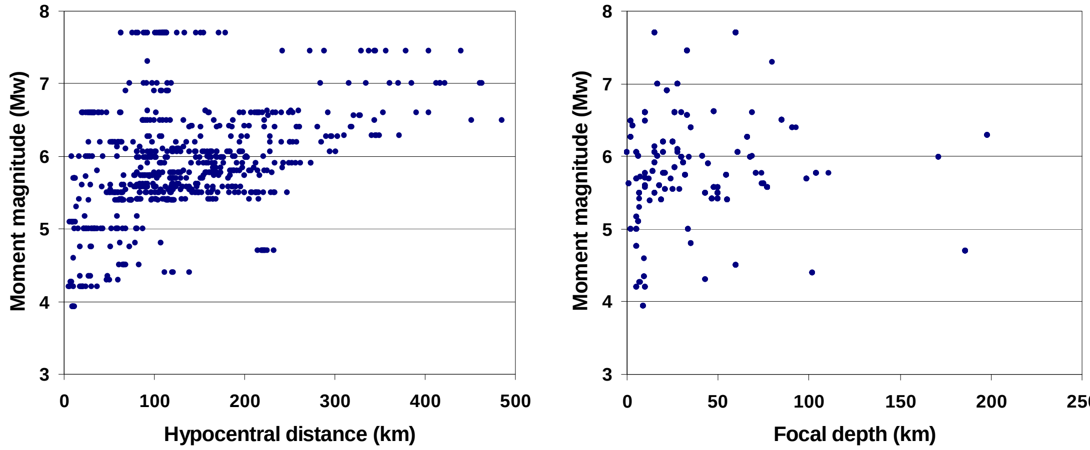


Figure 2 Magnitude distribution with respect to focal depth and hypocentral distance corresponding to the records used in the analysis.

The compiled database contains 681 PGA values (on rock and soil sites) related to 101 events, and 268 values of SA (0.3sec) and of SA (1sec) corresponding to 64 events (Table 2). From the total set, 313 PGA observations (41% of the total) and 149 SA observations (55 % of the total) were recorded on rock or firm soil conditions. The subsequent analyses will be carried out for this soil conditions.

The strong motion database was tabulated in a spreadsheet including the seismological information of each earthquake and of the recording stations, together with the corresponding recorded acceleration values (PGA, SA(0.3sec) and SA(1sec)). To obtain these values, the strong motion records were corrected and processed in each country, using Kinemetrics SMA software. A 0.12 - 45 Hz band-pass filter was applied to the records. Table 2 presents a summary of statistics, disaggregated by country and related seismic source.

Table 2 Amount of seismic events and records supplied by each country (complete data base)

| | Costa Rica | | | Nicaragua | | | El Salvador | | |
|---|---|---|---|---|---|---|---|---|---|
| | # Eqs | # records | | # Eqs | # records | | # Eqs | # records | |
| | | **PGA** | **SA** | | **PGA** | **SA** | | **PGA** | **SA** |
| Interface | 8 | 54 | 30 | 11 | 45 | 7 | 8 | 75 | 0 |
| Inslab | 7 | 60 | 18 | 12 | 56 | 8 | 14 | 149 | 12 |
| Shallow crust | 13 | 107 | 107 | 12 | 61 | 60 | 16 | 74 | 26 |

Three sub-databases, one per type of source (interface, inslab and shallow crust) and considering the class of soil, were prepared. The data from each group were used for comparison to the selected attenuation models (see next section). Soil categories at recording sites were sorted according to the geological and geotechnical information available and following the NEHRP Provisions classification. Soil class B and C sites were considered as *rock* sites.

The association of an earthquake to a specific source was done according to seismic reports or using the focal depth: events with focal depths lower than 25 km were taken as *shallow crustal* events, from 25 km through 45 km are considered of *interface subduction* events and deeper than 45 km were considered as *intermediate subduction, inslab* events. Such classification is based on results from Costa Rica (Sallares, *et al.*, 2000; DeShon *et al.*, 2006; Warren, *et al.*, 2008), observations obtained in Japan (Zhao *et al.*, 2006), and worldwide (interface events occur at depths shallower than 50 km, Tichelaar y Ruff, 1993; Youngs *et al.*, 1997).

## 5. CONTRAST OF MODELS: ANALYSIS OF RESIDUALS AND RESULTS

As commented above, ground-motion models selection was initially based on the comparison between different graphs representing observed and predicted strong-motion data together. A problem that arises in this kind of comparisons is the variability on magnitudes. In this case, different intervals of magnitude should be used to carry out the comparisons. As direct visual comparison between observed and predicted PGA and SA values gets complicated, we opted for complete the study with an analysis of residuals, defined as the difference of the natural logarithms of observed ($y$) and predicted ($Y^*$) values for similar magnitude, distance and soil conditions:

$$\text{Residual} = \ln y - \ln Y^*$$

A great amount of graphs were composed for the analyses of residuals, considering the type of source, the attenuation model and the ground motion component (PGA, SA) to analyze. However, only a few illustrative cases are shown in this paper. As an example, figure 3 shows the distribution of residuals as a function of distance for subduction interface sources (full lines represent the deviation of each model, $\mu \pm 1\sigma$). The interpretation of these graphs allows establishing certain conclusions about the good of fitness of observations to a given model. For instance, models CLI94 and AYB03 present a great dispersion of residuals as compared to the dispersion of the models, remaining a large percent (52 %) of them above the $\mu\pm1\sigma$ interval. Accordingly, these models are excluded for hazard analyses. For this type of source (Interface), models ZH06 and YOUN97 fit better the instrumental observations, with more uniform variations within the $\pm1\sigma$ limits: presenting ZH06 a 65% and YOUN97 a 74% of residuals within these limits. It is noteworthy mentioning that residual patterns for SA(1s ) are very similar to PGA residual patterns.

For inslab and shallow crustal sources a similar procedure was followed. For shallow crustal sources, PGA predictions of models ZH06, CLI94, SCH07 and SEA99, present a negative bias out of the $-\sigma$ limits. Hence, their use implies a hazard overestimation for distances shorter than 200 km. It was also observed that models SCH07, ZH06 and CLI94 show larger percents of amount of residuals within the $\pm 1\sigma$ limits. Equation CEP04 presents a more uniform distribution of residuals, for PGA with respect to the zero mean, with a 45% of residuals within the $\pm$ 1$\sigma$ limits, and presenting a larger positive bias. Then, its use involves an underestimation of hazard.

The use of CEP04 presents the limitation that it was only developed for spectral ordinates of 0,3 and 1,0 seconds. In the case of 1.0 s spectral residuals, models SCH97, CLI9, ZH06 and SEA99 present the largest amount of residuals within the $\pm 1\sigma$ limits and a fair uniform distribution with respect to zero mean. It is also important to note that the use of model SCH97 is limited because it increases hazard for return periods higher than 1000 years.

For inslab sources (deep subduction), models SEA99, ZH06 and GAR05 for PGA are the ones presenting a better resolution of residuals, with percents of 57%, 64% and 50% of them within the $\pm 1\sigma$ limits. Equation AYB03 presents a positive bias for most distances and CEP04 a negative one. For the 1s spectral component, AYB03 and GAR05 are the ones that better adjust, with 68 % and 47 % of residuals within the $\pm 1\sigma$ interval. Models CEP04, ZH06 and SEA99 show a negative bias.

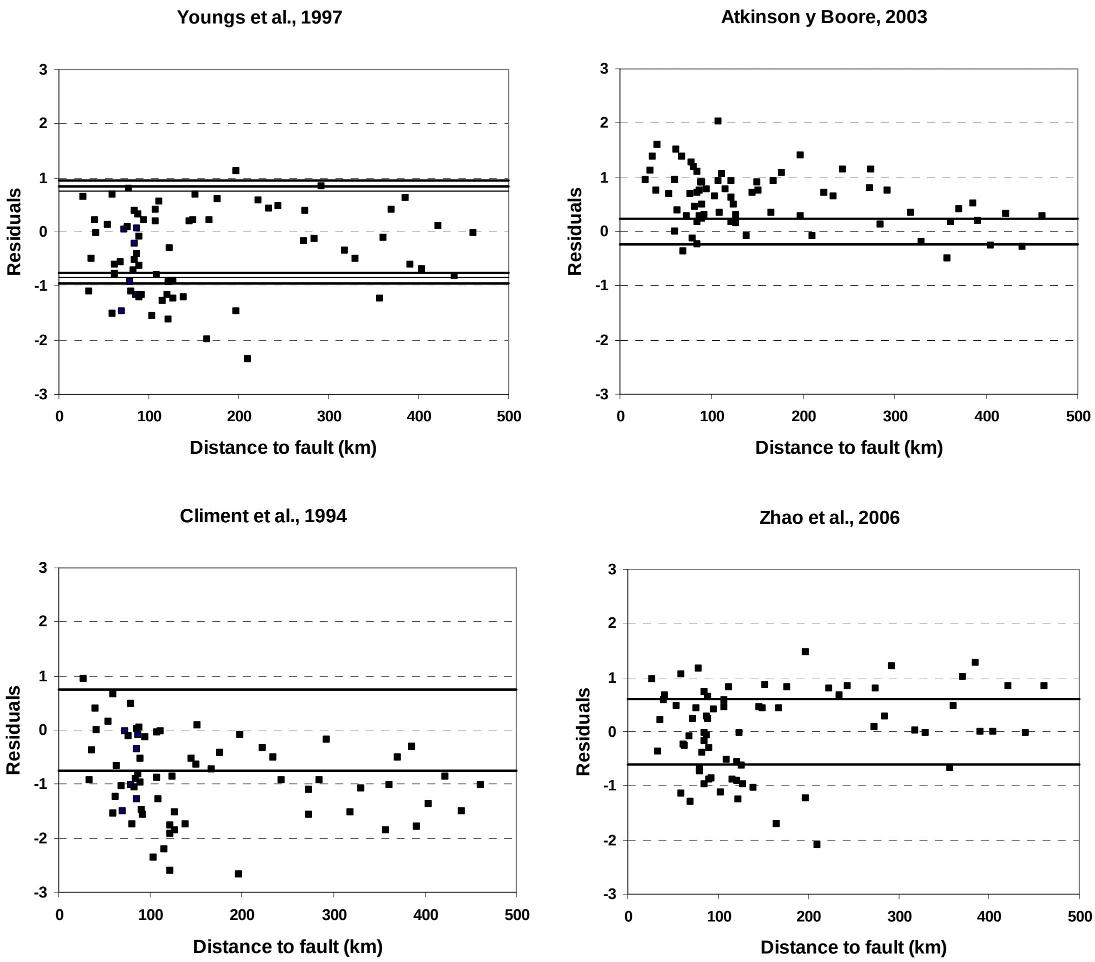


Figure 3. Distribution of residuals with distance corresponding to subduction interface sources. Dots represent PGA residuals and solid lines stand for the $\mu \pm 1\sigma$ interval of the model. For model AYB03, $\log_{10}$ is used.

## 6. CONCLUSIONS AND RECOMMENDATIONS

A ground-motion database containing instrumental data from Central America was used for contrasting observations and predictions of ground-motion models developed for other regions with seismotectonic affinity to Central America. The following conclusions can be drawn:
For shallow crustal sources, the use of models ZH06, CLI94 and SEA99 as well as of models SCH97 and CEP04 within the limitations cited above, is recommended. For subduction interface sources the use of models ZH06 and YOUN97 is recommended. Finally, for inslab subduction sources models ZH06, SEA99 and GAR05 is recommended.

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