**Development of Earthquake Ground Motion Relations for
Puerto Rico**

Submitted By
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The Faculty of Graduate Studies and Research
In partial fulfillment of requirements for the degree of
Doctor of Philosophy

Department of Earth Science,
Carleton University
Ottawa, Ontario, Canada
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In partial fulfillment of requirements for the degree of

Doctor of Philosophy

Chair, Department of Earth Science

Thesis Supervisor

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Abstract

Empirical ground motion relations are a key input to seismic hazard analysis. Ground motion relations describe the peak ground amplitudes and frequency response characteristics of seismic waves as a function of magnitude and distance. This thesis provides the first region-specific ground motion relations for Puerto Rico. This work is important because Puerto Rico is a region of high seismic hazard and dense population.

Due to a paucity of data at small distances and large magnitudes, there are insufficient Puerto Rico ground motion data to directly obtain ground motion relations for magnitudes and distances of most engineering interest. However data from moderate events can be used in conjunction with a seismological model to develop the relations. Fourier amplitudes and response spectra of Puerto Rico earthquakes of magnitude 3 to 5.5 have been analyzed to determine underlying regional model parameters. The regional data were used to determine key attenuation parameters, such as the quality factor Q , the duration of ground motion and generic site amplifications.

To overcome the incompleteness of the data set, stochastic finite fault modeling was applied to generate a set of generic artificial waveforms for different magnitudes and distances. In stochastic finite fault modeling a large fault is divided into N subfaults and each subfault is considered as a small point source. Ground motions of subfaults, each of which are calculated by the stochastic point-source method, are summed with a proper delay time in the time domain to obtain the ground motion from the entire fault. The input parameters for the simulations are based on the attenuation parameters obtained from the real recorded waveforms from small to moderate events.

Finite-fault simulations based on the stochastic method can be made using the computer program FINSIM. FINSIM has been validated in other regions, such as California, for which more data are available. FINSIM provides results that are comparable to the empirical attenuation relationships that can be obtained by regression analysis of a large strong motion database. Nevertheless, there are some conceptual aspects of FINSIM that should be improved, as described in this thesis.

A new approach has been introduced in the stochastic finite fault modeling based on the concept of the “dynamic corner frequency” (where the corner frequency is a parameter that controls spectral shape). In this approach, the corner frequency is a function of time, and the rupture history controls the frequency content of the simulated time series of each subfault. As the rupture propagates, the number of ruptured subfaults increases and the corner frequency of the subfaults decreases, approaching the corner frequency of the entire fault plane at the end of rupture. The advantage of this approach is that it allows realistic simulation of the frequency content and amplitudes of motion in an algorithm that is independent of the subfault size used in modeling. The new algorithm is named EXSIM.

The previous finite-fault simulation algorithm (FINSIM) has been applied to many real earthquakes and the approach has been calibrated to determine a “generic- “ finite fault model that produces good agreement between model and observations on average. The calibrated generic FINSIM model was used to calibrate the parameters of the new dynamic corner-frequency model, to ensure that it replicates the previous FINSIM results. Using the new concept of a dynamic corner frequency, motions were simulated for a wide range of earthquake magnitudes and distances, including far field, near-source, and regions of backward and forward directivity. The results of the dynamic corner

frequency method (EXSIM) are consistent with the results of previous calibrated finite-fault simulation methods (FINSIM), but offer conceptual advantages in application.

The calibrated EXSIM model was applied to generate a large suite of ground motions for Puerto Rico earthquakes for the magnitude-distance range of interest. The input parameters for the simulations are based on the attenuation parameters obtained from the moderate earthquakes records for Puerto Rico. The stochastic-model ground motion relations for Puerto Rico are validated using available seismographic data, and compared to ground motion relations for other regions. The recorded data were also used to validate the predicted ground motion relations.

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Original Contribution

This thesis contains only the original results of research conducted by the candidate under supervision of his mentor. The original contributions are summarized as follows:

Data retrieving from Puerto Rico Seismic Network and Puerto Rico Seismic Strong Motion network.

Calibration of Puerto Rico Seismic Network (PRSN) and derivation of instrument responses for some of the PRSN stations.

Data processing and signal analysis of the recorded earthquake waveforms for Puerto Rico region.

Estimation of attenuation parameters based on small to moderate earthquake waveforms to obtain the key regional parameters.

Development of a new approach to stochastic finite fault modeling based on the dynamic corner frequency. Calibration of the new approach with the previously calibrated stochastic finite fault modeling based on the static corner frequency.

Simulation of acceleration time series by stochastic finite fault modeling based on the regional attenuation key parameter of Puerto Rico.

Estimation of Puerto Rico ground motion relations for horizontal component of a generic soft rock site.

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Chapter 1: Introduction

1.1 Purpose of Study

In earthquake-prone regions, structural design of large or critical structures such as high buildings, dams, and bridges often involves quantitative dynamic analysis. Engineers need to know the earthquake ground motion spectra, and expected time histories of motion (waveforms) for their analysis. The maximum values of the ground motion such as peak ground acceleration, and peak ground velocity are of interest for some simple analysis, but for specific structural analysis, those parameters do not by themselves describe the intensity of shaking that structures or equipment experience. Other factors such as the duration and the frequency content of motion also influence the response of a structure. Peak ground motion describes only the maximum vibration amplitude. Duration of motion has an effect on severity of structural response to shaking. A ground motion with moderate peak amplitude but long duration may cause more damage than a ground motion with a larger peak amplitude and shorter duration. Frequency content and spectral shape of motion relate to the frequencies or periods of structural vibration. In a structure, ground motion is amplified the most when the frequency content of the ground motion and the natural vibration frequencies of the structure are close to each other. For these reasons, engineers typically use time histories or response spectra as input to structural analysis. Response spectra describe the maximum response of a damped single degree-of-freedom oscillator to an input time history.

The purpose of this project is to develop ground motion relations for Puerto Rico, describing the amplitude and frequency content of motion as functions of earthquake magnitude and distance. This work is important because Puerto Rico is a region of high seismic hazard and dense population. There are at present no region-specific ground

motion relations for Puerto Rico. Such relations are needed for earthquake design applications in Puerto Rico. The development blends empirical data analysis with ground motion simulation techniques, to gain insight into earthquake source and path processes in Puerto Rico.

Ground motions generated by an earthquake are usually simulated using one of three general approaches: purely theoretical, theoretical with empirical Green's functions, and empirical-stochastic. The first two are based on a theoretical description of faulting motion for a seismic source. The displacement caused by a slip dislocation across a fault surface is expressed as a space-time convolution of a slip function on the fault (i.e. source effect) with a Green's function, which represents the earth's impulse response (i.e. propagation-path effect). Methods that use Green's functions to describe path effects can be divided into two types: one is entirely theoretical and the other takes advantage of small-event records occurring near the source of a large earthquake to construct empirical earth responses (semi-empirical).

The third approach aims at simulating ground motion using a stochastic model, with underlying seismological model parameters as defined from past earthquake records. The parameters are typically defined from regression analysis of the characteristics of observed ground motion as a function of seismic magnitude, distance, local site effects and so on. In this approach, the key is the determination of an empirical source and attenuation model to be used as the input to a stochastic simulation method. The stochastic approach is preferred as a tool to develop regional ground motion relations, due to its simplicity and versatility.

1.2 Stochastic Ground Motion Model

1.2.1 Point Sources

The stochastic model is a widely-used tool to simulate acceleration time series and develop ground motion relations (Hanks and McGuire, 1981; Boore, 1983; Boore and Atkinson, 1987; Atkinson and Boore, 1995 and, 1997, Atkinson and Silva, 1997 and 2000). The goal of the method is to generate a transient time series whose spectrum matches, on average, a specified desired amplitude spectrum that has been randomized. The method begins by applying a window of specified duration to a time series of band-limited random white Gaussian noise with zero mean and unit variance. The windowed time series is transformed to the frequency domain and the amplitude spectrum of the noise time series is multiplied by the desired averaged amplitude spectrum. Transformation back to the time domain results in a time series whose average amplitude spectrum is the same as the desired spectrum. The application of this method clearly requires the specification of the target amplitude spectrum of the earthquake to be simulated. Therefore the stochastic method needs a model that specifies the Fourier spectrum of ground motion as a function of magnitude and distance. Often the acceleration spectrum is modeled by a spectrum with an ω^2 shape, where ω = angular frequency (Aki, 1967; Brune, 1970; Boore 1983). The “Brune model” spectrum is derived for an instantaneous shear dislocation at a point. The acceleration spectrum of the shear wave, $A(f)$, at hypocentral distance R from an earthquake is given by:

$$A(f) = CM_0 (2\pi f)^2 / [1 + (f/f_0)^2] \exp(-\pi f \kappa) \exp(-\pi f R / Q \beta) / R \quad (1.1)$$

where M_0 is seismic moment and f_0 is corner frequency, which is given by $f_0 = 4.9 \times 10^6 \beta (\Delta\sigma / M_0)^{1/3}$ where $\Delta\sigma$ is stress drop in bars, M_0 is in dyne-cm, and β is shear wave velocity in km/s (Boore, 1983). The constant $C = \mathcal{R}^{\theta\phi} F V / (4\pi\rho\beta^3 R)$, where

$\Re^{\theta\phi}$ = radiation pattern (average value of 0.55 for shear waves), F = free surface amplification (2.0), V = partition onto two horizontal components (0.71), ρ = density, β = shear wave velocity, and R = hypocentral distance (Boore, 1983). The term $\exp(-\pi f\kappa)$ is a high-cut filter to account for near-surface “*kappa*” effects, which describe the commonly observed rapid spectral decay at high frequencies. The quality factor, $Q(f) = [\log(e) \pi f] / (c \beta)$, is inversely related to the anelastic coefficient, $c(f)$. In the above equation the power of R in the attenuation term, $\exp(-\pi f R / Q \beta) / R$, is considered equal to 1, which is appropriate for body-wave spreading in a whole space. This value can be changed as needed in order to account for the presence of the postcritical reflections from the Moho discontinuity (discussed quantitatively in chapter 5). Figure 1.1 shows the Brune spectrum of equation 1.1, with no anelastic effect and no kappa factor for earthquakes of moment magnitudes 5 and 7. Figure 1.2 shows the Brune spectrum with anelastic effect ($Q=300 f^{0.5}$) but no kappa factor. Figure 1.3 shows the Brune spectrum with both the anelastic effects ($Q=300 f^{0.5}$) and kappa effects ($\kappa=0.03$).

We assume that the ground motion from small earthquakes at near-source distances ($R < 30\text{km}$) can be modeled as band-limited Gaussian noise with the acceleration spectrum of Eqn. 1. The spectrum is diminished with distance to account for empirically-defined attenuation behavior. In this research the applied window, $w(t)$, to the time series of band-limited random white Gaussian noise, is the shaped window of Saragoni and Hart(1974), which is a good representation of the average envelope of the squared acceleration time series. $w(t)$ is defined as follows:

$$w(t) = a t^b e^{-ct} H(t) \quad (1.2)$$

where $H(t)$ is the unit-step function. It is convenient to choose the shape parameters b , c such that: (1) the peak of the envelope occurs at some fraction of a specified duration T_w (not necessarily the end of the time series) and (2) the amplitude at time T_w is reduced to the fraction η of the maximum amplitude. These conditions yield

$$b = -\epsilon \ln \eta / [1 + \epsilon(\ln \epsilon - 1)] \text{ and}$$

$$c = b/\epsilon T_w, \text{ and}$$

$$a = (e/\epsilon T_w)^b$$

Figure 1.4 shows the shape of Saragoni and Hart window with $\eta=0.20$, $\epsilon=0.20$ and $T_w=10$ sec. These are the parameters adopted in this study.

The source term in Equation 1.1, $CM_0 (2\pi f)^2 / [1 + (f/f_0)^2]$, describes a point source model with a single corner frequency. Atkinson (1993) described an empirical source model for eastern North America that features two corner frequencies. A two-corner model has also been proposed for California (Atkinson and Silva, 1997,2000). In general, it is found that a Brune model provides a good description of small earthquakes ($M < 6$), but a two-corner model is superior for larger events (Atkinson and Silva, 2000). It has been suggested that the second corner is required to represent finite fault effects that are important for large events (Atkinson and Silva, 1997). In the two-corner model, the source term is given by $CM_0 (2\pi f)^2 \{ (1-\epsilon)/[1+(f/f_A)^2] + \epsilon/[1+(f/f_B)^2] \}$, where the parameters ϵ , f_A , and f_B are given by:

$$\log(\epsilon) = 2.52 - 0.637M \quad (1.3)$$

$$\log(f_A) = 2.41 - 0.533M \quad (1.4)$$

$$\log(f_B) = 1.43 - 0.188M \quad (1.5)$$

The stochastic method with a two-corner source has been used to derive ground motion relations for several different regions. Atkinson and Boore (1995) derived ground motion relations for eastern North America using a stochastic point-source model with an empirical two-corner source model. (Note: Toro *et al.* (1997) developed similar relations for eastern North America using a Brune point-source model.) Atkinson and Silva (2000) developed ground motion relations for California using a stochastic method that exploits the equivalence between the finite fault model and a two-corner point-source model of the earthquake spectrum. In each of these cases, region-specific input parameters derived from seismograms were used to drive the ground motion relations for that region. For California, where there is a good empirical strong-motion database, it was shown that the stochastic relations agree well with empirical regression equations (e.g. Abrahamson and Silva, 1997; Boore et al, 1997; Sadigh et al., 1997; Atkinson and Silva, 2000). The stochastic ground-motion relations provide a sound basis for estimating peak ground motions and response spectra for earthquakes of magnitude 4 through 8, at distances from 1 to 200 km over the frequency range 0.2 to 20 Hz.

1.2.2 Finite Faults

Point source models of earthquake ground motion are inappropriate for earthquakes that rupture an extended fault plane. The effects of a large finite source, including fault geometry, heterogeneity of slip on the fault plane and directivity, can profoundly influence the amplitudes, frequency content and duration of ground motion. Finite-fault effects in ground motions become important for earthquakes with magnitudes exceeding approximately 6.0. Finite fault modeling has been an important tool for the prediction of ground motion near the epicenters of large earthquakes (Hartzel, 1978; Irikura, 1983; Joyner and Boore, 1986; Heaton and Hartzel, 1989; Somerville et al., 1991; Tumarkin and Archuleta, 1994; Zeng et al., 1994; Beresnev and Atkinson, 1998a).

One of the most useful methods to simulate ground motion for a large earthquake is based on the simulation of a number of small earthquakes as subfaults that comprise a big fault. A large fault is divided into N subfaults and each subfault is considered as a small point source (introduced by Hartzel, 1978). The rupture spreads radially from the hypocenter. Ground motions of subfaults, each of which may be calculated by the stochastic point-source method as described above, are summed with a proper delay time in the time domain to obtain the ground motion from the entire fault, $a(t)$:

$$a(t) = \sum_{i=1}^{nl} \sum_{j=1}^{nw} a_{ij}(t + \Delta t_{ij}) \quad (1.6)$$

where nl and nw are the number of subfaults along the length and width of main fault, respectively ($nl * nw = N$), Δt_{ij} is the relative delay time for the radiated wave from the ij^{th} subfault to reach the observation point. The $a_{ij}(t)$ are each calculated by the stochastic point source method.

In this approach a basic understanding of earthquake generation and propagation processes can be combined with empirical information that can be obtained from recordings of small-to-moderate real events in order to determine key attenuation parameters. Large-magnitude events, which are important to practical applications, can then be simulated using the finite-fault extension of the stochastic approach. The input parameters for the simulations are based on the attenuation parameters obtained from the real recorded time series from smaller events.

Finite-fault simulations based on the stochastic method can be made using the computer program, FINSIM (Beresnev and Atkinson, 1998a). The FINSIM algorithm has

been designed to include fault geometry, heterogeneity of slip on the fault plane, directivity, near-source and duration effects. The model parameters of the FINSIM algorithm have been well established using data from many real earthquakes, including Michoacan, Mexico (1985), Northridge (1994), Valparaiso, Chile (1985), Saguenay, Quebec (1988) and many more (Beresnev and Atkinson 1997, 1998a, 1998b, 1999, 2000, 2001). The FINSIM approach has been applied to both eastern and western North American earthquakes, and the model parameters have been calibrated to determine a “generic “ finite fault model that produces good agreement between model and observations on average (Beresnev and Atkinson, 2000,2001) over a wide range of magnitudes, distances and tectonic environments.

A modified version of the computer program FINSIM (Beresnev and Atkinson, 1998) is developed in this thesis. The modifications (to be discussed in the next chapter) to FINSIM introduce the new concept of a “dynamic corner frequency” to more closely model real finite-fault dynamic behavior. The modified version replaces the “radiation strength factor” with a stress parameter that governs high-frequency energy. The new version also allows for variability in the “pulsing area” or the number of subfaults, which are considered as active subfaults, in the calculation of dynamic corner frequency.

1.3 Scope of Thesis

In chapter two of this thesis, I develop an improved finite fault simulation methodology, by making substantial modifications to FINSIM. The modified program has been renamed EXSIM. The generic model results of Beresnev and Atkinson (2001) were used to calibrate the revised code to ensure that it replicates the previous FINSIM results on average over all magnitudes and distances. The rationale for this calibration is that FINSIM has been extensively validated against real earthquake data over a wide

range of conditions. EXSIM produces approximately the same peak relations and response spectra as the FINSIM model of Beresnev and Atkinson (1998a), and provides good characterization of the main seismological effects, including source and path, for extended fault sources.

With the finite fault model established, the rest of the project aims to find the region-specific parameters needed for stochastic finite fault modeling and development of ground motion relations for Puerto Rico. The list of tasks is as follows:

1. Collect ground-motion data and instrument response parameters. The data sources include:
 - a) Short-period digital PRSN data collected since 1991 (more than 2000 waveforms);
 - b) Digitized strong-motion data collected by PRSMN;
 - c) IRIS/USGS data as they have been recorded since 1993 (more than 600 waveforms);
2. Process data to obtain Fourier and response spectra, correcting for instrument response as appropriate.
3. Use regression analysis to determine the attenuation of Fourier amplitudes as a function of distance and frequency, the source terms for moderate events, and the relative site terms for all stations. Analyze horizontal- to vertical-component ratios.
4. Evaluate the distance-dependence of the duration of ground motions.
5. Use the regression results to define the underlying parameters of the stochastic ground-motion model.
6. Use stochastic finite-fault modeling to produce acceleration time series for Puerto Rico for a wide range of magnitudes and distances.

8. Develop ground-motion relations (response spectra as a function of magnitude and distance) for Puerto Rico at different frequencies.
9. Validate the ground motion relations with the empirical database.

In the following section I overview empirical studies performed to obtain the region-specific parameters that are needed for stochastic finite fault modeling. Details are provided in chapter 4.

1.4 Region-specific parameters

The region-specific parameters needed for stochastic finite fault modeling are:

- A model of the attenuation of Fourier amplitudes with distance (geometric spreading and Q-value);
- A model of the duration of ground motion as a function of magnitude and distance; and
- Regional generic crust/site amplification factors.

I used the recorded empirical data to establish the underlying parameters, and then validated the model predictions to check for internal consistency. I am relying on digital records. Since several good small-to-moderate events are recorded every month, there is a reasonable database for small to moderate earthquakes.

The instrument response of all stations was obtained from a detailed calibration program that included in-situ field calibrations of instruments. All data were corrected to remove the instrument response as appropriate. Fourier amplitudes and response spectra of recorded time series were analyzed. The shear-wave portions of signal and pre-event noise have been windowed for all of the time series. I compiled data for which the signal

to noise ratio is at least a factor of 2. After compiling the ground-motion database, and finding the characteristics of the Fourier spectra, the Fourier amplitudes were fitted to an equation of the form:

$$\log A_{ij}(f, R) = \log A_{i0}(f) - b \log R_{ij} - c(f) R_{ij} + \log S_j(f), \quad (1.7)$$

where $A_{ij}(f)$ is the observed spectral amplitude of earthquake i at station j , for frequency f ; $A_{i0}(f)$ is the source amplitude of earthquake i , R is hypocentral distance, b is the geometric spreading coefficient, $c(f)$ is the coefficient of anelastic attenuation, and $S_j(f)$ is the site response term for station j (Shin and Herrmann, 1987; Atkinson and Mereu, 1992). The anelastic coefficient, $c(f)$, is inversely related to the quality factor, Q :

$$Q = [\log(e) \pi f] / (c \beta), \quad (1.8)$$

where β is the shear-wave velocity. Equation 1.7 may be applied to any ground-motion phase; the shear-wave phases are of most engineering interest, since their amplitudes are typically about five times larger than the P -wave amplitudes. Equation 1.7 was solved by the maximum likelihood method to find the source terms A_{i0} , geometric spreading coefficient b , and frequency-dependent attenuation c , providing a description of regional source, path, and site effects. It serves as the empirical underpinning for the development of ground-motion relations, using stochastic techniques.

In developing the attenuation model, it should be determined whether the ground-motion database can be adequately fit with a single geometric-attenuation term b , or whether this coefficient will take different values depending on the epicentral distance range. The presence of postcritical reflections from the Moho discontinuity, that causes

"flattening" of the attenuation, produces a hinged-trilinear curve for attenuation (Atkinson and Boore, 1995). I applied a set of hinge points in order to find those that resulted in the lowest bias of the above equation as compared to the real recorded data.

The Q-value and duration behavior have been studied based on the analyzed records. Most of the PRSN data collected to date are vertical-component recordings. However, there are also a large number of IRIS/USGS three-component data available. From three-component data, I established an empirical relationship between horizontal- and vertical-component amplitudes. These region-specific parameters are applied in the stochastic finite fault modeling as described in chapter 5.

1.5 Development of Ground Motion Relations for Puerto Rico

The focus of the last step of the project is the development of regional ground-motion relations. This is an important anticipated product of the research, which is urgently required for seismic-hazard calculations and other engineering applications. With the parameters established from empirical studies of the abundant moderate-magnitude data, I then used the calibrated EXSIM model to extend our ground motion predictions to the magnitude-distance range of engineering interest. EXSIM is used to simulate a ground motion database from which to develop ground motion equations. (I take this approach because there are not enough real data in the magnitude-distance ranges of engineering interest.) 1950 simulations were performed for a range of magnitudes and distances and for different directivity regions. I covered the distance range from $R = 1$ km to $R = 500$ km for earthquakes of $3.0 \leq M \leq 8.0$, in 0.2 magnitude-unit increments. Three profiles- backward, forward and null directivity- have been considered. Ten trials were used for each magnitude-distance combination. I generated response spectra for frequencies of 0.1 to 20 Hz, and peak ground acceleration and

velocity. I applied randomly generated slip distributions. This will give us the range of expected ground motions from future earthquakes, for which rupture scenarios cannot be predicted.

The maximum likelihood method was applied to fit our database of simulated acceleration time series to a simple functional form. I obtained analytical ground motion relations of the form $Y = f(f, M, R)$, where Y is the ground motion parameter of interest (eg. Response spectra and peak acceleration or velocity), M is magnitude and R is distance. I compared predictions with Puerto Rico data and with ground motion relations for other regions.

**Figure 1.1. Brune spectrum with no anelastic attenuation and no kappa factor.
stress=50 Bars**

Figure 1.2. Brune spectrum, $Q=300f^{0.50}$, and no kappa factor. stress=50 Bars

**Figure 1.3. Brune spectrum, $Q=300f^{0.50}$,
 $\kappa=0.03$. stress=50 Bars**

Figure 1.4. Saragoni and Hart window

Chapter 2: A New Approach to Finite Fault Modeling

2.1. Introduction

In this chapter I study the different features of the stochastic finite fault model and describe enhancements made to improve the method. The underlying idea is that ground motion for a large earthquake can be simulated by summing contributions from a number of small earthquakes that rupture its subfaults (Equation. 1.6). The ground motions of the subfaults are each calculated by the stochastic point source method. Assuming a Brune point source model for the subfaults, the acceleration spectrum of the ij^{th} subfault, $A_{ij}(f)$, is:

$$A_{ij}(f) = CM_{0ij} (2\pi f)^2 / [1 + f/f_{0ij}]^2 \exp(-\pi f/\kappa) \exp(-\pi f R/Q\beta) / R_{ij} \quad (2.1)$$

where M_{0ij} , f_{0ij} and R_{ij} are the ij^{th} subfault seismic moment, corner frequency and distance from the observation point, respectively. All of the other parameters are the same as defined for Equation (1.1) (page 1-3). There are different possible definitions for the calculation of M_{0ij} and f_{0ij} , which will be discussed later. For now let us consider $f_{0ij} = 4.9e+6 \beta (\Delta\sigma / M_{0ij})^{1/3}$ (Boore, 1983) and $M_{0ij} = M_0/N$ (where all of the subfaults are identical).

Studies have shown (Joyner and Boore, 1986, Beresnev and Atkinson, 1998) that in such kinematic models the obtained ground motion, $A(t)$, for a large fault depends on the subfault size or the number of subfaults, N . In other words, to get a proper ground motion for a large fault, there are some constraints on the subfault size or the number of subfaults. Spectra add coherently at low frequencies and incoherently at high frequencies (Joyner and Boore, 1986). If all of the N subfaults are identical then:

$$A(f) = \sqrt{N} A_e(f) \quad \text{at high frequencies} \quad (2.2)$$

$$A(f) = N A_e(f) \quad \text{at low frequencies} \quad (2.3)$$

where $A_e(f)$ is the subfault source spectrum. This statement raises a question. Is the total radiated energy from the fault conserved when we change the subfault size or the number of subfaults? Adding spectra coherently at low frequencies and incoherently at high frequencies may imply that the total radiated energy from the fault is not conserved. In this chapter, I free the simulations from the constraint of specified subfault size and study its consequences.

The computer program FINSIM (Beresnev and Atkinson, 1998) was used for this exercise. This program calculates acceleration time series for each subfault by the stochastic point source method (Equation 2.1), and then applies Equation 1.6 to compute the acceleration time series of the large fault. Instead of using $f_{0ij} = 4.9e+6 \beta (\Delta\sigma / M_{0ij})^{1/3}$ for calculation of corner frequency, this program calculates corner frequency using a similar formulation given by $f_{0ij} = \gamma \beta z / (\pi l)$, where γ is the ratio of the rupture velocity to shear wave velocity (0.8), z is a strength factor (1.6) that controls the high frequency level of acceleration spectrum, and l is the radius of subfault. The seismic moment of each subfault is calculated by $M_{0ij} = \Delta\sigma l^3$ and each subfault is triggered many times in order to conserve the total seismic moment of the main fault. To get a proper ground motion for a large fault by this program, there is a constraint on the subfault size, $\log l = -2 + 0.4M$ (Beresnev and Atkinson, 2000).

2.2. Radiated Energy From a Fault

The power spectral density (PSD) of an acceleration time series at the observation point represents the total received energy at that point from a fault. Power spectral density, $E(\omega)$, is defined as:

$$E(\omega) = \frac{1}{\pi T} |F(\omega)|^2 \quad (2.4)$$

where $F(\omega)$ is the Fourier amplitude of the acceleration time series. Usually power spectral density is represented in dB, in which case Equation. 2.4 should be written:

$$E(\omega) = 10 \log \left(\frac{1}{\pi T} |F(\omega)|^2 \right) \quad (2.5)$$

A vertical fault with length and width of 40km by 20km, respectively, was considered. The approximate magnitude based on (Wells and Coppersmith, 1994) empirical relationships between moment magnitude (M) and fault size is $M7.0$. Table 1 shows all of the input parameters to the simulations. I vary the number of subfaults and calculate the total received energy from the fault at the observation point. All of the other parameters have been kept the same in all simulations. In this step all of the subfaults are square, and identical in slip behavior and corner frequency. The observation point is far from the fault surface (more than 300km) so the attenuation effect would be almost the same for all of the subfaults. Simulations are performed for different subfault lengths, including 1, 2, 5 and 10 kilometers. The number of subfaults is 800, 200, 32 and 8 respectively, covering a wide range of subfault sizes. The size of the main fault is the same for all cases.

Figure 2.2.1 shows the power spectral density of the simulated acceleration time series at the observation point for different subfaults lengths. When the subfault length is 5 to 10km, we have a nearly flat spectral level from 0.1 to 5 Hz. By increasing the number of subfaults (thus decreasing their length), the energy at low frequencies is decreased while the energy at high frequencies is increased. If the entire fault is considered as 800 subfaults with the size of 1km*1km, the total received energy at the observation point is about 10 time greater than the total received energy when the entire fault is considered as 8 subfaults, each with the size of 10km*10km. Because of the logarithmic scale of the PSD, the difference may not be clear in Figure 2.2.1. Figure 2.2.2 shows the calculated PSD using a linear scale which more clearly shows the differences between the total received energy from the fault with different lengths of subfaults. The total received energy from the entire fault is not conserved as we change the length and the number of subfaults. Since the attenuation effects are almost the same for all of the subfaults in the far field, it follows that the total radiated energy from the entire fault also is not conserved.

Thus far I have investigated the total energy from the output acceleration time series, which is the end product of finite fault modeling. Let us now go a little bit further back in the subfault spectra calculation to a point before that, in which the stochastic element is introduced. The square of the acceleration spectrum (Equation.2.1) is proportional to the received energy from each subfault. Considering the model for different sizes of subfault as I have done before and computing the square of Equation. 2.1, gives us the total received energy from the main fault for different numbers of subfaults and subfault lengths (Figure2.2.3). Figure 2.2.4 shows that the total area under each curve, which represents the total received energy, is not conserved. Again, since the attenuation effects

are almost the same for all of the subfaults in the far field, it follows that the total radiated energy from the entire fault also is not conserved. This lack of energy conservation is an undesirable feature of the current stochastic finite fault modeling.

2.3. A New Approach: Dynamic Corner Frequency

We can consider the finite-fault modeling problem by imagining a subfault as a violin and the entire fault as a double-bass. Modeling a fault based on subfault radiation is akin to asking an orchestra of violin players to produce double-bass music. String instruments like the violin or double-bass produce different frequencies, which are related to the length of the string (as well as its tension). Thus, a violin produces higher frequencies than a double-bass. Using this orchestra analogy, if we model a large fault by subfaults that are small and identical in slip behavior and corner frequency, then we are playing with identical violins. Playing a number of small violins multiplies the frequency content of one violin and extends the playing time. An orchestra full of small violins produces high frequency music but cannot produce the music of a double-bass, no matter how we arrange the timing of each player.

What if we increase the length of strings and consider a cello? In that case we get closer to the frequency content of a double-bass. To get closer to the music of a double-bass we may thus need to put some constraint on the minimum length of the string for the instruments in our orchestra.

How can we produce a genuine double-bass sound in finite fault modeling? When playing a double-bass we may place our finger at one end of the string and gradually move our finger towards the other end of the string. By varying the total free length of string we vary the frequency content. As we approach to the full length of the string we

produce the low frequency music of the double-bass. This frequency content is closer to the reality of fault rupture in an earthquake.

Earthquake time history simulation deals with the time from the beginning of rupture to the time when the rupture stops. In our finite fault model we deal with a ruptured area that is time dependent; it is initially zero and is finally equal to the entire fault area. Corner frequency is inversely proportional to the ruptured area. Therefore in time history simulation the corner frequency may be considered as a function of time. The rupture begins with high corner frequency and progresses to lower corner frequencies. Let us consider a dynamic definition of corner frequency and assess the consequences of this assumption on the total radiated energy from the fault. We suppose that during an earthquake at each moment of time, the corner frequency is dependent on the cumulative ruptured area. The rupture history controls the frequency content of the simulated time series and the subfaults are no longer independent. By contrast, under our former concept of “static corner frequency”, the frequency content of each subfault was independent of the other subfaults.

In our dynamic approach, the corner frequency of the first subfault ($i=1, j=1$, near the beginning of rupture) is $f_{o11}=4.9e+6 \beta (\Delta\sigma / M_{o11})^{1/3}$ where M_{o11} is the moment of the first subfault defined by $M_{o11}= M_{oij}=M_o/N$. The dynamic corner frequency of the ij^{th} subfault, $f_{oij}(t)$, can be defined as a function of $N_R(t)$, the cumulative number of ruptured subfaults at time t .

$$f_{oij}(t)= 4.9e+6 \beta (\Delta\sigma / (N_R(t) M_{oij}))^{1/3} \quad (2.6)$$

The acceleration spectrum of the ij^{th} subfault, $A_{ij}(f)$, is thus:

$$A_{ij}(f) = C M_{oij} N_R^{1/2} f^2 / [1 + (f/f_{oij})^2] \exp(-\pi f \kappa) \exp(-\pi f R/Q \beta) / R_{ij} \quad (2.7)$$

When the rupture proceeds towards the end of the fault the number of ruptured subfaults increases and, based on the Equation 2.6, the corner frequency of the subfaults decreases. The dynamic corner frequency concept will tend to decrease the level of the spectrum, but this is counteracted by $N_R^{1/2}$ in Equation 2.7, which increases the level of the spectrum and keeps the total radiated energy from each subfault the same. Thus the diminishing effect of f_{oij} on the total radiated energy from the subfault is compensated for by the amplifying effect of $N_R^{1/2}$, in order to keep the total radiated energy unchanged. The total radiated energy from the ij^{th} subfault is equal to the total radiated energy from the first subfault, but the calculation of corner frequency, which controls the shape of spectrum, comes from the total ruptured area. In other words the total radiated energy remains unchanged but the distribution of energy tends to shift towards lower frequencies. In the language of our music analogy, when the finger of the player reaches the end of the string, a small part of the string cannot produce high frequencies. The frequency is based on the entire length of the string. Every small part feels the existence of the entire string and works with the entire length of the string to produce low frequencies.

The seismic moment of each subfault is controlled by the ratio of its area to the area of the main fault ($M_{oij} = M_o/N$). If the subfaults are not identical we can express the seismic moment of each subfault as:

$$M_{oij} = M_o / N (S_{ij} / (\sum_{l=1}^{nl} \sum_{k=1}^{nw} S_{kl}) / N) = M_o S_{ij} / (\sum_{l=1}^{nl} \sum_{k=1}^{nw} S_{kl}) \quad (2.8)$$

where S_{ij} is the slip weight of the ij^{th} subfault. The dynamic corner frequency of the ij^{th} subfault, $f_{oij}(t)$, is thus:

$$f_{oij}(t) = 4.9 \times 10^6 \beta (\Delta \sigma / (N_R(t) M_{\text{oave}}))^{1/3} \quad (2.9)$$

where $M_{\text{oave}} = M_o / N$ is the average seismic moment of subfaults.

The concept of a dynamic corner frequency was applied to the simulation cases previously discussed. A modified version of the computer program FINSIM (Beresnev and Atkinson, 1998) was used for this exercise. The modifications to FINSIM include the following features. The modified program has been renamed EXSIM.

- Calculation of power spectra density of the simulated accelerographs
- Calculation of received energy at the observation point.
- Inclusion of the new concept of “dynamic corner frequency”
- Calculation of subfault seismic moment based on dividing the total seismic moment of the earthquake fault by the number of subfaults
- Elimination of the “radiation strength factor”, with high-frequency energy now being governed by stress parameter, which will be discussed.
- Variability of pulsing area or the number of subfaults which is considered as active subfaults in the calculation of dynamic corner frequency, which will be discussed.

Figures 2.3.1 and 2.3.2 show the results. Comparison of Figure 2.3.1 and 2.3.2 with Figures 2.2.3 and 2.2.4 shows the difference that has been made by use of a dynamic corner frequency. In Figure 2.3.1 and 2.3.2, we see that the total radiated energy from the

fault is almost identical for all of the cases. Thus, the total radiated energy is conserved. (Note: the real paths from the subfaults to the observation point are not exactly the same, and therefore the attenuation effects are not identical for all of the subfaults. This explains the small differences between total received energy observed for different subfault size cases (Figure 2.3.2)).

The main contention here is that the total radiated energy should be independent of subfault size; but this is not necessarily the case for the total received energy. An earthquake with a specified magnitude is allowed to radiate a specified energy, no matter how we divide it amongst the subfaults. In the new approach the total radiated energy is conserved. The total received energy from the fault should not necessarily be conserved, due to the different path effects and directivity. The main idea behind the finite fault modeling is to divide a fault into subfaults and distribute the seismic moment or energy over them, in order to provide appropriate path effects that closely resemble a real earthquake. I have used a far-field example in order to provide a uniform path effect, and thus show the behavior of received energy and radiated energy.

Since the total radiated energy is the same over a wide range of subfault sizes, we can now apply a constant fault size, say 1km*1km, for the dynamic corner frequency approach. Figure 2.3.3 compares the total received energy from the fault by applying the dynamic corner frequency to the results obtained for the static corner frequency with different subfault sizes. This figure shows that the total power spectral density is close to the results from the static corner frequency with sizes 5 to 10 kilometers, which satisfy the subfault size constraints ($\log l = -2 + 0.4M$) introduced by Beresnev and Atkinson (2000) to reproduce ground motions for events of this magnitude (e.g. fault size 40*20km for event of M7.0).

2.4. Far Field Acceleration Time Series and Response Spectra

Both static and dynamic corner frequencies have been applied to all of the previous cases to obtain acceleration time series and response spectra. Figures 2.4.1 and 2.4.2 show the far field acceleration time series for the case of static and dynamic corner frequencies. In the case of static corner frequency (Figure 2.4.1) it is not surprising that as we decrease the subfault size, the acceleration time series become stronger; this is as a consequence of increasing the total radiated energy from the fault. By contrast the strength of the time series in the case of dynamic corner frequency (Figure 2.4.2) is almost the same for all of the cases. These results are similar to the case of static corner frequency with subfault size of 5-10 km, satisfying the subfaults size criteria for events of this magnitude (Beresnev and Atkinson, 2000).

Response spectra for the cases of static and dynamic corner frequency are shown in Figures 2.4.3 and 2.4.4. The response spectra are almost the same for all subfault sizes in the case of the dynamic corner frequency approach. Figure 2.4.5 compares the PSA from the dynamic corner frequency simulation to the results with static corner frequency, in the case of 5 and 10 km subfault sizes.

All of the above simulations were for an observation point that is located far from the source (more than 300km) since I wanted to make the attenuation effect for all of the subfaults the same. In the following section I explore the dynamic corner frequency concept for near-source sites.

2.5. Near-source Acceleration Time Series and Response Spectra

Near the earthquake source, the attenuation effect will be not the same for all of the subfaults. Thus, by changing the size or length of subfaults, we also change the attenuation effect on the simulated time histories. Therefore, we should not expect the total received energy to be independent of subfault size. However, the radiated energy should be conserved if we play back the effect of attenuation and calculate the radiated energy right at the subfault. Both static and dynamic corner frequencies have been applied to all of the previous cases in the far field to obtain acceleration time series and response spectra. In this exercise, I use the same input parameters as before but change the length and width of the fault to 100km and 20km, respectively. Three observation points are considered. The first point is located just 2km away from one end of fault, in the backward-directivity region. The second point is 3km away from the middle of fault, while the third point is located 5 km away from the other end of the fault, in the forward-directivity region.

Figures 2.5.1- 2.5.4 show the backward-directivity near-source results (2km away from the fault). Response spectra and acceleration time series are shown for both the static and dynamic corner frequency models for different subfault sizes. Figure 2.5.5 shows the PSA comparison between the dynamic corner frequency and static corner frequency results for 5 and 10km subfault sizes. These differences are relatively minor.

Figures 2.5.6- 2.5.10 show the corresponding results for the second observation point, 3km from the middle of the fault. Again differences between the dynamic and static corner frequency (5-10 km subfault size) results are small.

Comparison of acceleration time series for 1km*1km subfaults with those from 10km*10km subfaults, in Figure 2.5.6, shows that for large subfault sizes there may be some gaps in the time series. A subfault ruptures instantly and after a pause the next subfault ruptures. The length of the pause is a function of the distance between the centers of those two subfaults. When the subfaults are big the pause time is big, and this causes gaps in the simulated time series, especially near the source. This is a disadvantage of the use of large subfaults.

Figures 2.5.11-2.5.15 show results for the third observation point, which is 5km away from the other end of fault in the forward-directivity region. These results are also similar to those for the other observation points.

2.6. Seismic Moment of Subfaults

The new approach conserved the total seismic moment by using $M_{oij} = M_o/N$ and Equation 2.8 (section 2.3). The purpose of this section is to find a substitute for the multiple triggering of subfaults utilized in the previous approach. If we consider the seismic moment as a direct function of fault size:

$$M_o = \Delta\sigma LA \quad (2.10)$$

where L and A are the length and area of the fault and $\Delta\sigma$ is the stress parameter. If all of the subfaults are square and identical, the seismic moment of a subfault is $M_{oij} = \Delta\sigma la$, where l and a are subfault length and area. By subdividing a fault into a number subfaults (N), the total seismic moment should be conserved. In other words the sum of seismic moments of all subfaults should be the same as the seismic moment of the entire fault.

$$\begin{aligned}
M_o &= N M_{oij} \\
&= N \Delta \sigma l a \\
&= \Delta \sigma l (N a) \\
&= \Delta \sigma l A \\
&= \Delta \sigma L A \quad l/L \\
&= M_o \quad l/L
\end{aligned}$$

The right hand side of the above equation is supposed to be M_o . This shows the seismic moment will not be conserved unless $l=L$. As a result, multiple triggering of subfaults is generally used in order to achieve seismic moment conservation. The law of conservation of seismic moment suggests the seismic moment for a subfault should be:

$$M_{oij} = \Delta \sigma l a \sqrt{N} \quad (2.11)$$

By using Equation. 2.11 the seismic moment is totally conserved. If we go through the same calculation as before, we have

$$\begin{aligned}
M_o &= N M_{oij} \\
&= N \Delta \sigma l a \sqrt{N} \\
&= \Delta \sigma l \sqrt{N} (N a) \\
&= \Delta \sigma (l \sqrt{N}) (A) \\
&= \Delta \sigma L A \\
&= M_o
\end{aligned}$$

which is what we expect as a consequence of seismic moment conservation. Note that Equation. 2.11 is also valid for the entire fault (e.g. produces Equation. 2.10, when $N=1$) and is thus a more general case of Equation.2.10.

When the seismic moment or slip behaviors of individual subfaults are not identical the seismic moment of the ij^{th} subfault is:

$$M_{oij} = \Delta\sigma la N\sqrt{N} S_{ij} / \left(\sum_{l=1}^{nl} \sum_{k=1}^{nw} S_{kl} \right) \quad (2.12)$$

Again there is no need for multiple triggering of subfaults. As a matter of fact, the factor $\sqrt{N}$ in Equation 2.12 substitutes for the multiple triggering of subfaults. In order to compare Equation 2.12 to 2.8 that I applied before, Equation 2.12 can be rewritten as follows:

$$M_{oij} = \Delta\sigma (l\sqrt{N})(aN) S_{ij} / \left(\sum_{l=1}^{nl} \sum_{k=1}^{nw} S_{kl} \right)$$

$L = l\sqrt{N}$ and $A = aN$, therefore

$$M_{oij} = \Delta\sigma LA S_{ij} / \left(\sum_{l=1}^{nl} \sum_{k=1}^{nw} S_{kl} \right)$$

Since $M_o = \Delta\sigma LA$ then

$$M_{oi} = M_o S_{ij} / \left(\sum_{l=1}^{nl} \sum_{k=1}^{nw} S_{kl} \right)$$

Therefore Equation 2.12 and 2.8 are the same and give us the same subfault seismic moment.

2.7. Rise Time and Self Healing Subfault

The concept of dynamic corner frequency has been introduced, based on a corner frequency that grows with the cumulative ruptured area. Consider the case of a long fault (Figure 2.7.1.a). When a subfault ruptures, the total ruptured area (all of the black cells) contributes to the frequency content of the radiated wave from the rupturing subfault. This kind of model is close to a crack model, or healing-front model, in which a subfault will continue to slide until the information is received that the rupture front has stopped. By contrast, in the case of a slip pulse or self-healing model (Heaton, 1990), by the time that the wave front reaches a cell that is far away from the hypocenter, the hypocenter cell might not be active anymore. In other words, when a distant subfault produces a wave, there is a possibility that many of the other subfaults, which have already ruptured, have done their job and are no longer active. This depends on the rise time or slipping time of subfaults. In the self-healing model, a wave front has a tail which includes the pulsing subfaults and those subfaults that are still sliding. In the self-healing model, the passive area should not have any effect on the frequency content of the distant subfault. Figure 2.7.1.b illustrates this concept using a gray area, which should have effect on the dynamic corner frequency.

In the case of the front-healing model (figure 2.7.1.a), N_R in the equation $f_{0\text{dyn}}(t) = f_0 (N_R(t))^{-1/3}$ is the cumulative number of ruptured subfaults, but in the case of the self-healing model (figure 2.7.1.b), N_R is the cumulative number of pulsing subfaults, which would increase with time at the beginning of rupture but become constant after a while. Only subfaults in the pulsing area would have a significant contribution to the frequency content of the next rupturing subfault. This kind of self-healing behavior can be considered in EXSIM with application of the dynamic corner frequency concept. If we

consider the pulsing area, the dynamic corner frequency decreases with time near the beginning of the rupture, then would become constant. Even if we consider the pulsing model, in the case of a dynamic corner frequency, the total radiated energy would be conserved. Figures 2.7.2 and 2.7.3 show the received energy from a fault when the pulsing area is 20% and 50% of the total fault area. The pulsing area of 20% means that during the rupture of a subfault, at most 20% of all of the subfaults are active and thus contributing to the dynamic corner frequency; the other 80% of subfaults are passive.

Figures 2.7.4 and 2.7.5 show the response spectra and acceleration time series for different percentages of pulsing area (5%, 10%, 50%, 100%). In the case of 100% pulse area, all of the subfaults are active until the last subfault ruptures. This is actually a front-healing model (figure 2.7.1.a). The self-healing model gives ground motions that are independent of the size of the subfaults, but different percentages of pulsing area, like different stress parameters, will give different response spectra and acceleration time series. By decreasing the pulsing area, the acceleration time series and response spectra become richer at high frequencies and the amplitude of low frequencies decreases. A narrow pulsing area in Figure 2.7.1.b results in lower amplitudes at longer periods. Variation of this parameter can be used to adjust relative amplitudes of low-frequency motion in finite fault modeling of specific events.

2.8. Strength Factor and Stress Parameter

Finite fault modeling based on the static corner frequency approach introduced a new factor, the radiation strength factor (Beresnev and Atkinson, 1998a, 1999). This factor (z) was introduced in the definition of the static corner frequency of subfaults ($\omega_0 = \gamma z \beta / 2 l$), where γ is the ratio of the rupture velocity to shear wave velocity (0.8), and l is

the radius of subfault). The strength factor plays an important rule in controlling the amplitudes of response spectra at high frequencies in the static corner-frequency approach. In this section I illustrate the effect of the strength factor on acceleration time series and response spectra of an earthquake with **M**7.0 at 10km distance using the static corner-frequency approach. Figures 2.8.1 and 2.8.2 show the significant effect of strength factor on both acceleration time series and response spectra. Increasing this factor from 1 to 1.6 increases the amplitude of response spectra at high frequency by a factor of 2.5, as shown in our example. Based on the empirical studies, the strength factor may vary from 1.0 to 1.6 or may occasionally be as high as 2.2 (Beresnev and Atkinson, 2001).

In my new approach, by introducing the concept of dynamic frequency ($f_{\text{odyn}}(t) = 4.9 \times 10^6 \beta (\Delta\sigma / (N_R(t) M_{\text{oave}}))^{1/3}$) I eliminate the basis for the strength factor as previously defined. Now, however, the stress parameter plays an equivalent role in controlling the amplitudes of response spectra at high frequencies. Figures 2.8.3 and 2.8.4 show the effect of the stress parameter on acceleration time series and response spectra, in the application of the dynamic corner frequency model. The amplitudes of high frequencies increases with increasing stress parameter. By comparing figure 2.8.4 with 2.8.2, one can conclude that the role of the stress parameter in the dynamic corner frequency approach is similar to the role of the strength factor in the static corner frequency approach.

2.9. Comparison of Results of Static and Dynamic Corner Frequency application for different magnitudes and distances

The main purpose of this exercise is to determine the value of stress parameter in the new dynamic corner frequency approach that will replicate the previous calibrated results of FINSIM. FINSIM has been applied to many real earthquake faults (Michoacan, Mexico, 1985; Northridge 1994; Valparaiso, Chile, 1985; Saguenay, Quebec, 1988; Nahanni, Northwest Territories, 1985; Grand Banks, 1929; Timiskaming, Quebec, 1935; etc) and the model parameters have been calibrated to determine a “generic “ finite fault model that produces good agreement between model and observation on average (Beresnev and Atkinson 1997, 1998a, 1998b, 1999, 2000). This exercise is thus a short-cut for model validation. The best measure of the reliability of any ground motion model is the size of the database against which it has been validated. Because FINSIM has been calibrated based on extensive ground motion database (Beresnev and Atkinson, 2001), we can ensure a good fit to a large database by using the calibrated FINSIM model as a benchmark.

The FINSIM input parameters strength factor z (1.6) and subfault size ($\log l = -2 + 0.4M$, where l is in km) match the generic model parameters of Beresnev and Atkinson (2001). The values of ρ (2.6 g/cm³), β (3.6 km/sec) and ν (0.8) in EXSIM match those used in FINSIM. The calibration of EXSIM is performed for various magnitudes, at a far-field site ($R=333$ km), assuming 10% pulsing area. Figures 2.9.1-2.9.7 show that with the new approach, if I adjust the stress parameter to match the results of the previous generic model, the stress parameter decreases as we increase the magnitude of earthquakes. A simple regression analysis (figure 2.9.8) suggests that the EXSIM results, with

$$\Delta\sigma \text{ (bars)} = 288 - 21.1M \quad (2.13)$$

reproduces the FINSIM results obtained with $z=1.6$ and $\log l=-2+0.4M$. Figures 2.9.1-2.9.7 represent an overall good agreement between the results of the EXSIM and the FINSIM approach. Thus, I calibrated the new model to reproduce the previous results by changing the stress parameter, instead of varying the strength factor and subfault size.

Figures 2.9.9 – 2.9.12 compare results of the previous calibrated FINSIM model and the EXSIM model for two magnitudes (M5.0 and M7.0) and distances (10km, 50km). There is a very overall good agreement between the results. This suggests that the new dynamic corner-frequency model will replicate, on average, the previous calibrated results.

2.10.Comparison with the point source model

When a rupture begins, the corner frequency is initially high. As the wave front expands, the dynamic corner frequency shifts towards lower values. At the beginning of the rupture the dynamic corner frequency is calculated based on the size of the first subfault, which is allowed to have very small dimensions. At the end stages of the rupture the dynamic corner frequency is calculated based on the whole ruptured area (in the case of 100% pulsing area) and is as low as the static corner frequency of the corresponding point source model of that earthquake. This attribute of the dynamic corner frequency might be misunderstood or confused with the point source model. Therefore in this section I compare the results of the EXSIM approach with a point source model, conceptually and numerically.

Path effect. A point source model radiates the total energy of the earthquake from its center regardless of the fault size or dimensions. In finite fault modeling the energy is radiated from a large number of subfaults, which are distributed evenly over the surface

of the fault plane. In the point source model the earthquake wave just travels from the center of the fault and propagates towards the observation point. In finite fault modeling, in both the previous and the new approach, the earthquake waves propagate from the center of each of the subfaults. In the new approach the number of subfaults could be much larger than in the previous approach. Similar to our analogy of the double bass, in which energy is propagated from the whole length of its string, the energy is propagated from the whole area of the fault plane or the whole part of the pulsing area. An earthquake fault that propagates seismic energy from the center of hundreds of subfaults cannot be the same as the point source model of that earthquake, because of the differences in source and path effects.

Corner frequency. In the point source model there is just one corner frequency, which is calculated based on the total moment magnitude and stress parameter of the earthquakes. In the new approach there are hundreds of different corner frequencies. In our new approach the dynamic corner frequency covers a wide range; it starts with higher values, calculated from the size of the first subfault, and ends with lower values, calculated from the whole size of the fault. The final corner frequency is equivalent to the corner frequency of the corresponding point source model. Thus, the contribution of the first and the last subfaults to the total radiated energy is the same, but they produce different corner frequencies. Hundreds of subfaults have the same radiated energy; therefore hundreds of different corner frequencies have the same contribution to the total radiated energy. The corner frequency of the last subfault is equal to the corner frequency of the corresponding point source, but it just radiates a small amount of energy ($1/N$ of total radiated energy) from its center, which is located at the end of fault plane. The rest of the energy is radiated from different parts of the fault with different corner frequencies.

Directivity. A point source is not able to simulate directivity effects, since the energy is radiated from just one point. The new model is able to simulate the directivity effect since the energy is radiated from different parts of the fault with a proper time delay, which is calculated based on the distance between each subfault and the hypocenter.

The above-mentioned main differences between the new approach and the point source model are enough to produce different distribution of spectra and energy and make the new approach much closer to the reality of an earthquake. Let us compare the results of the point source model with the new approach as well as with previous approach. The previous vertical fault (section 2.2) with length and width of 40km by 20km, respectively, was considered. The approximate magnitude based on Wells and Coppersmith (1994) is **M7.0**. Three observation points are considered. The first point is located 10km away from one end of fault, in the backward-directivity region. The second point is 10km away from the middle of fault, while the third point is located 10 km away from the other end of the fault, in the forward-directivity region.

The corresponding point source model is considered, with rupture at the middle of fault plane (**M7.0**). The hypocenter for the second observation point (the null point) is considered at the middle of the fault plane (i.e. no directivity effect) which should produce the closest agreement with the corresponding point source model. In the case of forward and backward directivity regions the hypocenter is located at the very first subfault in order to simulate the directivity effect. Figure 2.10.1 shows the total received energy at those three observation points in comparison to that of the point source model. This figure shows that even for the second observation point, which is located at the

middle of fault, the obtained results from a finite fault and point source are different. Clearly when we locate the hypocenter at the very end of fault plane, the directivity effect boosts the differences between the results of the finite fault and the point source model. Figure 2.10.2 shows the differences between response spectra of simulated time series for the above-mentioned cases.

The same simulations have been performed using the previous FINSIM approach with static corner frequency and constrained subfault size. Figure 2.10.3 shows the differences between response spectra of simulated time series for a point source compared to those based on the previous FINSIM approach. Comparison between figures 2.10.2 and 2.10.3 shows that different approaches produce slightly different results but they differ from the results of the point source model in the same manner.

Table 1. Modeling parameters

Q (f)	$333f^{0.74}$
Distance dependent duration	$T_0 + 0.1R$
Kappa	0.03
Stress parameter (bars)	50
Crustal Shear wave velocity (km/sec)	3.7
Rupture velocity/ Shear wave velocity	0.8
Crustal density (g/cm ³)	2.8
Geometric spreading	$1/R$ ($R \leq 70$)
	$1/R^0$ ($70 < R < 130$)
	$1/R^{0.5}$ ($R \geq 130$)

Fig 2.2.1. Far field received Power Spectra Density of a fault with different subfault lengths

Fig 2.2.2. Far field received Power Spectra Density of a fault with different subfault lengths

Fig 2.2.3. Far field received energy of a fault with different subfault lengths

Fig 2.2.4. Far field received energy of a fault with different subfault lengths

Fig 2.3.1. Far field received energy of a fault with different subfault lengths, Using Dynamic Corner frequency

Fig 2.3.2. Far field received energy of a fault with different subfault lengths, Using Dynamic Corner frequency

**Fig 2.3.3. Comparison between Static and Dynamic
Corner frequencies on Far field received energy**

**Fig 2.4.1. Far field acceleration time series of fault with different subfault lengths, Using
Statistic Corner frequency**

Fig 2.4.2. Far field acceleration time series of fault with different subfault lengths, Using Dynamic Corner frequency

Fig 2.4.3. Far field PSA with different subfault lengths, Using Static Corner frequency

Fig 2.4.4. Far field PSA with different subfault lengths, Using Dynamic Corner frequency

Fig 2.4.5. Comparison between Static and Dynamic Corner Frequencies on far field PSA

Fig 2.5.1. Backward near source acceleration time series of fault with different subfault lengths, Using Static Corner frequency

Fig 2.5.2. Backward near source acceleration time series of fault with different subfault lengths, Using Dynamic Corner frequency

Fig 2.5.3. Backward near source PSA with different subfault lengths, Using Static Corner frequency

Fig 2.5.4. Backward near source PSA with different subfault lengths, Using Dynamic Corner frequency

Fig 2.5.5. Comparison between Static and Dynamic Corner Frequencies on backward near field PSA

Fig 2.5.6. Near source acceleration time series of fault with different subfault lengths, Using Static Corner frequency

Fig 2.5.7. Near source acceleration time series of fault with different subfault lengths, Using Dynamic Corner frequency

Fig 2.5.8. Near source PSA with different subfault lengths, Using Static Corner frequency

Fig 2.5.9. Near source PSA with different subfault lengths, Using Dynamic Corner frequency

Fig 2.5.10. Comparison between Static and Dynamic Corner Frequencies on near source PSA

Fig 2.5.11. Forward near source acceleration time series of fault with different subfault lengths, Using Static Corner frequency

Fig 2.5.12. Forward near source acceleration time series of fault with different subfault lengths, Using Dynamic Corner frequency

Fig 2.5.13. Forward near source PSA with different subfault lengths, Using Static Corner frequency

Fig 2.5.14. Forward near source PSA with different subfault lengths, Using Dynamic Corner frequency

Fig 2.5.15. Comparison between Static and Dynamic Corner Frequencies on forward near source PSA

Figure 2.7.1.a 100 % Pulsing area

Figure 2.7.1.b 25% Pulsing area

**Fig 2.7.2. Far field received energy of a fault with different subfault lengths, Using Dynamic Corner frequency
pulsing area = 50%, M7.0 , R=333km**

**Fig 2.7.3. Far field received energy of a fault with different subfault lengths, Using Dynamic Corner frequency
pulsing area = 20%, M7.0 , R=333km**

**Fig 2.7.4. Far field PSA with different pulsing
area percentages , M7.0, R=333km, M7.0 ,
R=333km**

**Fig 2.7.5. Far field acceleration time series of fault with different pulsing area percentages ,
Using Dynamic Corner frequency, M7.0 , R=333km**

Fig 2.8.1. Comparison between acceleration time series from Static corner frequency with different S factors(M=7.0, R=10km)

**Fig 2.8.2. Comparison between response spectra
from Static corner frequency with different S
factors (M=7.0, R=10km)**

Fig 2.8.3. Comparison between acceleration time series from Dynamic corner frequency with different stress parameter ($M=7.0$, $R=10\text{km}$)

**Fig 2.8.4. Comparison between response spectra from
Dynamic corner frequency with different Stress
parameter (M=7.0, R=10km)**

Fig 2.9.1. Comparison between response spectra from Static corner frequency with SF=1.6 and Dynamic corner frequency with stress =180bars, (M5.0, R=333km)

**Fig 2.9.2. Comparison between response spectra
from Static corner frequency with SF=1.6 and
Dynamic corner frequency with stress =170 bars,
(M5.5, R=333km)**

Fig 2.9.3. Comparison between response spectra from Static corner frequency with SF=1.6 and Dynamic corner frequency with stress =160bars, (M6.0, R=333km)

Fig 2.9.4. Comparison between response spectra from Static corner frequency with SF=1.6 and Dynamic corner frequency with stress =150bars, (M6.5, R=333km)

**Fig 2.9.5. Comparison between response spectra
from Static corner frequency with SF=1.6 and
Dynamic corner frequency with stress =140bars,
(M7.0, R=333km)**

**Fig 2.9.6. Comparison between response spectra
from Static corner frequency with SF=1.6 and
Dynamic corner frequency with stress =130bars,
(M7.5, R=333km)**

Fig 2.9.7. Comparison between response spectra from Static corner frequency with SF=1.6 and Dynamic corner frequency with stress =120bars, (M8.0, R=333km)

Figure 2.9.8 Stress parameter as a function of magnitude, $\text{Stress} = 288 - 21.1 \cdot M$

**Fig 2.9.9 Comparison between response spectra
from Static corner frequency with SF=1.6 and
Dynamic corner frequency with stress =180 bars,
(M5.0, R=10km)**

**Fig 2.9.10. Comparison between response spectra
from Static corner frequency with SF=1.6 and
Dynamic corner frequency with stress =140 bars,
(M7.0, R=10km)**

**Fig 2.9.11. Comparison between response spectra
from Static corner frequency with SF=1.6 and
Dynamic corner frequency with stress =180 bars,
(M5.0, R=50km)**

Fig 2.9.12. Comparison between response spectra from Static corner frequency with SF=1.6 and Dynamic corner frequency with stress =140 bars, (M7.0, R=50km)

Fig 2.10.1. Comparison between PSA from the point source model and finite fault modeling by using static corner frequency (R=10km, M7.0, L=40km, width=20km)

Fig 2.10.2. Comparison between PSA's from the point source model and finite fault modeling by using dynamic corner frequency (R=10km, M7.0, L=40km, width=20km)

Fig 2.10.3. Comparison between PSA's from a point source and a fault, using static corner frequency ($R=10\text{km}$, $M7.0$, $L=40\text{km}$, $\text{width}=20\text{km}$)

Chapter 3: Puerto Rico Ground Motion Data

3.1. Introduction

Puerto Rico lies on the boundary between the North American and the Caribbean plates (Figures 3.1 & 3.2). Puerto Rico has a high level of seismic activity, due to its location. At least four destructive earthquakes are documented in the historical records before 1700. There was a possible great earthquake in 1787 ($M \sim 8$), a major earthquake in 1918 ($M7.3$) (McCann, 1985, 2002a), and about 9000 recorded earthquakes since the inception of the Puerto Rico Seismic Network in 1974. A felt seismic event occurs about once per month, with several large and damaging earthquakes having occurred during the time of historical record (Table 3.1). Thus, Puerto Rico's 3.8 million inhabitants are exposed to a significant earthquake hazard.

In terms of tectonics (Figure 3.2), Puerto Rico lies near the northeastern corner of the Caribbean Plate (CA). To the north and east lies the westerly moving North American Plate (NA), locally represented by the floor of the Atlantic Ocean. To the south and west lie the various basins of the Caribbean Sea, within the rigid Caribbean Plate. The Puerto Rico- Virgin island (PRVI) platform straddles and is cut by major tectonic and seismically active features that form the plate boundary zone between the major plates. The northeastern Caribbean is dominated by the slow subduction of the North American Plate (NA) beneath the leading edge of the Caribbean Plate (CA). The geometric model of this subduction is shown in Figure 3.3.

Focal mechanisms of earthquakes on the plate interface indicate interplate slip in a direction of $S70^\circ W$ (Deng and Sykes, 1995). The rate of movement between the major plates, as measured by GPS, is about 21 mm/yr (Dixon et al, 1998). Rates of movement along secondary features representing interblock movements are about a factor of ten less

(McCann, 1985; Jansma et al., 2000). NA-CA slip directions have remained essentially unchanged for at least the last five Ma (Muller et al., 1999). Major earthquakes within the upper plate such as those in 1867 ($\sim 7.3 M_s$), 1918 ($7.3 M_s$) and 1974 ($7.1 M_s$) indicate that important active faults exist in the region in addition to the main interplate faults (Figure 3.2). Based on the historical information and tectonic setting this region has a potential for great earthquakes of $M > 8.0$ (McCann 2000).

3.2. Seismic networks and Recordings

Locations of seismographic networks, which provide ground motion data for the Puerto Rico and Virgin Island region, are shown in figure 3.4.

The Puerto Rico Seismic Network (PRSN), consisting of 13 vertical component short-period 1Hz natural frequency seismometers was installed in 1974. Digital time series have been recorded by the PRSN since 1991 in IASPEI format (16-bit A to D converter, 100 samples/Sec). More than 2000 time series recorded by the PRSN, from more than 300 events with $M \geq 3.0$ have been compiled. Time series recorded before 1991 cannot be used due to lack of information about the instrument responses. Nine new three component broadband stations are being installed as of 2000 and will soon provide additional data.

The Puerto Rico Strong Motion Network (PRSMN) has been installed gradually since 1994, and now comprises 32 strong motion stations. The number of recorded acceleration time series is limited, since the earthquake ground motion must be strong enough to trigger these accelerographs. About 30 acceleration time series from 4 events are available from this network.

There has been a single **IRIS/USGS** station (SJG) operating in Puerto Rico since 1993; it includes five broadband seismometers (three-component), and one short period seismometer (three-component). The sampling rate of the short period three-component seismometers is 80 samples/sec. The highest sampling rate for the broadband seismometer data is 20 samples/sec (The sampling rate of the other broadband seismometers at SJG station is too low to be used for our study.). From SJG station, 1289 time series from 319 events with $M \geq 3.0$ have been compiled (where M is the catalog magnitude). These are the data with highest reliability, and well known instrument response.

Lamont-Doherty Earth Observatory. (LDEO) operated a 17 station short-period vertical-component network for several years. Digital time series recorded by LDEO from 1979 to 1983 are available on magnetic tapes. The instrument responses of the stations are not available.

3.3. Instrument Response Issues

In order to study ground motion processes, we need to remove all instrument response effects from the records, so that we can obtain the actual motion of the ground. Therefore, we need detailed information on the transfer function of the instruments. Instrument-corrected data then allow compilation of a regional ground-motion database in a uniform format for ground motion studies. In this section I review instrument responses for available seismographic recordings.

PRSN- The main purpose of the PRSN network was to locate local earthquakes. Instrumentation response information, specifically the poles, zeros and constant of the transfer function, are necessary for removing the instrument response from the time

series, but were not available. (Using the recorded time series of PRSN for the purpose of ground motion studies was not the main purpose of that network.) Fortunately however, one of the PRSN stations is located at the IRIS/USGS broadband site (SJG station). Since the instrument response of IRIS/USGS is well known, SJG records may be used to calibrate the instrument response of the PRSN equipment.

In order to best record small local earthquakes with local networks the gain (VCO gain) of stations is generally high. Consequently the recorded time series of moderate to large earthquakes or very nearby earthquakes are clipped. About 75% of recorded time series of the PRSN have been clipped and cannot be used for the purpose of this project.

PRSMN- The instrument response information for the PRSMN strong motion network is well known. All PRSMN records are suitable for our research.

IRIS/USGS- The instrument response information for all channels at the IRIS/USGS station SJG is available, but there were some difficulties. Comparison of earthquake ground motion recorded by both the broadband and short-period seismometer at the SJG station led us to discover that the vertical-component of the short-period seismometer was not stable since a few months after its installation. Therefore the recorded time series from the short-period vertical-component at SJG cannot be used.

Furthermore, comparison of times series which were recorded on horizontal components by different channels also revealed problems with the response of the horizontal-component of the short period seismometer at SJG.

Due to these apparent problems and in view of the importance of having reliable instrument corrections at each site, I decided to measure instrument response for all of the recorded time series of the PRSN in situ. One of the PRSN station is located at the IRIS/USGS broadband site (SJG station). Since the instrument response of the broadband component of the SJG site of IRIS/USGS is available and reliable, SJG broadband records were considered as a reference for calculation of instrument response of the corresponding PRSN site. A portable seismograph (Orion system manufactured by Nanometrics Ltd.) with a broadband seismometer (CMG40T) was placed at the SJG site, in order to accurately calibrate the instrument responses. The instrument response of the Orion with the CMG40T seismometer is well known and plotted in figure 3.5. Appendix A describes the procedures for calculation of the instrument response of the Orion+CMG40T. The Orion was left at SJG for long enough to record 3 local earthquakes. By comparing these Orion recordings to the IRIS and PRSN records, I confirmed the response information for the IRIS broadband site, and calculated the response for the co-located PRSN station. Therefore the instrument response of that PRSN station has been obtained.

In order to obtain the instrument response of the other PRSN stations a sine wave generator was used to input a sine electrical current to the calibration coil of seismometer at remote sites. The relation between the AC input current and the corresponding mass velocity is known through the manufacturer's manuals. Therefore the input velocity to the seismometer at remote site can be calculated. Knowing the input velocity to the seismometer at the remote sites and then recording the output sine waves at the central recording site allowed us to obtain the relative instrument responses of the PRSN stations. That response includes the instrument response of the seismometer plus all of the other equipment, including the VCO, telemetry equipment, amplifier, digitizer and

anything in between which can influence the recorded seismic wave. By comparing the known instrument response of the PRSN station at SJG with the relative instrument responses of the PRSN stations, I determined the actual instrument responses for the other PRSN stations. Figures 3.6 shows the obtained instrument responses for some of the PRSN stations (as of 2000).

In order to determine the stability over time of the obtained instrument responses of the PRSN stations, the residuals (e.g. deviations from calculated model values) of the Fourier spectra have been plotted versus time for all of the recorded data. (The procedures for calculating residuals will be discussed later, at this point we are just interested in viewing the residual pattern over time to spot any likely instrument response problems.) Figure 3.7 shows the log residuals versus time of the IRIS, SJG station (broadband seismometers). The figure shows that instrument response has not changed over time. Figure 3.8 shows residuals of the calibrated stations of the PRSN versus time (based on the obtained instrument responses). The variability of residuals in figure 3.8 as compared to figure 3.7 reflects not only greater uncertainty in instrument response, but also variability of site responses at different PRSN stations. Data which deviate from the mean trend by log factors of 1.5 or more likely reflect a change in the VCO gain setting at a specific station and time. (The VCO gain is a parameter that can be easily changed by this kind of seismic network in order to increase the quality of transmitted data.). These suspect data were removed from the ground motion database.

3.4. Compilation of time series

I began this study with a detailed inventory of the recorded time series available from the Puerto Rico Seismic Networks. Based on the above-mentioned difficulties with instrument responses, I am relying mostly on the digital records obtained in the period

from 1993 through 2000. Since several small-to-moderate events are recorded every month, these data allow compilation of a good regional ground-motion database, in a uniform format readily accessible for computer analysis.

For the broadband seismometers at SJG, considering the Nyquist frequency of 10 Hz and the flat part of instrument response, the maximum reliable frequency has been considered as 8Hz for the calculation of response spectra and Fourier amplitudes. The minimum frequency may be as low as 0.1 Hz, depending on the signal/noise ratio of each recording. For PRSN data the reliable frequency range is approximately 0.5 to 8 Hz.

Fourier amplitudes and response spectra of more than 3000 time series (of known/calibrated instrument response) from more than 300 earthquakes in the Puerto Rico region have been analyzed. The S window and background noise have been windowed for all of the time series. I compile data for which the signal to noise ratio is at least a factor of 2. For each record, the time series were processed as follows:

- Define S-window and pre-event noise (minimum 10 second noise window were used for calculation of signal to noise ratio). The S-window includes the strongest shaking and its coda.
- Remove any glitches.
- Taper the windowed time series using a 5% taper on each end of signal.
- Zero-Pad the time series to the next greatest power of 2.
- Transfer to frequency domain by application of Fast Fourier transform.
- Calculate instrument response based on the poles, zeros and constant for that specified component of the seismographic station.

- Remove the instrument response in the frequency domain by dividing the recorded spectrum by the instrument transfer function.
- Convert Fourier spectra of velocity to Fourier spectra of acceleration (done in the same step as removal of instrument response).
- Transfer to time domain by applying the inverse Fourier transform.
- Calculate response spectra for 5% damping from corrected acceleration time series.
- Discard data points at the frequencies showing signal to noise ratio less than 2 (Note: the noise window is normalized to the same length as the signal window to check the signal/noise ratio.)
- Smooth the Fourier spectra by using a weighted 9-point smoothing algorithm.

Figure 3.9 plots two typical events (mb4.2 at 68km and mb4.2 at 350km) for Puerto Rico region showing the S-window.

3.5. Features and Limitations of database

I focus on digitally recorded earthquakes within 500km of Puerto Rico, with magnitude (mb or M) greater than 4.0, recorded since 1993. There are few data at large magnitudes and at short distances (less than 100 kilometers). To overcome the paucity of data at short distances I also compiled and included records for smaller earthquakes ($3.0 \leq M \leq 4.0$) recorded at close distances (≤ 200 km). (Note: For small earthquakes, since there is usually no estimate of M or mb, the local coda magnitude is quoted.) I processed the time series available for all such recordings. Among more than 3000 time series, more than half of them were unusable due to unstable instrument responses, unavailable instrument responses, or clipping.

Table 3.2 shows the list of earthquakes which have good records (1289 records for 302 events for magnitude greater or equal M3.0), which were used in our study. Figure 3.10 and 3.11 show the epicenter and depth distributions of the used earthquakes, respectively. The influence of subduction at both the North America plate boundary to the north of Puerto Rico and Los Muertos Trough to the south of Puerto Rico can be seen in the deep earthquakes. Seismicity related to the subducting slab is of two general types: interface earthquakes, which are the result of direct contact between two plates and in-slab earthquakes, which are the result of the internal deformation in the downgoing slab. As well as subduction seismicity, which can be both shallow and deep earthquakes, there is also crustal seismicity (above 40 km) due to the other seismic sources in Puerto Rico region. Data from the Puerto Rico networks reveal that earthquake activity is not evenly distributed, in either space or in time. Distinct regions of persistently high levels of seismic activity are observed along the main plate interface and within the plate boundary zone (McCann, 2002). Individual as well as spatially and temporally clustered earthquakes swarms are observed. This seismicity reflects a slab of North American lithosphere continuous from the Puerto Rico Trench to depths of 125 km or more (McCann, 2002). Based on the scattered distribution of events shown in Fig. 3.11 it is not feasible to class each event as crustal, interface or in-slab. However we can examine the influence of focal depth on results as a way of partially addressing this issue.

Figure 3.12 shows the magnitude and distance distribution of the time series used. The problem of paucity of data at short distances has been overcome by including the smaller earthquakes, but the crucial lack of big earthquakes in our database still remains. In table 3.2 the moment magnitude is listed for each event. The determination of these magnitudes is discussed later (chapter 5).

Figure 3.1. Seismicity of Central America: 1977 - 1997

Figure 3.2. Puerto Rico lies near the northeastern corner of the Caribbean Plate. To the north and east lies the westerly moving North American Plate. The northeastern Caribbean is dominated by the slow subduction of the North American Plate (NA) beneath the leading edge of the Caribbean Plate. Important active faults (black lines) exist in the region.

The diagram illustrates the tectonic setting of the Puerto Rico Trench. A thick black line represents the **North American Plate**, which is shown dipping towards the **South**. A horizontal double-headed arrow indicates a distance of **130 km** from the trench to the left. Within the plate, an arrow points to **Intraslab Earthquakes**. The plate dips at an angle of **41°** relative to a horizontal line. At the trench, the plate is **40 km** below **Sea Level**. Below the main plate, a dashed line represents the **Interface**, with an arrow pointing to **Interface Earthquakes**. This interface dips at an angle of **21°** towards the **North**. The **Puerto Rico Trench** is shown as a curved line at the surface, with a depth of **7.5 km** indicated. A bracket on the left side of the diagram indicates a width of **50 km**. The **South** direction is indicated at the top, and the **North** direction is indicated at the bottom.

Figure 3.4. Locations of The Puerto Rico Seismic Network (PRSN), consisting of 13 vertical-component short-period seismometer (red triangle). Nine new three component broadband stations (green star) are being installed as of 2000 and will soon provide additional data.

**figure 3.5. instrument response of Orion and
CMG-40T**

**figure 3.6. instrument response of PRSN
Stations**

Figure 3.7. Residuals of IRIS sig station records

Figure 3.8. PRSN all stations residuals

Figure 3.9. Typical waveforms for two events in Puerto Rico Region

Figure 3.10. epicenter distribution of the used earthquakes

Figure 3.11. Depth Distribution of the used events

Figure 3.12. Magnitude and distance distribution of used time series

**Table 3.1. SIGNIFICANT EARTHQUAKES IN THE PUERTO RICO REGION
(FROM PRSN WEBSITE)**

September 8, 1615: Earthquake in the Dominican Republic that caused damages in Puerto Rico (A).

August 15, 1670: Damages in San Germán and San Juan (MJ).

1717: Church San Felipe in Arecibo and the parochial house in San Germán were destroyed (A).

August 30, 1740: The Church of Guadalupe in Villa de Ponce was destroyed (A). Intensity VII, there is only information from Ponce that the earthquake was felt, absence of information of San Germán and the information of Yauco and Lajas, suggest a superficial earthquake to Ponce (G).

May 2, 1787: A strong earthquake was felt in the whole island, damages of all places were reported, except in the South. In the islet of San Juan there were considerable damages and several structures collapsed (DH, according to information of the Town hall of San Juan, 1787). The walls of the Guadalupe Church in Ponce were cracked (G).

April 20, 1824, 3:00am: Strong earthquake in San Tomas, a building was destroyed (RT).

April 16, 1844, 9:20am: the epicenter was located to the north of the island and felt in Puerto Rico (VII-VIII, (RF)) and San Tomas. Several buildings collapsed and cracked. A tower of the Church of Isabela was cracked. It was felt for about 30 seconds (RT). In San Juan almost all the stone houses were cracked @ (Barbadian Newspaper, May 25 of 1844). Intensity of VII in San Juan (SL).

May 5, 1844: A strong earthquake was felt in Ponce. It was accompanied by a strong underground noise; a terrible earthquake for the island (G). Asencio (1980) also includes it in its listing (it puts 3 references). Note: Since the different catalogues talk about to the tremor of April 16 or May 5, with the exception of MJ that question the one of the 5 of May, it can be that it only happened one of these tremors. November 28, 1846, 5:00pm: Sense in all the island, more force and damages in the northwest with Maxima intensity of VII (RF). Origin probably in the Passage of Mona (RT).

February 22, 1851: The walls of the Mayorship of San Juan were cracked (RT).

December 14, 1855, 8:15am: Salt mines VI and Good Waters V (RF). One says that it is the tremor more hard than one has felt in Salt mines. Origin probably to the south of the island (RT). Diaz Hernandez reported it like of the 4 of February of 1855.

October 23, 1860: Tremor of strong earth with some damages in Mayagüez, Intensity VI-vii (RT). May 12, 1865, 9:30am: Two strong tremors in San Tomas, the second caused damages (RT).

August 30, 1865: Churches in Manatí and Ponce were cracked. The origin could have been the center of the island. Intensity of VI (RF) (RT). It happened at night, origin probably in the central part of the deep island and (50-100 km) (G).

November 18, 1867, 2:50pm: The epicenter of this earthquake was located between San Tomas and Santa Cruz in the Virgin Islands, $M=7.3$ (PS). It produced ample damages in the Islands Vírgenes and Puerto Rico by the acceleration of the ground and tsunami. Reid and Taber assigned an intensity equivalent from elevated a VIII to IX to this earthquake. One felt strong in all Puerto Rico, but the most severe effects were in the Eastern part. A fort tsunami was observed for this earthquake, specially in the Virgin Islands, its height was considered in about twenty feet. Tsunami was observed throughout the coasts of the east and the south of Puerto Rico. Observations of peak altitudes for the waves in Puerto Rico went of three on five feet, in cercanías of Stream, the suroriental coast. Although to this earthquake an intensity equivalent to elevated a VIII to IX by Reid was assigned to him and Taber, Robson proposed that this earthquake had an intensity of VIII. It had more than 500 retorts during a period of six to seven months (PRWRA). In Ponce, 70 of the 80 chimneys of the talents of azúcar colapsaron (intensity MM = VI; SL).

December 1, 1867: Three retorts of the earthquake of November 18, intensity VII-viii (RF). Additional damages in Puerto Rico and Islas Vírgenes (RT).

March 17, 1868, 6:45am: Greater retort of the earthquake of the 18 of November of 1867. It happened to 30 miles to the southwest of the original epicenter. Smaller damages mainly in the Eastern part of the Island of Puerto Rico (PRWRA). Intensity, RG of VII - VIII (RT).

September 17, 1869, 3:00pm: Almost equal earthquake in San Tomas from fort like the one of November 18, 1867 (RT).

August 26, 1874, 6:15am: Hard tremor (V-vi) registered in Puerto Rico (in the morning). One inquired into destroyed houses (DH). In San Juan, the vibration lasted two minutes, the houses moved of side to side, the inhabitants was alarmed, did not report victims, intensity of VI (SL).

December 8, 1875, night: Apparently it happened an earthquake near Arecibo. Few damages were reported, except in a church that suffered enough. Originally había assigned an intensity of VII-viii (RF), but Reid and Taber to him concluded that it is too much discharge, because damage in only a site was reported (PRWRA). In Ponce one felt with force, center surely in the island between 50-100 km (G).

August 15, 1890 1:45am: A violent earthquake was reported from different towns from the island. In Arecibo the bells of the church repicaron and in Ponce the municipal jail suffered damages (DH). In Ponce the event lasted about 8 to 10 seconds (G).

May 13, 1902: Sense very hard (V-vi in San Tomas) (RT).

September 27, 1906, 10:41am: The epicenter of this earthquake was considered to about 50 kms to the north of the island. The Maxima intensity was of VI in San Juan where cracks in the Cathedral and many houses were observed. The intensity in the rest of the island was of IV - V. Tsunami was not reported. It was felt from Santo Domingo to San Tomas, a distance of 500 km (RT). In addition to San Juan, other towns reported damages (DH).

October 20, 1906, 4:10pm: Sense in almost all the island. IV-vi (RF) reported from San Juan and Crossings (PRWRA; DH; RT).

August 4, 1908, 6:20am: Strong earthquake (VI, (RF)) in Ponce where there were some damages, also felt in Alto de la Bandera, Yauco, Arecibo and San Germán (RT). Origin probably in the south-center area of the island (G).

August 13, 1908, 4:07am: Strong Earthquake felt in Ponce, the Building of Post office suffered damages. It was a heave, very rare in this zone. Weigh in Carmelite. Origin probably near Ponce (RT).

February 17, 1909, 2:50am: Tremor felt in the Virgin Islands and almost all Puerto Rico. In San Tomas and Culebra an intensity of up to VI (RF); 90 kms NNE of Vieques (RT).

October 11, 1918, 10:14am: The epicenter was located about 35 km to the Northwest of Aguadilla, PR in the Tube of Mona. Magnitude of 7.3 (PS). Reid and Taber assigned a Maxima intensity of IX (equivalent to VIII - IX in MM) in the western part of the island and of V - VI in Guayama. This earthquake generated tsunami (tidal wave) that reached 20 feet in Bored End (8 people reported themselves like drowned), 12 feet in Aguadilla (32 people died drowned), 5 feet in Mayag5uez (116 people died because of the earthquake, including the 40 victims of the tidal wave). The losses by damages to the property were considered in more than \$4.000,000 (RT). By several months they were continued feeling retorts of this earthquake, strongest being those of the 24 of October and 12 of November.

October 24, 1918, 11:43pm: Retort of the earthquake of the 11 of October. Maxima intensity in the island was VII (RF).

November 12, 1918, 5:45pm: Another retort of the earthquake of the 11 of October. Maxima intensity in the island was VI (RF, RT).

February 10, 1920, 6:07pm: Earthquake felt in all Puerto Rico. Maximum intensity was VI (DH), M=6.5.

December 18, 1922, 8:35am: Earthquake felt in all Puerto Rico. Maximum intensity in the island was VI (DH), M=6.3.

June 12, 1939 12:05am: Earthquake felt in all of the island. Maximum intensity of VI (DH).

July 28, 1943, 11:02pm: It happened to the Northwest of Puerto Rico. Its magnitude was of 7.5 (PS). It was felt by many people around Puerto Rico, but it did not cause damages.

August 4, 1946, 1:51pm: This earthquake of magnitude 7.8 (PS) happened outside the northeastern coast of the Dominican Republic. Ample damages and tsunami were reported in Haiti and the Dominican Republic. This earthquake was felt with an intensity of up to VI in the Mona Island and the western coast of Puerto Rico. In the rest of the island an intensity of V was reported. A tsunami of 2 feet was observed in the western and north coast of the island (PRWRA). Smaller damages in all Puerto Rico were reported (DH).

August 8, 1946, 9:28am: Earthquake in Dominican Republic (M=7.4, PS). Small tidal wave in Mayaguez and Aguadilla.

March 23, 1979 3:33pm: Strong earthquake felt in all the area of the Caribbean; in Puerto Rico it was felt with an intensity of VI. It was reported in Haiti, Colombia, Venezuela and Dominican Republic (DH). Epicenter to the south of the Dominican Republic, 17.89N, 68.97W, and 73 km of depth, M=6.1 (USGS).

August 24, 1981 5:50am: Strong earthquake felt in all Puerto Rico, M=5.7. Epicenter in the Mona Channel. There were only slight damages in Guayanilla (DH).

May 30, 1987 1:55pm: Strong earthquake felt in the southwest of the island, M=4.6, intensity VI. Epicenter near Big hole. There were slight damages (USGS).

* All hours are local. M is the magnitude that reflects the energy released by the earthquake. If it is not specified that the intensity is RF (RossiForell), it is MM (Modified Mercalli).

Table 3.2. Used earthquakes in this study

	date			Time	LAT.	LONG.	DEPTH	catalogue	Moment
	Y	M	D	h				Magnitude	Magnitude
1	1993	7	22	20	18.58	-69.00	109	4.8 mb	4.5
2	1993	8	1	19	17.40	-65.72	25	5.3 Mw	5.3
3	1993	8	10	7	19.35	-64.89	36	4.5 mb	4.3
4	1993	9	30	0	18.75	-62.80	33	4.3 mb	3.5
5	1993	10	3	13	17.80	-62.75	10	4.2 Md	3.8
6	1993	10	18	9	18.66	-64.45	30	4.3 mb	4.0
7	1993	10	24	17	19.68	-70.38	33	4.0 mb	4.1
8	1993	11	5	2	19.02	-66.01	48	4.9 mb	4.4
9	1993	11	8	3	19.20	-68.08	10	4.6 mb	4.1
10	1994	1	6	17	18.05	-68.37	87	4.0 mb	4.2
11	1994	1	8	22	18.22	-64.33	103	4.8 mb	4.6
12	1994	1	13	20	18.84	-66.18	47	4.0 mb	3.7
13	1994	1	18	12	18.58	-68.82	163	4.6 mb	4.3
14	1994	1	21	18	19.67	-64.43	10	4.0 mb	3.8
15	1994	2	25	16	19.25	-64.23	33	4.3 mb	4.2
16	1994	2	25	17	19.25	-64.33	32	4.9 mb	4.7
17	1994	3	1	18	19.39	-65.16	10	4.3 mb	4.1
18	1994	3	10	3	17.81	-65.35	10	4.1 mb	3.8
19	1994	4	21	17	18.00	-62.88	75	5.0 mb	4.8
20	1994	5	1	4	17.93	-64.70	162	4.3 mb	3.9
21	1994	6	25	6	19.01	-66.83	46	4.7 mb	4.3
22	1994	6	25	8	18.94	-66.68	33	4.0 Md	3.4
23	1994	7	11	3	19.23	-66.76	10	4.4 mb	4.1
24	1994	7	17	23	17.63	-62.94	131	4.2 mb	4.0
25	1994	9	23	23	18.43	-61.53	31	4.4 Md	4.3
26	1994	10	12	3	18.24	-68.37	107	4.4 mb	4.3
27	1994	11	17	3	17.92	-68.69	33	4.5 mb	4.3
28	1994	11	17	14	18.62	-68.34	81	4.7 mb	4.7
29	1994	11	30	2	19.53	-64.60	19	4.5 mb	4.5
30	1995	1	1	9	19.22	-69.42	42	4.8 mb	4.9
31	1995	1	18	20	18.89	-70.33	91	5.0 mb	5.1
32	1995	2	1	10	18.19	-68.36	179	4.6 mb	4.7
33	1995	2	16	11	18.88	-64.18	33	4.1 mb	4.3
34	1995	2	16	14	19.48	-65.79	33	4.0 mb	4.3
35	1995	5	4	20	18.89	-64.29	47	4.5 Md	4.3
36	1995	6	20	13	17.88	-62.85	100	4.2 mb	4.3
37	1995	7	9	18	19.62	-67.14	33	4.6 mb	4.1
38	1995	7	26	9	19.19	-64.67	52	4.6 mb	4.5
39	1995	7	28	0	19.57	-69.62	33	4.2 mb	4.3
40	1995	8	13	9	19.41	-69.36	10	4.4 mb	4.3
41	1995	9	19	3	18.79	-62.53	10	4.7 mb	4.1
42	1995	10	8	4	19.01	-66.96	46	4.8 Md	4.4
43	1995	10	31	1	19.70	-69.75	62	4.8 mb	4.2
44	1995	12	9	5	18.89	-65.71	50	4.2 mb	3.8
45	1995	12	31	0	18.44	-64.60	33	4.7 Ml	4.2
46	1996	1	2	18	18.79	-62.70	33	4.5 Ml	3.9
47	1996	1	24	1	18.19	-69.99	50	4.4 mb	4.1
48	1996	3	20	12	19.22	-66.75	33	4.1 mb	3.9
49	1996	4	9	19	18.88	-69.72	88	4.1 mb	4.2

50	1996	5	11	2	19.31	-64.96	35	5.1 Mw	5.1
51	1996	5	12	4	18.48	-63.84	33	4.7 mb	4.4
52	1996	5	14	11	18.94	-65.08	33	4.2 mb	3.9
53	1996	5	29	11	18.06	-69.64	52	4.0 mb	4.1
54	1996	6	11	16	17.25	-68.28	33	5.5 mb	4.7
55	1996	6	12	3	20.03	-70.19	33	4.5 mb	4.3
56	1996	7	21	9	18.30	-62.41	60	4.5 mb	4.2
57	1996	10	17	17	19.02	-69.11	33	4.4 mb	4.3
58	1996	11	1	1	18.60	-64.28	33	4.4 mb	3.8
59	1996	11	6	2	18.85	-64.32	21	5.1 mb	4.7
60	1996	11	8	7	18.04	-68.53	73	4.8 mb	4.5
61	1996	12	4	19	19.04	-69.26	108	4.2 mb	4.3
62	1997	2	24	4	19.32	-69.23	90	4.5 mb	4.1
63	1997	3	17	5	19.01	-62.84	33	5.5 Mw	5.5
64	1997	4	5	21	19.08	-63.12	33	4.3 mb	4.0
65	1997	5	14	2	19.63	-70.29	54	4.7 mb	4.7
66	1997	7	30	16	18.00	-70.32	10	4.9 mb	4.1
67	1997	10	12	15	18.58	-66.22	100	3.7 Md	3.3
68	1997	10	15	19	18.67	-67.44	10	3.3 Md	3.5
69	1997	10	24	0	17.99	-65.31	5	3.2 Md	3.1
70	1997	11	2	11	19.24	-66.34	33	4.3 mb	4.1
71	1997	11	21	7	18.56	-67.01	100	3.2 Md	3.2
72	1997	12	6	17	18.75	-67.34	80	3.5 Md	3.2
73	1997	12	21	2	18.58	-66.54	80	3.1 Md	3.0
74	1997	12	26	0	18.18	-68.44	94	4.7 mb	4.3
75	1997	12	27	13	17.82	-66.10	5	3.0 Md	2.8
76	1997	12	31	3	17.84	-66.10	10	3.0 Md	2.8
77	1997	12	31	21	18.50	-66.13	100	3.1 Md	3.2
78	1998	1	16	12	18.55	-66.12	106	3.1 Md	3.0
79	1998	1	17	23	18.96	-64.61	72	3.5 Md	3.3
80	1998	1	18	14	19.17	-64.66	25	4.4 mb	4.0
81	1998	1	18	13	18.98	-64.64	52	3.6 Md	3.3
82	1998	1	19	22	18.20	-67.17	13	3.7 Md	3.3
83	1998	1	20	12	19.03	-65.09	97	3.5 Md	3.3
84	1998	2	13	3	19.09	-66.09	27	3.0 Md	3.1
85	1998	2	13	18	18.05	-65.46	14	3.7 Md	3.3
86	1998	2	18	16	18.37	-64.97	24	3.3 Md	3.1
87	1998	2	19	5	19.15	-66.43	37	3.0 Md	3.1
88	1998	3	5	7	20.01	-63.15	33	5.1 Mw	5.1
89	1998	3	10	23	18.04	-65.60	1	3.2 Md	3.0
90	1998	3	12	6	18.14	-66.70	60	3.5 Md	3.3
91	1998	3	19	1	18.86	-66.02	56	3.1 Md	3.1
92	1998	3	25	8	19.38	-67.09	25	4.9 mb	4.4
93	1998	3	27	3	18.66	-64.25	50	3.4 Md	3.4
94	1998	4	1	6	18.15	-67.34	0	3.1 Md	3.1
95	1998	4	10	12	18.15	-66.85	16	3.0 Md	2.9
96	1998	4	15	6	18.18	-64.20	25	3.5 Md	3.3
97	1998	4	15	17	17.92	-65.54	2	3.8 Md	3.5
98	1998	4	16	18	17.78	-65.61	2	3.1 Md	3.1
99	1998	4	16	20	18.02	-65.63	0	3.6 Md	3.0
100	1998	4	16	22	18.07	-65.54	0	3.0 Md	2.9
101	1998	4	17	6	19.08	-67.36	22	3.1 Md	3.2
102	1998	4	18	9	18.65	-67.49	1	3.6 Md	3.3
103	1998	4	20	15	18.67	-66.72	79	3.4 Md	3.1
104	1998	4	25	5	19.00	-67.49	25	3.3 Md	3.2

105	1998	4	26	10	18.22	-67.09	20	3.6 Md	3.1
106	1998	4	26	14	19.07	-66.41	30	3.3 Md	3.0
107	1998	4	29	15	18.16	-65.87	87	3.8 Md	3.5
108	1998	4	30	0	18.71	-65.04	71	3.2 Md	3.2
109	1998	5	12	4	18.04	-65.55	0	3.1 Md	2.8
110	1998	5	14	6	17.95	-64.67	25	3.6 Md	3.2
111	1998	5	15	21	19.14	-66.49	49	3.5 Md	3.3
112	1998	5	22	4	19.22	-66.70	36	3.8 Md	3.4
113	1998	5	24	5	19.11	-67.17	25	3.6 Md	3.2
114	1998	5	27	19	19.23	-66.65	24	3.7 Md	3.4
115	1998	5	29	15	19.66	-66.95	10	3.6 Md	3.5
116	1998	6	8	11	18.19	-66.54	66	3.6 Md	3.2
117	1998	6	13	4	17.75	-64.14	30	3.6 Md	3.3
118	1998	6	13	9	19.48	-66.36	48	3.9 Md	3.4
119	1998	6	14	13	18.62	-65.27	48	3.9 Md	3.5
120	1998	6	18	22	18.08	-65.53	0	3.3 Md	2.9
121	1998	6	21	2	18.97	-64.30	58	3.6 Md	3.4
122	1998	6	23	19	19.42	-65.28	49	3.8 Md	3.5
123	1998	6	24	22	17.74	-66.33	17	3.6 Md	3.2
124	1998	6	25	4	18.68	-65.99	68	3.1 Md	3.1
125	1998	7	4	23	18.32	-65.95	135	3.7 Md	3.1
126	1998	7	5	7	18.85	-67.23	18	3.0 Md	3.0
127	1998	7	19	9	18.30	-65.10	131	4.6 mb	4.2
128	1998	7	25	22	19.12	-66.11	15	3.1 Md	3.2
129	1998	7	27	1	18.71	-66.51	25	3.1 Md	3.1
130	1998	7	28	8	18.69	-65.00	25	3.3 Md	3.2
131	1998	8	2	2	18.84	-67.27	13	3.1 Md	3.1
132	1998	8	3	21	18.61	-67.44	12	3.3 Md	3.2
133	1998	8	4	15	19.23	-64.66	60	3.8 Md	3.8
134	1998	8	4	21	19.13	-64.51	56	3.6 Md	3.3
135	1998	8	5	23	19.23	-64.66	60	3.7 Md	3.7
136	1998	8	8	7	18.01	-66.61	13	3.0 Md	2.8
137	1998	8	9	11	19.74	-70.00	33	4.5 mb	4.0
138	1998	8	9	21	18.97	-64.93	22	3.5 Md	3.2
139	1998	8	9	23	18.85	-64.55	95	3.6 Md	3.4
140	1998	8	10	21	18.65	-70.54	58	5.2 Mw	5.2
141	1998	8	10	0	19.16	-64.77	72	3.7 Md	3.5
142	1998	8	10	8	19.30	-64.74	25	3.6 Md	3.3
143	1998	8	11	6	19.21	-66.14	25	3.0 Md	3.0
144	1998	8	26	10	18.75	-65.99	69	3.6 Md	3.3
145	1998	8	30	20	18.69	-70.27	33	4.2 mb	4.0
146	1998	9	2	8	17.96	-66.34	9	3.3 Md	2.8
147	1998	9	3	15	17.94	-66.33	8	3.2 Md	2.7
148	1998	9	12	4	17.94	-66.32	6	3.2 Md	2.7
149	1998	10	10	2	18.25	-66.29	6	3.2 Md	2.6
150	1998	10	15	21	18.49	-70.47	68	4.4 mb	4.4
151	1998	10	15	4	18.86	-65.16	53	3.6 Md	3.2
152	1998	10	18	0	17.96	-65.68	5	3.2 Md	2.9
153	1998	10	22	7	18.92	-65.14	59	3.6 Md	3.4
154	1998	10	23	18	18.87	-64.38	33	4.0 Md	3.7
155	1998	10	23	19	19.50	-64.55	65	3.8 Md	3.9
156	1998	10	24	1	18.86	-64.32	56	4.6 mb	4.2
157	1998	10	24	14	18.62	-66.73	19	3.4 Md	3.0
158	1998	10	29	4	18.20	-65.94	14	3.0 Md	2.7
159	1998	11	1	21	19.04	-65.23	45	3.6 Md	3.3

160	1998	11	1	22	19.14	-65.13	67	3.6 Md	3.4
161	1998	11	3	19	18.84	-65.07	25	3.4 Md	3.1
162	1998	11	4	2	18.75	-65.93	73	3.1 Md	3.0
163	1998	11	9	5	19.30	-65.25	75	3.7 Md	3.4
164	1998	11	11	8	18.24	-67.04	17	3.9 Md	3.4
165	1998	11	15	0	18.82	-66.25	35	3.1 Md	3.0
166	1998	11	16	12	18.90	-67.38	58	3.1 Md	3.1
167	1998	11	21	1	18.84	-65.23	72	3.1 Md	3.2
168	1998	11	23	7	18.72	-66.12	25	3.1 Md	2.9
169	1998	11	24	6	19.14	-67.78	33	4.4 mb	4.1
170	1999	1	18	19	18.86	-67.22	33	5.0 Mw	5.0
171	1999	1	25	10	16.89	-62.50	140.3	4.6 mb	4.0
172	1999	1	25	17	19.50	-66.69	50.1	4.6 mb	4.0
173	1999	1	27	12	18.94	-63.26	33	4.1 mb	4.2
174	1999	4	20	5	18.58	-65.37	91.8	4.2 mb	3.6
175	1999	8	5	15	18.88	-67.18	71.6	4.3 mb	4.0
176	1999	8	7	12	18.76	-66.86	63.4	4.5 mb	4.1
177	1999	10	28	12	18.72	-67.25	33	4.1 mb	3.8
178	1999	12	20	10	17.31	-61.71	58.8	5.4 mb	5.0
179	2000	1	6	11	18.26	-68.32	178	4.0 Md	3.8
180	2000	1	9	2	17.94	-67.00	28	3.1 Md	3.4
181	2000	1	9	5	18.77	-67.25	68	3.2 Md	3.2
182	2000	1	13	18	18.97	-66.58	45	3.1 Md	3.0
183	2000	1	14	6	18.14	-67.91	131	3.4 Md	3.4
184	2000	1	18	11	17.93	-65.66	4	3.1 Md	2.9
185	2000	1	18	23	18.93	-68.10	10	3.8 Md	3.4
186	2000	1	22	12	18.63	-66.88	12	3.0 Md	2.8
187	2000	1	25	14	19.61	-68.06	69	4.1 Md	3.7
188	2000	1	26	15	19.00	-67.76	34	3.0 Md	3.2
189	2000	1	29	3	18.89	-64.30	50	4.4 mb	4.1
190	2000	2	2	9	18.28	-66.23	74	3.0 Md	2.9
191	2000	2	3	11	19.17	-66.52	9	3.6 Md	3.2
192	2000	2	4	0	19.48	-68.05	15	3.7 Md	3.4
193	2000	2	4	23	17.86	-67.04	28	3.2 Md	3.1
194	2000	2	6	21	17.99	-65.55	4	3.1 Md	2.9
195	2000	2	9	4	18.69	-67.52	2	3.5 Md	3.3
196	2000	2	10	4	18.07	-65.86	7	3.8 Md	3.3
197	2000	2	21	16	18.32	-67.88	108	4.4 mb	4.0
198	2000	2	26	12	18.93	-65.90	76	3.9 Md	3.3
199	2000	2	27	23	17.83	-60.99	16	5.0 Md	4.6
200	2000	3	2	14	18.89	-65.18	42	3.7 Md	3.3
201	2000	3	5	6	18.91	-66.85	10	3.2 Md	2.9
202	2000	3	5	16	19.04	-66.86	40	3.3 Md	2.9
203	2000	3	5	20	18.95	-66.91	46	3.0 Md	3.0
204	2000	3	6	1	18.89	-66.40	46	3.0 Md	2.9
205	2000	3	6	2	18.13	-66.92	13	3.2 Md	3.1
206	2000	3	8	2	18.08	-67.11	18	3.0 Md	2.9
207	2000	3	8	9	19.16	-66.48	41	3.6 Md	3.1
208	2000	3	9	0	17.83	-65.66	8	3.4 Md	2.9
209	2000	3	14	18	18.01	-67.07	5	3.5 Md	3.1
210	2000	3	15	9	19.72	-66.04	72	3.9 Md	3.5
211	2000	3	20	15	18.41	-66.62	119	3.9 Md	3.7
212	2000	3	22	2	18.52	-67.56	9	3.0 Md	3.2
213	2000	3	25	7	19.58	-68.15	25	3.8 Md	3.4
214	2000	3	25	13	19.26	-67.55	14	3.4 Md	3.3

215	2000	3	26	3	18.61	-67.70	33	4.5 Md	4.0
216	2000	3	30	9	18.82	-68.01	46	4.3 Md	3.8
217	2000	4	4	23	18.97	-67.31	4	3.3 Md	3.1
218	2000	4	7	2	18.27	-67.58	6	3.3 Md	3.0
219	2000	4	8	7	18.16	-67.36	18	3.4 Md	3.2
220	2000	4	10	11	18.95	-64.23	84	4.0 Md	3.6
221	2000	4	10	22	18.67	-66.80	25	3.8 Md	3.0
222	2000	4	13	18	19.64	-63.29	33	4.2 mb	3.9
223	2000	4	18	2	19.08	-69.52	89	4.5 mb	3.9
224	2000	4	30	3	18.46	-67.97	22	3.6 Md	3.4
225	2000	5	3	1	17.67	-62.86	200	3.6 Md	3.6
226	2000	5	4	2	17.80	-65.62	3	3.3 Md	3.1
227	2000	5	8	5	19.45	-68.50	33	4.5 mb	3.9
228	2000	5	15	5	18.24	-66.35	35	3.5 Md	2.9
229	2000	5	20	22	19.38	-67.26	56	3.8 Md	3.5
230	2000	5	26	9	19.04	-63.88	10	3.8 Md	3.6
231	2000	6	1	21	19.42	-65.42	49	4.6 Md	4.3
232	2000	6	11	20	19.91	-70.85	33	4.4 Md	4.3
233	2000	6	18	10	17.93	-66.84	16	3.1 Md	3.1
234	2000	6	23	8	19.41	-65.19	76	3.6 Md	3.6
235	2000	6	24	2	18.08	-65.73	3	3.2 Md	3.0
236	2000	6	25	10	19.39	-65.11	66	3.8 Md	3.3
237	2000	7	5	12	18.40	-65.89	34	3.5 Md	3.0
238	2000	7	7	14	18.93	-66.76	53	3.3 Md	3.0
239	2000	7	24	15	18.15	-67.01	21	3.3 Md	3.0
240	2000	7	26	2	17.85	-61.51	33	4.0 mb	3.9
241	2000	7	28	9	18.70	-64.29	71	4.1 Md	3.6
242	2000	7	28	15	18.93	-64.68	62	4.4 mb	4.2
243	2000	7	29	7	17.84	-68.70	33	4.4 mb	4.3
244	2000	7	30	18	18.79	-69.42	87	3.9 Md	3.7
245	2000	7	31	11	18.77	-64.65	25	4.0 Md	3.3
246	2000	8	1	23	17.46	-68.24	117	4.2 Md	3.7
247	2000	8	2	1	18.39	-66.65	13	3.6 Md	2.9
248	2000	8	12	9	18.03	-66.60	15	3.6 Md	2.9
249	2000	8	15	9	19.16	-66.84	57	3.3 Md	3.2
250	2000	8	16	8	18.40	-65.91	105	3.2 Md	3.1
251	2000	8	17	6	18.11	-64.74	60	3.3 Md	3.2
252	2000	8	19	0	18.06	-65.51	0	3.6 Md	3.0
253	2000	8	19	8	17.92	-66.94	3	3.8 Md	3.3
254	2000	8	31	1	18.75	-64.00	74	4.1 Md	3.5
255	2000	9	3	12	18.70	-66.73	12	3.5 Md	2.7
256	2000	9	4	6	19.27	-65.99	107	3.5 Md	3.2
257	2000	9	4	15	19.05	-66.32	43	3.6 Md	3.4
258	2000	9	5	20	19.00	-68.09	113	4.1 Md	3.4
259	2000	9	7	0	18.87	-65.26	35	3.4 Md	3.1
260	2000	9	12	16	17.97	-65.93	5	3.6 Md	2.8
261	2000	9	15	6	18.87	-67.47	32	3.4 Md	3.3
262	2000	9	18	10	20.06	-70.07	33	4.4 mb	4.3
263	2000	9	22	23	19.02	-64.93	25	4.0 MI	3.4
264	2000	9	23	22	19.26	-64.15	21	4.0 Md	3.3
265	2000	9	24	7	19.47	-66.07	64	3.7 Md	3.2
266	2000	9	25	5	19.23	-62.56	33	4.7 Md	4.2
267	2000	9	25	6	19.19	-62.52	33	4.9 mb	4.0
268	2000	9	25	23	18.12	-67.29	18	3.3 Md	3.0
269	2000	9	27	7	19.11	-64.79	50	3.7 Md	3.2

270	2000	9	28	6	19.26	-66.68	48	3.8 Md	3.2
271	2000	9	29	19	19.36	-66.27	27	3.7 Md	3.1
272	2000	9	30	2	19.42	-65.12	28	3.9 Md	3.5
273	2000	10	1	19	18.88	-64.66	25	3.5 Md	3.2
274	2000	10	2	15	18.90	-68.31	41	4.0 Md	3.7
275	2000	10	2	17	18.17	-67.41	7	3.7 Md	3.4
276	2000	10	8	11	18.78	-64.26	37	3.7 Md	3.2
277	2000	10	9	5	19.19	-65.40	90	3.9 Md	3.5
278	2000	10	11	1	18.93	-64.41	25	3.7 Md	3.2
279	2000	10	11	4	18.98	-66.60	68	3.1 Md	3.0
280	2000	10	13	0	18.64	-66.47	71	3.3 Md	3.1
281	2000	10	14	2	19.04	-67.42	30	3.2 Md	3.1
282	2000	10	15	0	18.55	-65.11	20	3.6 Md	3.0
283	2000	10	16	12	19.21	-64.48	45	4.0 Md	3.5
284	2000	10	16	13	19.25	-65.85	33	3.7 Md	3.0
285	2000	10	17	3	18.81	-67.34	6	3.5 Md	3.1
286	2000	10	17	8	19.65	-68.68	13	4.0 Md	3.6
287	2000	10	22	3	19.03	-64.96	68	3.8 Md	3.2
288	2000	10	23	5	18.79	-65.03	53	3.8 Md	3.2
289	2000	10	25	16	17.85	-66.91	41	3.8 Md	3.1
290	2000	10	25	21	17.86	-66.91	39	3.9 Md	3.4
291	2000	10	27	18	17.65	-61.17	42	4.7 Md	4.5
292	2000	10	27	19	17.60	-61.19	37	5.6 Md	5.2
293	2000	10	29	3	17.98	-66.94	16	3.6 Md	3.2
294	2000	10	30	14	18.71	-67.34	21	3.7 Md	3.4
295	2000	11	1	10	18.44	-67.05	102	3.4 Md	3.2
296	2000	11	6	3	18.00	-68.81	94	3.6 Md	3.5
297	2000	11	16	19	19.84	-65.13	24	4.0 Md	3.9
298	2000	11	25	11	17.78	-65.97	46	3.2 Md	2.8
299	2000	11	30	16	18.63	-66.71	85	4.1 Md	3.8
300	2000	12	1	11	18.56	-66.68	86	3.1 Md	3.0
301	2000	12	1	15	19.30	-67.95	55	4.3 Md	4.1
302	2000	12	8	8	17.86	-68.55	35	3.7 Md	3.5

mb Body wave
Magitude
Md Duration
Magitude
Ml Local
Magitude
Mw Moment
Magitude

Chapter 4: Ground Motion Attenuation

There is a shortage of ground motion data in Puerto Rico for large-magnitude earthquakes, and data close to the earthquake source are scarce at all magnitudes. Thus the data are insufficient for direct empirical regressions to obtain ground-motion relations for the magnitudes and distances of most engineering interest. However, the data are sufficient to establish attenuation rates for small events. A big earthquake fault can be divided into small earthquake faults (subfaults). Then, by knowing the attenuation behavior of small earthquakes over a wide range of distances from near source to far field, and by applying the model introduced in Chapter 2, we can simulate the acceleration time series for large earthquakes at any distances. These simulated records can then be used to define ground motion relations for the magnitudes of engineering interest.

In this chapter I combine a basic theoretical understanding of earthquake generation and propagation processes with empirical information that can be obtained from recordings of small-to-moderate real events, in order to determine key attenuation parameters. Large-magnitude events, which are important to practical applications, can then be simulated using the finite-fault extension of the stochastic approach. The input parameters for the simulations are based on the attenuation parameters obtained from the real recorded time series from smaller events.

The key to the stochastic simulation model is the specification of the Fourier acceleration spectrum as a function of magnitude and distance. In order to specify the Fourier spectrum, we need the parameters that prescribe the earthquake source level, attenuation of ground motion and site response. The necessary attenuation parameters are the geometric spreading and the coefficient of anelastic attenuation. Other region-specific

parameters are the apparent source amplitudes, as determined by the underlying source spectra and their modification through propagation through the regional crustal velocity profile, as well as any generic soil responses. We also need to know the duration of shaking.

In this chapter I determine the duration of seismic waves and the geometric and anelastic attenuation parameters, all based on the recorded ground motion data in Puerto Rico. This sets the stage for stochastic simulations to provide regional ground-motion relations satisfying the immediate and most significant needs of the engineering community for seismic design applications.

4.1. Ground Motion attenuation model

One of the most important characteristics of the propagation path is seismic wave attenuation. The frequency-dependent attenuation of Fourier amplitudes can be determined from ground motion data by regression analysis, as described by Atkinson and Mereu (1992). These regressions may also be used to determine source amplitudes for specific events, and relative site terms for all stations. In this chapter regression analysis is used to generalize the characteristics of the Fourier spectra or response spectra.

Fourier amplitudes can be fit to an equation of the form:

$$\log A_{ij}(f, R) = \log A_{i0}(f) - b \log R_{ij} - c(f) R_{ij} + \log S_j(f) \quad (4.2)$$

where $A_{ij}(f)$ is the observed spectral amplitude of earthquake i at station j , for frequency f ; $A_{i0}(f)$ is the source amplitude of earthquake i , R is hypocentral distance, b is the geometric spreading coefficient, $c(f)$ is the coefficient of anelastic attenuation, and $S_j(f)$ is

the site response term for station j (Shin and Herrmann, 1987; Atkinson and Mereu, 1992). The anelastic coefficient, $c(f)$, is inversely related to the quality factor, Q :

$$Q = [\log(e) \pi f] / (c \beta), \quad (4.3)$$

where β is the shear-wave velocity. Equation (4.2) may be applied to any ground-motion phase; the shear-wave phases are of most engineering interest, since they have the largest amplitudes (typically about five times larger than the P -wave amplitudes).

In developing the attenuation model, we must determine whether the ground-motion database can be adequately fit with a single geometric spreading rate b , or whether this coefficient will take on different values depending on the epicentral distance range. For example, in eastern North America, the attenuation is described by a "hinged-trilinear" form (Atkinson and Mereu, 1992; Atkinson and Boore, 1995) in which geometric attenuation goes as R^{-1} to 70km, then as R^0 for 70 to 130km, then $R^{-1/2}$ beyond 130km. This behavior is explained by the presence of strong post-critical reflections from the Moho discontinuity that cause "flattening" of the attenuation curve, leading to almost no apparent geometric spreading between approximately 70 and 100 km. It follows that the details of the empirical attenuation provide valuable clues as to the regional crustal structure and the presence of major velocity discontinuities that affect ground-motion amplitudes.

In order to find the hinge points of the attenuation curve, representing the transition from direct S-wave to post-critical Moho reflection, I applied a trial profile of different hinge points to equation 4.2 using the ground motion database to determine the best-fit

model. The first hinge point, representing the transition from direct wave spreading to the first post-critical reflections, is incremented from 40 to 105 km by 5km steps. The second hinge, representing the transition to surface-wave spreading, is incremented from 40 to 150km with the same step distance. For each trial pair of hinge points, regression by the maximum likelihood method (Joyner and Boore, 1993) has been applied to equation 4.2 to determine the value of the coefficients. Then the residuals for all records, for frequencies from 0.1 to 8Hz, have been calculated, where residual = log of observed PSA – log of predicted PSA by equation 4.2. Table 4.1 shows the calculated average residuals over all frequencies for each pair of hinge points. The average of the absolute values of the residuals over all frequencies has been calculated for each event, and for each specific pair of hinge points. Figure 4.1 shows the distribution of residuals averaged over all frequencies for different hinge points. This figure shows that the residuals approach zero, which represents the best candidates for hinge points. The hinge points at 75 and 100 km produce the lowest averaged residuals. This is also clear in table 4.1, which shows that the pair of hinge points at 75 and 100km produces the lowest residuals (almost zero).

As Figure 4.2 shows with hinge points at 75 and 100km the regression residuals have a good distribution versus distance, with no trend. By contrast, Figure 4.3 demonstrates a poor distribution of residuals, obtained for hinge points at 40km and 130km. Figure 4.4 shows the distribution of residuals (for hinge points at 75, 100km) for shallow events ($h \leq 30\text{km}$), while Figure 4.5 shows the corresponding distribution for deeper events ($h > 30\text{km}$). The attenuation model appears to fit the deep events well, while shallow events show a slight trend in the residuals that is indicative of greater average attenuations.

4.2. Q-Value

Equation (4.2) has been solved by the maximum likelihood method (Joyner and Boore, 1993) to obtain the source terms A_0 , the geometric spreading coefficient b , and the frequency-dependent attenuation c , providing a description of regional source and path effects for small-to-moderate earthquakes. In this section I am principally interested in the frequency-dependent attenuation coefficient c , which is related to the regional Q-value through equation 4.2.

Figure 4.6 shows the determined Q values for shallow ($h \leq 30\text{km}$) and deep ($h > 30\text{km}$) earthquakes. The deeper events have slightly higher Q, but the standard error of mean Q-value spans a wider range than the difference between Q-values for the deep and shallow earthquake subsets. Figure 4.7 shows the determined Q values considering earthquakes of all depth. The determined Q values (equation 4.3) are given in table 4.2. The Q-values are described by the equation:

$$Q = 359 f^{0.59} \quad (4.5)$$

The modest differences in attenuation according to earthquake depth are too small to warrant developing separate ground motion relations at this time. Figure 4.7 compares the Q values obtained in this study for Puerto Rico to Q-values obtained for Eastern North America (Atkinson and Boore, 1995) and California (Raoof et al, 1999). The Puerto Rico Q-values are intermediate to those for ENA and California.

4.3. Duration of Ground Motion

Several investigators have proposed procedures for computing the duration of earthquake ground motion. Page et al (1972) proposed the *bracketed duration*, which is

the time interval between the first and the last peaks greater than a specified value (usually 0.05 g). Trifunac and Brady(1975) defined the duration of the strong motion as the time interval in which the motion has a significant contribution to the total amount of ground motion energy (usually 90%). Raoof et al (1999) have defined a window (based on the integration on the S wave) within 5% and 75% of its maximum integrated value. Atkinson (1993) used an rms measure of duration, which is calculated by applying Parseval's theorem to find the duration that links the time domain velocity to the Fourier spectrum of velocity.

The duration (T) of an earthquake signal at epicentral distance R can generally be represented as(Atkinson and Boore, 1995):

$$T(R)=T_0+dR, \quad (4.6)$$

where T_0 is the source duration, and d is the coefficient controlling the increase of duration with distance; d is derived empirically. d may be a single coefficient describing all distances of interest (eg. Atkinson, 1995), or it can take different values depending on the distance range (eg. Atkinson and Boore, 1995). The resulting model can be used as input to stochastic simulations. The relations developed in this chapter will be used in the stochastic-model approach.

Using the Puerto Rico ground motion data, I calculated T_0 for each record where $T_0=1/2f_A$ and $\log(f_A)= 2.41-0.533M$ (Atkinson and Boore, 1995). For each record the duration was chosen subjectively based on the strong portion of S-window as shown in Figure 3.9. this is similar to the Trifunac and Brady(1975) window. In order to study the behavior of d in equation 4.6, I plotted $T(R)-T_0$ versus distance in Figure 4.8. This figure

shows the behavior of duration (corrected for source duration) versus distance. (The source duration, T_0 , is short for these records due to their small magnitude.) The change of slope at around 75 and 100km again suggest a trilinear attenuation curve for the Puerto Rico region, similar to observations for Eastern North America (Atkinson and Boore, 1995). Figure 4.9 compares the duration behavior of Puerto Rico with that of Eastern North America (using ENA data of Atkinson and Boore 1995, which are defined using an rms duration definition consistent with the stochastic model). Although the duration definition for Puerto Rico differs from that used in ENA, the inferred values and trends for the duration are very similar. Based on Figure 4.9 I adopt the ENA duration model of Atkinson and Boore (1995) with the obtained hinge points for Puerto Rico (75 and 100 km) for the simulations as follows:

$$\begin{array}{ll}
 T = T_0 & R < 10\text{km} \\
 T = T_0 + 0.16 R & 10\text{km} \leq R \leq 75\text{km} \\
 T = T_0 - 0.03R & 75\text{km} < R \leq 100\text{km} \\
 T = T_0 + 0.04R & R > 100\text{km}
 \end{array}$$

4.4. H/V

The ratio of the horizontal to vertical component of ground motion (H/V) is an important parameter since most of the seismographic stations in Puerto Rico record only the vertical component, whereas the horizontal component is of primary engineering interest. The H/V ratio is believed to reflect amplification effects, both from the crustal velocity gradient, and from near-surface soils (Nakamura 1989, Atkinson and Cassidy, 1999; Lermo and Chavez-Garcia, 1993). Earthquake waves propagate from the source region, where the shear wave velocity is typically about 3.6 km/sec, towards the surface,

where the average shear wave velocity may be around 620m/sec for generic soft rock sites (Boore and Joyner, 1997). The spectrum will be amplified through this velocity gradient by seismic impedance effects. If ρ_1 and ρ_2 are the densities of two layers with shear wave velocity of β_1 and β_2 then the amplification is given by $(\rho_2\beta_2/\rho_1\beta_1)^{1/2}$ (Boore and Joyner, 1997). This amplification is strong for the horizontal component but weak for the vertical component. Hence the H/V ratio is a rough measure of site amplification.

Most of the PRSN data collected to date are vertical-component recordings. However, there are also a limited number of three-component data available. I used three-component data to establish an empirical relationship between horizontal and vertical component amplitudes. This makes it possible to use the entire PRSN database in the development of regional ground-motion relations.

Figure 4.10 compares H/V ratios for the IRIS 3-component broadband station in Puerto Rico (SJG) with the observed H/V ratios for various Geomatrix site classes in other regions. Information on H/V ratio for these other regions is given in Chen (2000) and Chen and Atkinson (2001). Geomatrix site classes are as described by Abrahamson and Silva (1997): A₀=hard rock ($v_s > 1500$ m/s), A/B= rock or shallow soil over rock ($v_s \approx 600$ m/s), C/D= soil ($v_s \approx 300$ m/s). The observed H/V at SJG suggests an amplification at high frequencies, which probably means that there is a thin soft layer under the site (Note: the frequency of amplification is inversely proportional to the thickness of the amplifying layer, while the degree of amplification depends on the seismic impedance contrast). The trend of H/V at the SJG station in Puerto Rico looks very much like the trend of the H/V ratios for class A sites in Japan (from Chen, 2000) but with a slight shift to higher amplification values. The class A sites in Japan represent a shallow soft layer

over rock. For the 45 stations in the Japan data set that are class A, an average shear wave velocity over the top 30m is about 738 m/sec, and the average layer thickness (over rock) is about 11m (Casey, 2002).

For simulation of ground motions in Puerto Rico the obtained H/V at SJG will be applied as a generic site amplification for all sites, since there is no specific studies on the shear wave velocity for the PRSN stations. Based on the field observations made at sites, all appear to be similar in terms of site conditions. They can be characterized as soft rock sites, and likely have a weathered layer that overlies harder rock.

Figure 4.1. Residuals obtained for each combinations of "hinge points" in the attenuation relation. The lowest residuals are obtained for hinge points at 75km and 100km.

**Figure 4.2. Distribution of residuals, for hinge points 75,
100km and $f = 1.0$ Hz**

Figure 4.3. Distribution of residuals, for hinge points 40 and 130km and $f = 1.0$ Hz

**Figure 4.4. Distribution of residuals for shallow events
($h \leq 30\text{km}$), for hinge points 75, 100km and $f = 1.0\text{ Hz}$**

**Figure 4.5. Distribution of residuals for deep events
($h > 30\text{km}$), for hinge points 75, 100km and $f = 1.0\text{ Hz}$**

4.6. Q value for shallow and deep earthquakes in Puerto Rico region

4.7. Q value for Puerto Rico and some regions

Figure 4.8. Duration of recorded time series for Puerto Rico Region

Figure 4.10. H/V ratio for Puerto Rico in comparison to that for other regions (from Chen, 2000). Letters give Geomatrix site class.

Table 4.1. average absolute values of residuals for different distance of hinge points

Bold number is the lowest residuals in this table for hinge points at 75 and 100 km

	S e c o n d															H i n g e (km)														
	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150							
F	40	20.26	18.34	17.66	19.22	18.72	19.17	16.94	19.42	18.75	22.19	19.1	19.6	21.12	21.98	17.72	20.38	19.46	19.17	22.67	21.03	22.68	21.98	21.17						
I	45	20	19.6	19.36	18.85	21.38	22.48	18.12	19.09	19.66	19.63	18.26	22.46	20.71	23.5	19.82	21.15	20.13	21.44	22.74	24.75	22.04	22.9	25.43						
r	50	20.29	21.86	19.57	18.94	19.27	19.5	19.26	19.57	18.04	21.26	20.18	20.77	20.12	23.01	19.96	19.32	19.11	20.27	21.03	23.87	20.97	24.25	23.64						
S	55	13.58	15.36	17.52	21.6	18.72	22.03	21.2	20.63	21.01	18.54	21.76	21.5	19.75	20.62	21.25	20.63	24.14	22.74	25.64	25.25	23.18	21.83	24.48						
t	60	12.99	14.12	16.1	20.71	21.27	19.71	18.25	21.31	18.95	21.19	20.59	20.75	21.31	24.45	23.44	23.43	20.93	21.79	21.13	22.71	23.95	23.39	22.29						
H	65	9.28	12.2	9.22	15.19	18	18.39	17.6	19.12	23.22	22.21	22.01	20.42	20.51	21.64	21.88	21.08	24.12	22.24	25.03	21.81	21.46	21.41	21.12						
i	70	75.53	75.19	76.55	78.35	83.12	88.83	20.73	19.29	21.98	19.49	23.59	20.54	19.82	21.37	20.15	21.78	23.67	21.97	24.81	24.32	21.99	21.86	23.28						
n	75	71.57	74.16	73.3	78.39	81.06	90.16	20.04	18.47	20.68	18.35	22.26	22.86	21.03	20.01	21.1	21.36	22.53	21.96	22.95	23.66	22.59	22.79	22.1						
i	80	67.89	66.43	70.72	71.93	76.33	83.79	14.47	16.49	21.02	19.01	21.33	20.1	21.21	22.21	18.68	19.35	21.87	22.25	23.37	21.69	24.4	24.3	24.15						
n	85	65.37	65.14	65.46	71.65	73.41	82.79	9.79	10.43	17.3	21.33	20.1	22.43	21.36	18.44	20.45	19.58	20.9	23.92	22.97	23.76	23.23	23.76	23.88						
g	90	66.22	66.87	62.25	71.28	71.64	78.89	3.69	7.49	14.12	19.61	19.53	20.95	22.77	18.34	17.12	20.33	22.04	23.08	21.28	22.1	24.25	24.05	23.09						
g	95	59.8	62.77	62.59	65.16	72.9	77.99	6.15	6.42	12.56	13.32	21.79	17.69	19.23	19.57	19.83	20.56	23.08	19.88	21.12	19.26	18.55	18.49	19.98						
e	95	59.8	62.77	62.59	65.16	72.9	77.99	6.15	6.42	12.56	13.32	21.79	17.69	19.23	19.57	19.83	20.56	23.08	19.88	21.12	19.26	18.55	18.49	19.98						
(km)	100	58.11	60.51	58.9	63.99	67.37	72.7	0.81	0.03	9.86	9.75	13.79	16.09	18.5	17.81	18.34	19.97	19.68	21.16	20.51	22.39	22.14	22.04	23.05						
	105	49.4	45.79	48.91	52.43	55.45	62.61	12.8	6.99	3	0.88	6.85	6.73	10.61	20.87	17.35	16.39	19.57	20.07	22.58	20.33	22.37	20.78	21.13						

Table 4.2. The Q-value for Puerto Rico region

f (Hz)	Q-value
0.40	208
0.50	239
0.63	274
0.79	313
1.00	359
1.26	411
1.59	471
2.00	540
2.51	618
3.16	708
3.98	811
5.01	929
6.31	1064
7.94	1219

Chapter 5: Simulation of Acceleration Time Series for Puerto Rico Earthquakes

An observation point near a large fault is actually a remote site for many of its subfaults, since the size of subfaults is small compared to the size of the main fault (figure 5.1). Based on the work presented in chapter 4, we know the attenuation behavior of small earthquakes in Puerto Rico. We also know that a big earthquake fault can be modeled by small subfaults (chapter 2). Thus we can model the acceleration time series for large extended earthquake faults in Puerto Rico.

In this chapter EXSIM is used to simulate a ground motion database from which to develop ground motion equations. The input parameters for the simulations are based on the attenuation parameters obtained from the real recorded time series from smaller events. I take this approach because there are not enough real data in the magnitude-distance ranges of engineering interest to drive ground motion relations directly. However, the empirical data can be used to validate the model predictions, at least for moderate events.

5.1. Input parameters

The following describes the input parameters to EXSIM for the time series simulations.

Earthquake Magnitude and Distance. Acceleration time series for earthquakes with magnitudes from M3.0 to M8.0, and hypocentral distances from 1km to 500km, are simulated. Although our database is rich in small to moderate events, I simulate those magnitudes in order to compare the simulated time series with the real recorded ones. Simulation is performed in magnitude steps of 0.2 units. For each simulated earthquake fault plane, I perform simulations for 25 different locations of the observation point. In order to have a uniform distribution of

distances in log unit the distances are 1, 2.2, 3.1, 3.8, 4.4, 5.4, 7, 9, 11, 14, 17, 21, 27, 33, 42, 52, 66, 82, 103, 129, 162, 203, 254, 318, 399, 500 km. Three profiles for the above mentioned distances have been considered. In the first profile the observation point is located in the backward directivity region and moves from 500km to 1km, where the angle between the azimuth of the observation points and the fault strike varies from 180 to 90 degrees as we approach the fault plane. The hypocenters of earthquakes are located at the nearest subfault. In the second profile, the observation point moves from 500km to 1km, where the angle between the azimuth of the observation points and the fault strike is fixed at 90 degrees as we approach the middle of the fault surface from larger distances. The hypocenters of earthquakes are located at the middle of the fault plane; this case produces no directivity effect. In the third profile the observation point is located in the forward directivity region and moves from 1km to 500km, where the angle between the azimuth of the observation points and the fault strike varies from 90 to 0 degrees as we move away from the fault plane. The hypocenters of the earthquakes are located at the farthest subfault to maximize directivity. Figure 5.2 illustrates the placing of the observation points relative to the fault.

Fault geometry. There is little information about the specific fault geometry to be modeled, as Puerto Rico is affected not only by the subduction zone (about 200 km away), but also by many other local faults of unknown location and orientation. Therefore the dip is considered 90° . The length and width of faults are calculated from the target moment magnitude based on the Wells and Coppersmith (1994) empirical formulas between magnitude and fault size (area and length). Thus fault length, L , is given by $\log(L) = -3.22 + 0.69M$, while fault width, W , is given by $\log(W) = -1.01 + 0.32M$.

Attenuation. In chapter 4, I showed that the Fourier amplitudes of Puerto Rico earthquakes follow a trilinear curve for attenuation, which has hinges at 75 and 100km. The slope of the geometric attenuation is -1.0 , 0.0 and -0.5 for the three different parts of the curve, respectively. The inelastic attenuation associated with this model is expressed by the regional quality factor $Q=359 f^{0.59}$.

Duration. As shown in chapter 4, duration increases with distance. It is modeled as:

$$T = T_0 + bR$$

where T_0 is the source and bR represents the distance dependent of duration. The distance dependence of duration is modeled as trilinear, using the transition distances of 75 and 100km, obtained in the last chapter. The slope b is adopted from Atkinson and Boore (1995); it is zero for $R < 10\text{km}$, 0.16 for $10\text{km} \leq R \leq 75\text{km}$, -0.03 for $75\text{km} < R \leq 100\text{km}$ and 0.04 for $R > 100\text{km}$.

Stress parameter. Based on the calibration studies of chapter 2, the stress parameter is given as $\Delta\sigma = 288 - 21.1M$. Thus the stress parameter has a value of 225bars at M3, 183bars at M5 and 120bars at M8. With these values, the EXSIM source model produces equivalent results to the generic finite-fault source model validated for eastern and western North America by Beresnev and Atkinson (2001).

Kappa. High frequency amplitudes are reduced through the kappa operator (Anderson and Hough 1984) by applying the factor $\exp(-\pi f \kappa)$. This factor, which models near surface attenuation, generally varies between 0.02 to 0.04 for rock sites (Anderson and Hough; 1984, Boore et al, 1992; Atkinson and Silva, 1997; Boore and Joyner, 1997). $\kappa=0.03$ is adopted as a compromise between regional estimates.

Slip distribution. The relative slip distribution for subfaults can be input to the model. The actual slip distribution will be determined by the program, based on the seismic moment distribution on the fault surface and the relative slip distribution (equation 2.8). I choose a random relative slip distribution, since this gives us the range of expected ground motions from future earthquakes, for which rupture scenarios cannot be predicted.

Crustal amplification. Earthquake waves propagate from the source region, where the shear wave velocity is approximately 3.6 km/sec, towards the surface, where the average shear wave velocity is about 620m/sec for a generic soft rock site for California (Boore and Joyner, 1997). The spectrum is amplified by this velocity gradient. This effect is modeled by multiplying the spectrum by the frequency-dependent crustal amplification. H/V , which has been discussed in chapter 4, will be applied as a generic PRSN site response in acceleration time series simulation. This is believed to represent amplification by a shallow soft layer over rock. There is no specific information regarding the shear wave velocity at PRSN sites. Generally speaking the PRSN seismic station sites can be considered as stiff soil or soft rock.

Other parameters. The sampling rate, near-source shear wave velocity and density will be considered as 100 sample/sec, 3.6 km/sec and 2.8 g/cm^3 respectively. Rupture propagation speed is 0.8 times the shear-wave velocity. Ten trials were used for each magnitude-distance combination. I generated response spectra for frequencies of 0.1 to 20 Hz, and peak ground acceleration and velocity.

5.2. Simulated acceleration time series

Applying the above-mentioned input parameters, 1950 acceleration time series for magnitudes from **M3.0** to **M8.0** and distances from 1km to 500km have been simulated. The response spectra (pseudoacceleration, PSA, 5% damped) of the simulated time series have been calculated for frequencies from 0.1Hz to 20Hz. Figures 5.3 shows the PSA of the simulated acceleration time series at 5.0Hz versus distance for different magnitudes. Each of three directivity cases are plotted. The obtained PSA show a well-behaved trend versus distance.

Seismic moment is the most important parameter that controls the overall level of the response spectra. By increasing the magnitude the seismic moment is increased, and consequently the PSA is increased. Figure 5.3 shows that by increasing the magnitude, the ground motion amplitude is increased, but the curves become closer together at larger magnitudes. This is a consequence of the extended fault effects, and becomes dominant at large magnitudes. By increasing the magnitude from **M7.0** to **M8.0** the length of the fault increases from 49km to 200km. (Note: the fault length of earthquakes with magnitude **M4.0**, **M5.0**, **M6.0**, **M7.0** and **M8.0** are approximately 1km, 3km, 13km, 49 and 200km, respectively.) In the case of magnitude **M7.0** (with about 50km length), the near-source observation point, which is located 2km away from the middle of the fault, is a far-field site for many of the most distant subfaults. If we increase the length of the fault to reach 200km (**M8.0**), we add many subfaults that are very far from the observation point. These effects are not as pronounced for smaller magnitudes, due to the logarithmic behavior of the relationship between fault length and magnitude.

Figures 5.4 and 5.5 show response spectral amplitude for 1Hz and 0.5Hz respectively. There is an interesting behavior at low frequency (0.5Hz), which is clear in Figure 5.4. For larger magnitudes a level section appears in the attenuation curve at short

distances. This near-source effect at low frequencies is a consequence of the extended fault.

5.3. Comparison of simulated PSA's with ground motion relations of other regions.

In this section I compare the response spectra for Puerto Rico (section 5.1 and 5.2) with the ground motion relationships for other regions. The other regions are Eastern North America (Atkinson & Boore, 1995), California (Atkinson & Silva, 2000) and the global database for subduction zones (Atkinson & Boore, 2002). In each case, I selected ground motion relations that can be referenced to a specific model. The ENA relations of Atkinson and Boore (1995) are based on a stochastic point source model with a two-corner source spectrum to mimic finite fault effects. The California relations are based on a two-corner stochastic source model calibrated against the California strong motion database. The global subduction relations of Atkinson and Boore (2002) are strictly empirical, based on regression analysis of thousands of records; separate regressions were performed for in-slab and interface events.

The ground motion relations for bedrock for ENA have been multiplied by generic factors (Adams et al., 1999) to convert them to a “firm ground” (NEHRP C) site condition. NEHRP site classification is based on the shear wave velocity (see Borchardt, 1995): NEHRP A=($v_s > 1500$ m/s), B=(760-1,500 m/s), C=(360-760 m/s), D=(180-360 m/s) and E=(< 180 m/s). The generic soft rock site condition (NEHRP C) applies for the California relations (“rock” relations of Atkinson & Silva, 2000) and is provided for the global subduction zones (Atkinson & Boore, 2002). Recall that the Puerto Rico curves are assumed to represent soft rock (NEHRP C). The plotted curves are thus roughly comparable with the attenuation relations of the other regions in terms of site conditions.

Figures 5.6-5.8 show the regional comparison at 5Hz frequency for magnitudes of **M5.0**, **M6.0** and **M7.0**. The Puerto Rico ground motions are broadly comparable to stochastic ground motion relations obtained for North America (where the California and ENA relations are similar). Differences are attributable to regional variations in ground motion parameters. There are three main parameters that control the behavior of PSA and which may vary regionally. The first one is the crustal and near-surface amplification. For Puerto Rico this is modeled by the H/V ratio. The other ground motion relations each represent slightly different overall site effects. Another parameter that controls the behavior of PSA, especially at large distances, is the regional Q-value. At large distances Puerto Rico ground motion curves lie between those of ENA and California, since the Puerto Rico Q-value (Figure 4.5) is intermediate to those for ENA and California.

The third parameter that makes the PSA in Puerto Rico relations deviate from the other relations for North America is differences in the hinge points of the attenuation curve, reflecting regional differences in crustal structure. Figures 5.9- 5.11 and 5.12-5.14 compare PSA in Puerto Rico with the above-mentioned relations for 1Hz and 0.5Hz respectively. Overall, the Puerto Rico relations agree well with stochastic relations for California and ENA.

The motions calculated by the global subduction database are different from those suggested by this study. The global subduction relations are applicable for **M**>6.0 (for both interface and in-slab events) and **R**>40km (for in-slab events), thus the Puerto Rico PSA cannot be compared with the global subduction relations beyond these limits (Graphs 5.6, 5.9 and 5.12 do not have global subduction relations curves). The global subduction relations are entirely empirical. The database of interface events has been separated from the database of in-slab events in deriving the empirical regressions. On

the other hand the Puerto Rico relations are based on the combination of events of all types. Crustal events have contributions to the Puerto Rico relations as well as interface and in-slab events. The attenuation behavior in the global subduction relations is a generic behavior of attenuation of seismic waves averaged over several subduction zones. By contrast the Puerto Rico ground motions are based on the region-specific attenuation behavior of seismic waves. The geometric attenuation of seismic wave in Puerto Rico has a "hinged-trilinear" form. This behavior is explained by the presence of post-critical reflections from the Moho. The database of global subduction relations does not appear to show this behavior. These factors contribute to the observed differences between global subduction ground motion relations and Puerto Rico ground motion relations.

5.4. Comparison of simulated acceleration time series with data

In this section I qualitatively compare response spectra calculated from simulated records for Puerto Rico with those calculated from actual seismographic records. More quantitative comparison will be made in the next chapter. For a proper comparison we need to have the same type of magnitude for both the simulated time series and the real recorded data. The simulated time series are based on moment magnitude, M . The reported magnitudes for the real records include M , m_b and local magnitudes based on duration. Thus we first need to obtain the moment magnitudes for the real earthquakes, using the Fourier spectra of the records.

Based on the Brune point source model (since small earthquake can be considered as a point source) the spectra of the recorded acceleration time series can be modeled using equation 1.1. The spectra of displacement can be obtained by:

$$D(f) = (2\pi f)^{-2} A(f)$$

or

$$D(f) = (2\pi)^{-2} CM / [1 + f/f_0]^2]$$

At low frequencies ($f \ll f_0$) at a distance of $R=10\text{km}$, the spectra of displacement would be:

$$D(f) = CM$$

(Using $R=10\text{km}$ in the constant C ; see Eqn 1.1).

If we play back the attenuation effects (including anelastic and trilinear hinged geometric behaviors) to $R=10\text{km}$, then M_0 and hence M can be calculated. These calculated moment magnitudes have significant uncertainty, as they are mostly single-station estimates, based on the records at SJG.

Figures 5.15-5.18 show the distribution of simulated PSA at 0.5Hz in comparison to the distribution of PSA from the real recorded data. Figures 5.19-5.26 show corresponding plots for 1.0 and 5.0 Hz. The good agreement gives us confidence in the overall trend of our simulated acceleration time series. The calculation of residuals of simulated PSA versus real PSA will be discussed after regression analysis to determine prediction equations for PSA. There are some discrepancies between simulated and real data, which may be partly attributed to the large uncertainties in estimated moment magnitude.

Figure 5.1. Observation point near a big earthquake fault plane and subfaults as small earthquakes

Figure 5.2. Profiles of observation points for an earthquake fault.

**Figure 5.3. Horizontal PSA of Simulated
Acceleration Time Series, $f=5.0$ Hz**

**Figure 5.4. Horizontal PSA of Simulated
Acceleration Time Series, $f=1.0$ Hz**

**Figure 5.5. Horizontal PSA of Simulated
Acceleration Time Series, $f=0.5$ Hz**

Figure 5.6. PSA for Puerto Rico and PSA of the other regions. M5.0, f=5.0 Hz (NEHRP C)

Figure 5.7. PSA for Puerto Rico and PSA of the other regions. M6.0, f=5.0 Hz (NEHRP C)

Figure 5.8. PSA for Puerto Rico and PSA of the other regions. M7.0, f=5.0 Hz (NEHRP C)

Figure 5.9. PSA for Puerto Rico and PSA of the other regions. M5.0, f=1.0 Hz (NEHRP C)

Figure 5.10. PSA for Puerto Rico and PSA of the other regions. M6.0, f=1.0 Hz (NEHRP C)

Figure 5.11. PSA for Puerto Rico and PSA of the other regions. M7.0, $f=1.0$ Hz (NEHRP C)

Figure 5.12. PSA for Puerto Rico and PSA of the other regions. M5.0, f=0.5 Hz (NEHRP C)

- x Puerto Rico
- ENA(Atkinson & Boore, 1995)
- California(Atkinson & Silva, 2000)

Figure 5.13. PSA for Puerto Rico and PSA of the other regions. M6.0, $f=0.5$ Hz (NEHRP C)

- x Puerto Rico
- ENA(Atkinson & Boore, 1995)
- California(Atkinson & Silva, 2000)
- Subduction interface (Atkinson & Boore, 2002)
- △ Subduction in slab (Atkinson & Boore, 2002)

Figure 5.14. PSA for Puerto Rico and PSA of the other regions. M7.0, f=0.5 Hz (NEHRP C)

**Figure 5.15. PSA from simulated time series
and PSA of real data, M3.0-M3.5, $f=0.5\text{Hz}$**

**Figure 5.16. PSA from simulated time series
and PSA of real data, M3.5-M4.0, $f=0.5\text{Hz}$**

**Figure 5.17. PSA from simulated time series
and PSA of real data, M4.0-M4.5, $f=0.5\text{Hz}$**

**Figure 5.18. PSA from simulated time series
and PSA of real data, M4.5-M5.0, $f=0.5\text{Hz}$**

**Figure 5.19. PSA from simulated time series
and PSA of real data, M3.0-M3.5, $f=1.0\text{Hz}$**

**Figure 5.20. PSA from simulated time series
and PSA of real data, M3.5-M4.0, $f=1.0\text{Hz}$**

**Figure 5.21. PSA from simulated time series
and PSA of real data, M4.0-M4.5, $f=1.0\text{Hz}$**

**Figure 5.22. PSA from simulated time series
and PSA of real data, M4.5-M5.0, $f=1.0\text{Hz}$**

**Figure 5.23. PSA from simulated time series
and PSA of real data, M3.0-M3.5, $f=5.0\text{Hz}$**

**Figure 5.24. PSA from simulated time series
and PSA of real data, M3.5-M4.0, $f=5.0\text{Hz}$**

**Figure 5.25. PSA from simulated time series
and PSA of real data, M4.0-M4.5, $f=5.0\text{Hz}$**

**Figure 5.26. PSA from simulated time series
and PSA of real data, M4.5-M5.0, $f=5.0\text{Hz}$**

Chapter 6: Ground Motion Relations

In this chapter regression analysis is used to obtain ground motion relations that describe the simulated response spectra as simple functions of magnitude and distance. The maximum likelihood method (Joyner and Boore, 1993) has been applied, for frequencies from 0.1 to 20Hz. The ground motion relations are for a generic soft rock site condition (NEHRP C).

6.1. Functional Form

Figures 5.3-5.5 show the following different important characteristics of the response spectra curves to be modeled:

- 1- They are flat in the near-source region. The length of the flat part of the curve is magnitude dependent. The flat portion extends only 1-2km for **M4.0**, while it extends about 10km for **M7.0**.
- 2- The slope of the curves beyond the flat portion and before the first hinge point (75km) varies with magnitude and is magnitude-dependent. It is about -1.4 for **M3.0** and -0.6 for **M8.0**
- 3- The slope between the two hinge points is almost flat.
- 4- Beyond the second hinge point, the slope is the about the same for all magnitudes.

Response spectra can be fit to an equation of the form:

$$\log PSA(f, R) = c_1 + c_2(M-b) + c_3(M-b)^n + hingeFunction + c_4R \quad (6.1)$$

where PSA is the random horizontal-component acceleration response spectra with 5% damping,

M= Moment magnitude

$$R = (D^2 + \Delta^2)^{0.5}$$

D = closest distance to fault surface , in km

$$\Delta = c_5 + c_6 \mathbf{M}$$

$c_4(f)$ = the coefficient of anelastic attenuation

$$\text{hingeFunction} = (c_7 + c_8 \mathbf{M}) \log(R) \quad \text{for } R \leq 75 \text{ km}$$

$$\text{hingeFunction} = (c_7 + c_8 \mathbf{M}) \log(75) \quad \text{for } 75 \text{ km} \leq R \leq 100 \text{ km}$$

$$\text{hingeFunction} = (c_7 + c_8 \mathbf{M}) \log(75) - 0.5 \log(R/100) \quad \text{for } R \geq 100 \text{ km}$$

Some of the main seismic sources are located more than 200km to the north of Puerto Rico. Therefore extending the attenuation formula to large distances is important. The *hingeFunction* defines the hinged behavior of ground motion curves for different distances and allows accurate relations over a wide range of distances.

6.2. Regression Analysis

The maximum likelihood regression algorithm of Joyner and Boore (1993) requires a linear equation for regression. Thus some of the constants must be pre-set to linearize the final regression. Specifically b , n , c_5 , c_6 , c_7 and c_8 are constants that are pre-set based on initial analysis to determine the best fit and distribution of residuals. Atkinson and Boore (1995, 1997) applied $b=6$ and $n=2$, while Abrahamson and Silva (1997) applied $b=8.5$ and $n=2$ or 3. In order to find the best b and n values to set in the source terms, I applied a set of different trial values for both constants to Equation 6.1. b values from 1 to 10 were considered, while n was varied from 1 to 4. For each pair of b and n the maximum likelihood method has been applied to Equation 6.1 and the average absolute value of residuals for each magnitude for frequencies from 0.1 to 20Hz has been

calculated. Figure 6.1 and Table 6.1 show the distribution of averaged residuals over frequency for different combinations of b and n . This figure shows that the best candidate for n is 2 since regardless of the value of b , $n=2$ produces the lowest values of the residuals (as shown by a valley in Figure 6.1). Figure 6.2, which is a zoom of Figure 6.1, shows that the values $b=6$ and $n=2$ produce the lowest averaged residuals, although there is not that much difference between different b values. Thus I apply $b=6$ and $n=2$ in the Puerto Rico region ground motion relations.

It was determined that a linear relation between M and the regression parameter Δ provides a good distribution of residuals (e.g. $\Delta = c_5 + c_6 M$). Therefore the parameter space was sampled to find the values of c_5 and c_6 that would result in the lowest overall regression residuals. In order to find the best values for c_5 and c_6 I applied the same approach as used for b and n . These coefficients control the flat portion of the attenuation relations in the near-source region. I consider values of Δ_4 (the value of Δ for $M=4.0$) that vary from 1 to 10, while the value of Δ_7 (the value of Δ for $M=7.0$) is varied from 1 to 40. For each pair of Δ_4 and Δ_7 I calculated c_5 and c_6 ; then the maximum likelihood method was applied to Equation 6.1 for all magnitudes from $M3.0$ to $M8.0$, for all distances, and the average residuals were calculated. Figure 6.3 shows the distribution of averaged residuals over frequency for Δ_4 and Δ_7 . This figure shows that the residuals approach a minimum, which represents the best candidates for Δ_4 and Δ_7 . Table 6.2 shows the absolute value of averaged residuals for each pair. I conclude that $\Delta_4=2$ and $\Delta_7=9$ produce the lowest averaged residuals. Thus I use the function $\Delta = -7.333 + 2.333M$, based on these obtained values of Δ , and so set $c_5 = -7.333$ and $c_6 = 2.333$.

The slope of the curve beyond the flat portion and before the first hinge point (75km) varies with magnitude. It is about -1.3 for **M**3.0 and -0.6 for **M**8.0. This leads us to set the slope = -1.88 + 0.14**M**. Thus $c_7 = -1.88$ and $c_8 = 0.14$.

The above mentioned procedures to determine b , n , c_5 , c_6 , c_7 and c_8 have been iterated many times to find the final values of the parameters which produce the lowest residuals. Figures 6.1-6-3 and Tables 6.1-6.2 show the final values that have been obtained. Therefore Equation 6.1 becomes as follows:

$$\log PSA(f, R) = c_1 + c_2(M-6) + c_3(M-6)^2 + hingeFunction + c_4R \quad (6.2)$$

where PSA is the observed acceleration response spectra with 5% damping

f = frequency in hertz

M = Moment magnitude

$$R = (D^2 + \Delta^2)^{0.5}$$

D = closest distance to fault surface, in km

$$\Delta = -7.333 + 2.333M$$

$$hingeFunction = (-1.88 + 0.14M) \log(R) \quad \text{for } R \leq 75 \text{ km}$$

$$hingeFunction = (-1.88 + 0.14M) \log(75) \quad \text{for } 75\text{km} \leq R \leq 100\text{km}$$

$$hingeFunction = (-1.88 + 0.14M) \log(75) - 0.5 \log(R/100) \quad \text{for } R \geq 100\text{km}$$

$c_4(f)$ is the coefficient of anelastic attenuation.

Table 6.3 shows the final results of maximum likelihood regression analysis of the simulated data to Equation 6.2. Figures 6.4-6.6 show the predicted PSA's by this ground motion relation (Equation 6.2) in comparison to the simulated input PSA values. The equations provide a good prediction of the simulated PSA values over all magnitudes and

distances, although there is a slight tendency to underestimate PSA for earthquakes of M5 to M6 at distances less than 5km from the fault.

Figure 6.7 shows the distribution of residuals versus magnitude, where the residual is defined as: $\text{residual} = \log \text{ of observed PSA} - \log \text{ of predicted PSA by Equation 6.2}$. Figure 6.8 shows the corresponding distribution of residuals versus distance. The distribution of residuals for the simulated data lie within the range from -0.5 to 0.5 (log units) with no trend, which indicates a good agreement between predicted values and simulated values. The distribution of residuals for the real recorded data lie between -1.5 and 1.5 ; this large scatter reflects the uncertainties in both the data and the relations. Figures 6.9-6.12 show the distribution of residuals versus magnitude and distance for 1.0Hz and 5.0Hz, respectively. Overall, the agreement between the data and predictions is considered satisfactory. There is a tendency towards overestimation of PSA at large distances ($> 100\text{km}$), but this is not critical for engineering applications.

Figure 6.1. Distribution of average residual for different values of b and n in source terms

Figure 6.2. Distribution of average residual for different values of b and n in source terms

Figure 6.3. Distribution of average residual for different values c7 and c8

Figure 6.4. Comparison between the results of ground motion relations and input data, $f=5.0\text{Hz}$

**Figure 6.5. Comparison between the results
of ground motion relations and input data,
 $f=1.0\text{Hz}$**

Figure 6.6. Comparison between the results of ground motion relations and input data, $f=0.5\text{Hz}$

Figure 6.7. Residuals versus magnitude for $f=0.5\text{Hz}$

Figure 6.8. Residuals versus distance for $f=0.5\text{Hz}$

Figure 6.9. Residuals versus magnitude for $f=1.0$ Hz

Figure 6.10. Residuals versus distance for $f=1.0$ Hz

Figure 6.11. Residuals versus magnitude for $f=5.0$ Hz

Figure 6.12. Residuals versus distance for $f=5.0$ Hz

Table 6.1. Sum of residuals for different values of b and n over frequency of PSA
 * sum: is the absolute value of sum of residuals for a given b and n

		1			
		n			
		1	2	3	4
b	1	4.735	1.863	1.892	1.995
	2	4.737	1.865	1.915	2.071
	3	4.735	1.863	1.972	2.217
	4	4.734	1.865	2.162	2.485
	5	4.736	1.865	3.505	2.618
	6	4.735	1.863	3.572	2.906
	7	4.734	1.864	2.285	2.712
	8	4.737	1.864	2.031	2.355
	9	4.733	1.864	1.958	2.158
	10	4.737	1.863	1.924	2.061

Table 6.2. Sum of residuals for different values of Delta 4 and delta 7

	DELTA 7																	
	1	3	5	7	9	11	13	15	17	19	21	23	25	27	29	31	33	
DELTA 4	1	2.37	2.14	1.90	1.74	1.68	1.68	1.74	1.83	1.93	2.04	2.16	2.28	2.40	2.52	2.65	2.77	2.89
	2	2.33	2.10	1.88	1.73	1.67	1.70	1.77	1.85	1.95	2.06	2.18	2.29	2.41	2.53	2.65	2.77	2.88
	3	2.32	2.10	1.89	1.75	1.71	1.74	1.80	1.90	2.00	2.10	2.21	2.33	2.44	2.56	2.67	2.79	2.89
	4	2.36	2.15	1.95	1.82	1.77	1.79	1.86	1.95	2.05	2.16	2.27	2.38	2.49	2.60	2.71	2.82	2.92
	5	2.45	2.26	2.06	1.93	1.88	1.88	1.94	2.02	2.12	2.22	2.33	2.44	2.55	2.66	2.76	2.87	2.96
	6	2.57	2.39	2.20	2.07	2.01	2.01	2.06	2.12	2.21	2.31	2.41	2.51	2.62	2.72	2.82	2.92	3.01
	7	2.70	2.55	2.37	2.23	2.18	2.16	2.20	2.25	2.33	2.42	2.51	2.60	2.70	2.80	2.89	2.99	3.08
	8	2.84	2.70	2.53	2.40	2.35	2.33	2.36	2.40	2.46	2.54	2.62	2.71	2.79	2.88	2.97	3.06	3.15
	9	2.98	2.86	2.71	2.58	2.52	2.50	2.52	2.56	2.62	2.68	2.75	2.82	2.90	2.98	3.07	3.15	3.22
	10	3.12	3.02	2.87	2.75	2.69	2.66	2.68	2.72	2.77	2.82	2.89	2.95	3.02	3.10	3.17	3.24	3.31

Table 6.3. Ground Motion Relations for Puerto Rico (Horizontal Component)

$$\log PSA(f, R) = c_1 + c_2(M-6) + c_3(M-6)^2 + \text{hingeFunction} + c_4R$$

$$R = (D^2 + \Delta^2)^{0.5}$$

$$\Delta = -7.333 + 2.333 M$$

$$\text{hingeFunction} = (-1.88 + 0.14 M) \log(R) \quad \text{for } R \leq 75 \text{ km}$$

$$\text{hingeFunction} = (-1.88 + 0.14 M) \log(75) \quad \text{for } 75 \text{ km} \leq R \leq 100 \text{ km}$$

$$\text{hingeFunction} = (-1.88 + 0.14 M) \log(75) - 0.5 \log(R/100) \quad \text{for } R \geq 100 \text{ km}$$

PSA is 5% damped horizontal component pseudo-acceleration in cm/sec^2 ; f in hertz; M , Moment magnitude; D = closest distance to fault surface in km. All log's are in Base 10.

f (Hz)	c_1	c_2	c_3	c_4
0.10	1.49	0.87338	-0.06085	-0.00185
0.13	1.66	0.83964	-0.05755	-0.00168
0.16	1.81	0.84255	-0.07228	-0.00156
0.20	1.98	0.82488	-0.07993	-0.00141
0.25	2.14	0.80463	-0.08661	-0.00127
0.32	2.31	0.77829	-0.09453	-0.00115
0.4	2.49	0.74685	-0.10534	-0.00111
0.5	2.66	0.70911	-0.11769	-0.00112
0.6	2.85	0.67139	-0.13161	-0.00114
0.8	3.03	0.62954	-0.14195	-0.00117
1.0	3.19	0.59407	-0.14813	-0.00122
1.3	3.37	0.55285	-0.15348	-0.00129
1.6	3.54	0.51563	-0.15932	-0.00141
2.0	3.69	0.47664	-0.15903	-0.00151
2.5	3.83	0.44721	-0.15754	-0.00161
3.2	3.95	0.41559	-0.15291	-0.00181
4.0	4.03	0.38958	-0.14469	-0.00201
5.0	4.10	0.35585	-0.13450	-0.00219
6.3	4.10	0.34067	-0.12530	-0.00235
8.0	3.96	0.33553	-0.11937	-0.00253
10.0	3.94	0.29497	-0.11064	-0.00259
12.5	3.89	0.28660	-0.10038	-0.00271
16.0	3.84	0.29420	-0.09576	-0.00272
PGA	3.67	0.33228	-0.11308	-0.00244
PGV	2.37	0.51396	-0.10160	-0.00184

Chapter 7. Summary and Conclusion

In finite fault modeling a large fault is divided into N subfaults, where each subfault is considered as a small point source. The ground motions contributed by each subfault are calculated by the stochastic point source method, and then summed at the observation point, with a proper time delay, to obtain the ground motion from the entire fault. A new variation has been introduced based on the “dynamic corner frequency”. In this approach, the corner frequency is a function of time, and the rupture history controls the frequency content of the simulated time series of each subfault. The rupture begins with a high corner frequency and progresses to lower corner frequencies as the ruptured area grows. As the rupture propagates, the number of ruptured subfaults increases and the corner frequency of the subfaults decreases, approaching the corner frequency of the entire fault plane. Limiting the number of active subfaults in the calculation of dynamic corner frequency can simulate the notion of self-healing slip pulses.

In the new approach, the total radiated energy from the fault and the total seismic moment are conserved independent of subfault size over a wide range of subfault sizes. The total radiated energy from a subfault is calculated based on the size of subfault and a weighting function, but the calculation of corner frequency, which controls the shape of spectrum, comes from the total ruptured area.

The moment of each subfault is controlled by the ratio of its area to the area of the main fault ($M_{oi}=M_o/N$). If the subfaults are not identical we apply a weighting function for each subfault based on the relative slips of subfaults. Limiting the number of active subfaults in the calculation of dynamic corner frequency can simulate the notion of self-healing slip pulses. In the new approach, the total radiated energy from the fault and the

total seismic moment, as well as the response spectra and time series, are conserved independent of subfault size over a wide range of subfault sizes.

I modified the computer program FINSIM (Beresnev and Atkinson, 1998) to implement the above-mentioned concepts. The modifications to FINSIM introduce the new concept of a “dynamic corner frequency” to more closely model real finite-fault dynamic behavior. The modified version replaces the “radiation strength factor” with a stress parameter that governs high-frequency energy. The new version also allows for variability in the “pulsing area” or the number of subfaults, which are considered as active subfaults, in the calculation of dynamic corner frequency. The modified program has been renamed EXSIM. FINSIM was used to calibrate EXSIM over all magnitudes and distances. The rationale for this calibration is that FINSIM has been extensively validated against real earthquake data over a wide range of conditions. The calibrated EXSIM model produces approximately the same peak ground motions and response spectra as the FINSIM model of Beresnev and Atkinson (1998a), and provides good characterization of the main seismological effects, including source and path, for extended fault sources. The advantage of EXSIM is that it introduces conceptual improvements and allows simulation of self-healing slip pulses.

The second part of the project was to develop ground motion relations for Puerto Rico to aid in seismic hazard evaluations. Fourier amplitudes and response spectra of more than 3000 waveforms from about 300 Puerto Rico earthquakes of magnitude 3 to 5.5 have been analyzed. Due to a paucity of data at small distances and large magnitudes, the ground motion data cannot be used directly to obtain ground motion relations for magnitudes and distances of most engineering interest. Instead the data were used to determine key attenuation parameters, such as regional Q , duration behavior and generic

site amplification that are input to EXSIM to allow simulation of larger events. The simulated data were then used to develop the ground motion relations.

The developed ground motion relations for Puerto Rico are validated using available seismographic data, and compared to ground motion relations for other regions. These are the first region-specific ground motion relations for Puerto Rico. The developed ground motion relations for Puerto Rico are specially calibrated using Puerto Rico region-specific parameters. Thus they resemble the seismic wave attenuations in that region more closely than the other generic ground motion relations. These relations are also controlled by a model that has been well-calibrated against larger databases. They therefore provide a much-needed tool to enable engineers to more accurately assess and mitigate seismic hazards in Puerto Rico.

8. References

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Appendix A

Instrument Response

This appendix describes the instrument response of the field system used to calibrate PRSN station. The system consists of a Guralp CMG-40T seismometer connected to a Nanometrics Orion seismograph. Consider a linear time-invariant (LTI) system with input $x(t)$, output $y(t)$, and impulse response $h(t)$, so that $y(t)$ is the convolution of $x(t)$ with $h(t)$

$$Y(t) = \int_{-\infty}^{+\infty} x(\tau)h(t-\tau) d\tau$$

Using the Fourier transform, the convolution operation becomes a simple multiplication in the frequency domain. Therefore we can write

$$Y(\omega) = H(\omega) X(\omega)$$

The Fourier transform of the impulse response of a system is generally referred to as the frequency response or the transfer function of the system or (in our case) the instrument response. The instrument response can be written in the following form:

$$H(\omega) = K \frac{\prod_{j=1}^N (i\omega - z_j)}{\prod_{j=1}^M (i\omega - p_j)}$$

where

$$i = \sqrt{-1},$$

K is a constant factor,

Z_j and P_j are the zeros and the poles of the system respectively

N is the number of zeros

M is the number of poles

Determining the instrument response requires the specification of the poles and zeros and the value of K. For our purposes it is sufficient to represent the frequency response of the system in this form.

Instrument response of CMG-40T +Orion

The CMG-40 seismometer has three zeros and three poles. From the manual one can find the position of these poles and zeros, a normalization factor and the sensitivity. For example the poles and zeros of CMG-40 with serial number T4774 are:

$$Z_1 = (0, 0)$$

$$Z_2 = (0, 0)$$

$$Z_3 = (159, 0)$$

$$P_1 = (-50, 0)$$

$$P_2 = (0.02356, -0.02356)$$

$$P_2 = (-0.02356, +0.02356)$$

Normalization factor = -0.314 (nominal)

Seismometer Sensitivity = 800 (nominal)

Connecting the CMG-40 seismometer with an Orion seismograph introduces a series of electronic circuits each with its own transfer function. The overall transfer function of CMG-40T plus Orion is the multiplication of all of their transfer functions. The location of all zeros and poles of the seismograph are usually very far from the location of the poles and zeros of the seismometer, in such a way that the transfer function of each component of the seismograph system acts as a constant (unless the sampling rate is too low or a high-cut or low-cut filter has been applied). In the other words, the location of the poles and zeros of the seismometer control the shape of the overall system transfer function and all of the other elements in the circuit can be represented by a factor, that shifts the overall transfer function up or down. The combination of a CMG-40 and an Orion makes a set of poles and zeros and an overall constant, that can be written as follows:

$$Z_1 = (0, 0)$$

$$Z_2 = (0, 0)$$

$$Z_3 = (159*2\pi, 0)$$

$$P_1 = (-50*2\pi, 0)$$

$$P_2 = (0.02356*2\pi, -0.02356*2\pi)$$

$$P_2 = (-0.02356*2\pi, +0.02356*2\pi)$$

$$\text{constant} = \text{seismometer Normalization factor} * \text{seismometer Sensitivity} * \text{Orion sensitivity}$$

All of the poles and zeros should be multiplied by 2π , in order to convert them to radians. Normalization factor also should be modified if the number of poles and zeros are not the same.

The Orion has been calibrated to have the multiplication factor (seismometer Sensitivity * Orion sensitivity) equal to $1e+9$ (nominal). If we consider all of the nominal constants (Normalization factor = -0.314 , Sensitivity = 800), the sensitivity of the Orion should be $1.25e+6$. In the nominal case, the poles, zeros and overall constant are as follows:

$$Z_1 = (0, 0)$$

$$Z_2 = (0, 0)$$

$$Z_3 = (159*2\pi, 0)$$

$$P_1 = (-50*2\pi, 0)$$

$$P_2 = (0.02356*2\pi, -0.02356*2\pi)$$

$$P_2 = (-0.02356*2\pi, +0.02356*2\pi)$$

$$\text{Overall constant (nominal)} = 0.314*800*1.25e+6$$

These are nominal values and should be replaced by actual numbers, which are indicated in the as-shipped pages. Knowing the values of the poles and zeros in radians and the overall constant, the instrument response can be removed from a recorded seismogram by dividing the Fourier transform of the signal by the transfer function.

Removing instrument response from a seismograms in SAC

This describes the procedures used to correct seismograms for instrument response using the well-known SAC (Seismic Analysis Code) program distributed by Lawrence Livermore Lab.

- 1- Convert Orion recorded data to SEED (Standard for the Exchange of Earthquake Data) format.
- 2- Convert SEED data to SAC format. By converting SEED data to SAC format, an ASCII file can be generated containing instrument response in terms of poles and zeros and overall constant. To remove instrument response in SAC you need to have a file of the form:

ZEROS 3

999.0260

0.000

0.000

POLES 3

-0.1480 0.1480

-0.1480 -0.1480

-314.1600 0.0000

CONSTANT 3.228397e+08

- 3- Run the following commands in SAC

read seismogram.SAC

transfer from POLEZERO subtype PolesAndZerosFileName

Note: the generated poles and zeros of the instrument response are the displacement instrument response. Applying the above commands without any changes results in a seismogram with units of displacement. You may convert the displacement seismograms into velocity or acceleration seismograms in the frequency domain. You may also manipulate the number of zeros to convert displacement instrument response to velocity or acceleration instrument response or vice versa.

Instrument response of S13

The PRSN uses Geotech S13 seismometers. The characteristic parameters of the mechanical system of S13 are :

$m[\text{kg}]$ = suspended mass

$d[\text{Ns/m}]$ = damping constant

$c [\text{N/m}]$ = spring constant

$f_o [\text{Hz}]$ = $\sqrt{c / m} / 2\pi$

α = $d/(2m\omega_o)$ (critical damping means $\alpha=1$)

The transfer function of S13, $H(s)$, relates the mass displacement to the ground displacement, corresponding to a normalized second order high pass characteristic:

$$H(s) = \frac{s^2}{s^2 + 2\alpha\omega_o s + \omega_o^2} = \frac{(s-z_1)(s-z_2)}{(s-p_1)(s-p_2)}$$

Where $s = i\omega$

z_1 , z_2 , p_1 and p_2 can be calculated from above parameters. The above transfer function (displacement instrument response) consists of two zeros at the origin and two poles whose locations depend on the damping and the natural frequency of the system. Zeros at the origin simply introduce a constant phase shift, which can be used to obtain velocity instrument response. Usually an S13 is connected to some electronic instruments like low-cut and high-cut filters and amplifiers. These filters depend on their electronic design and have their own instrument response, but can still be represented in terms of poles, zeros and a constant. Finally, the overall instrument response is the multiplication of all of the instrument response functions in the frequency domain.

c EXSIM is FINSIM program which has been modified to include the following features:

- c - Calculation of power spectra density of the simulated accelerographs
- c - Calculation of received energy at the observation point
- c - Inclusion of new concept of the dynamic corner frequency
- c - Calculation of seismic moment based on the dividing the total seismic moment of earthquake fault divided by number of subfaults
- c - Substituting of the strength factor by stress parameter
- c - Variability of pulsing area or the number of subfaults which is considered as active subfaults in calculation of dynamic corner frequency.

c

c

c some of variables have been renamed for easier future modification.

c

c

c FINSIM Program By:Igor A. Beresnev and Gail M. Atkinson (September'97)

c This is the program simulating horizontal component of shear wave from a finite fault. The large fault plane is subdivided into rectangular elements, each element (subfault) is assigned an w-squared spectrum, and delayed contributions from all subfaults are summed up in the time domain. In generating subfault accelerograms, a stochastic point-source technique ("band-limited white noise method") is followed (Boore, 1983; Boore and Atkinson, 1987). The units of simulated accelerogram are cm/sec**2. The accelerogram, simulation parameters, and pseudo-acceleration response spectrum are written into specified ascii files

c

c The program is limited to simulations of frequencies of 0.25 Hz and higher. The subfault size should not be less than appr. 5 km to make simulations reasonably subfault-size independent

c

c The user should provide fault discretization and slipWeights distribution models.

c The input data should be prepared in a file. The program will ask for the name of input file. An example input file is enclosed

c

c All subroutines are attached

cc

c Authors: Igor A. Beresnev and Gail M. Atkinson (September'97) c

cc

c

c The dimension of the array totalWave, containing simulated finite-fault accelerogram, is 20000. Data are sampled at dt sec. The iFFTpoints-point Fast Fourier Transform is used. dt and iFFTpoints are user-specified. Maximum nl (number of subfaults along fault strike, Figure 1) is 50. Maximum nw (number of subfaults along dip) is 50

c

c reading input parameters (see Figure 1 for geometry)

c A rectangular fault with horizontal upper and lower sides is assumed.

c Origin O is always placed at the upper corner of the fault, opposite to strike direction. A convention defining strike direction is that fault always dips to the right of it (Aki and Richards, "Quantitative Seismology", Fig.4.13). FaultLat and FaultLon are latitude and longitude of surface projection (O1) of the origin (see Aerial View in Figure 1)

c

c comm - comment to be written as first line in output parameter file
(70 characters)

c FaultStrike - fault strike (degrees) (0 to 360)

c FaultDip - fault dip measured from horizontal (degrees) (0 to 90)

c h - depth to upper edge of the fault (km)
 c FaultLat,FaultLon - latitude and longitude of the origin (degrees). Convention
 c for sign of coordinates: '+' for North and East, '-' for South
 c and West
 c SiteLat,SiteLon - latitude and longitude of the observation point (degrees)
 c FaultLength - fault length along strike (km)
 c FaultWidth - fault width downdip (km)
 c nl - number of subfaults along strike
 c nw - number of subfaults along dip
 c i0,j0 - the indices of the subfault that contains the hypocenter
 c i and j increase along strike and downdip, respectively,
 c starting from 1 at origin (Figure 1)
 c iFFTpoints - number of points in Fast Fourier Transform used to calculate
 c subsurface accelerograms. Must be a power of two (maximum of
 c 8192 is allowed). If not sufficient, the program will give
 c you a warning
 c dt - time-series sampling interval (sec)
 c beta - crustal shear-wave velocity (km/sec) (e.g., average value
 c for depth of event)
 c rho - crustal density (g/cm**3)
 c amag - moment magnitude of modeled (target) event
 c stress - "stress" parameter (bars). Controls subfault moment and total
 c number of subsources summed. To avoid insufficient number of
 c "active" subsources, we recommend it be always kept at
 c "average" value of 50 bars. Lower values are possible; higher
 c values should not generally be used
 c iKapa - 0 or 1 for "fmax" and "kappa" low-pass filters, respectively
 c fmax - cutoff frequency of "fmax" filter (if iKapa=0) or parameter
 c "kappa" (if iKapa=1)
 c Q0,eta - parameters of attenuation model $Q(f)=Q0*f**eta$
 c igeom,rg1,rg2,pow1,pow2,pow3
 c - geometric attenuation model. If igeom=0, 1/r model is
 c applied. If igeom=1, "trilinear" form is used: $r**pow1$
 c ($r \leq rg1$), $r**pow2$ ($rg1 < r \leq rg2$), $r**pow3$ ($r > rg2$). rg1
 c and rg2 are in km
 c rmin,rd1,
 c rd2,durmin,
 c b1,b2,b3 - parameters of "trilinear" distance-dependent duration model
 c used for subevents. A constant term durmin is added to source
 c rise time at $r \leq rmin$. Duration increases linearly with distance
 c as $dur(r) = b*r$ with slopes b1, b2, b3 at distances between
 c rmin and rd1, rd1 and rd2, and beyond rd2, respectively. r's
 c are in km, durmin is in sec.
 c A model rmin = 50 km, durmin = 1.4 sec, b1 = 0.07, and rd1, rd2
 c set to "infinite" values is approximately valid for subduction-
 c zone events ("one-slope" model) (Atkinson, BSSA, no.5/95;
 c Beresnev and Atkinson, BSSA, no.1/97).
 c For eastern North America, one might use rmin = 10 km,
 c rd1 = 70 km, rd2 = 130 km, durmin = 0 sec, b1 = 0.16,
 c b2 = -0.03, b3 = 0.04 (Atkinson and Boore, BSSA, no.1/95).
 c To keep duration equal to source rise time at all distances,
 c simply set durmin = 0 sec and rmin at "infinite" value
 c iwind - if 0, a cosine-tapered boxcar window will be applied to
 c subfault time series; if 1, a Saragoni-Hart window will be
 c applied. Using 1 produces more realistic-looking accelerograms
 c when total number of subfaults summed is relatively low,

c e.g., for target magnitudes of about 6-7

c nfreq,

c freq1,freq2 - response spectrum is calculated at nfreq logarithmically-spaced frequencies between freq1 and freq2 (Hz). freq1 should be no lower than 0.25 Hz. nfreq cannot exceed 100

c facc,fpar,

c fpsa - names of ascii files in which to save acceleration time history, simulation parameters, and average response spectrum, respectively

c namp1,fresp1- namp1 determines if spectra should be amplified by site amplification function. For convenience, user may specify two separate amplifications: e.g., one due to generic crustal model and one due to local site response. Application of second function is controlled by namp2,fresp2 below. If namp1 is set to 0, no amplification is introduced. If you enter a non-zero value, prepare an ascii file and provide its name as fresp1. The file should have two columns, frequency (real) and amplification (real), separated by space or tab. The file should contain namp1 lines; maximum namp1 is 100. Program will interpolate. For frequencies to the left and right of lowest and highest values provided, amplification will be assumed constant. For example, if you provide response function between 1 and 10 Hz, amplification below 1 Hz will be assumed as at 1 Hz, and above 10 Hz as at 10 Hz. Put any dummy file name if namp1 = 0

c namp2,fresp2- same as namp1,fresp1 for second amplification function

c ntrial,damp - number of simulations to calculate average response spectrum (ntrial). A time series saved is from first simulation. damp is percentage of critical damping for calculation of response spectrum

c IslipWeigth - enter 0 if you use your own slipWeights distribution model. Then provide slipWeights(i,j) below. Enter any other integer number if you don't want to enter your model. The program will skip reading array slipWeights(i,j) and will generate random normally distributed slipWeights with standard deviation equal to mean. IslipWeigth will be the seed of random-number generator

c slipWeights(i,j) - array of slip weights on individual subfaults in any relative units. Allows to specify inhomogeneous slipWeights. Slip weights need not sum to unity; program will do normalization. Subfault moments will be weighted accordingly so that total moment is conserved. First enter upper horizontal row, then second horizontal row, and so on to the bottom (Figure 1). The array is (nl x nw). If slipWeights is homogeneous, enter same number for all subfaults. Because subfault moments are discrete, the given slipWeights distribution slipWeights(i,j) will be mimicked but not exactly reproduced. The program will return the actual slips on subfaults in meters in an output parameter file

c

c dl and dw below are subfault length and width, respectively. nl and nw should be specified in such a way that (dl+dw)/2 is no less than 5 km

```
dimension wave(8192),totalWave(20000),subWave(20000)
dimension energy(8192),totalEnergy(8192)
dimension slipWeights(50,200),actualSlip(50,200)
dimension weightedMoment(50,200)
dimension freq(100),psa(100),averagePSA(100)
```

```

character facc*30,finp*30,fpar*30,fpsa*30,fresp1*30,fresp2*30
character fEnergy*30,fPSD*30
character*80 inputFileName
character title*80

common /par/ maxPointsOfWave,iFFTpoints,dt
common/ioFiles/ioPar,ioPsa,ioEnergy,ioAcc,ioIn,ioPSD
common /seed/ IslipWeigth
common /fnames/ fresp1,fresp2
common /sub/subFaultMoment,f0,rho,beta,iKapa,fmax,Q0,eta,riseTime,
*   rmin,rd1,rd2,durmin,b1,b2,b3,igeom,rg1,rg2,pow1,pow2,pow3,
*   iwind,namp1,namp2
data   averagePSA /100*0./
integer soFarWVMs
integer maxPointsOfWave
integer totalPointsOfWave

ioIn=2
ioPar=12
ioPsa=13
ioEnergy=14
ioPSD=17
maxPointsOfWave=20000
pi=3.141593
y=0.80

call openInputFiles(iRow,jColumn)
call getInputParameters(FaultStrike,FaultDip,h,
*   FaultLat,FaultLon,
*   SiteLat,SiteLon,FaultLength,FaultWidth,nl,nw,
*   i0,j0,iFFTpoints,dt,beta,rho,amag,
*   stress,iKapa,fmax,Q0,eta,igeom,rg1,rg2,pow1,
*   pow2,pow3,rmin,rd1,rd2,durmin,b1,b2,b3,iwind,
*   nfreq,freq1,freq2,facc,fpar,fpsa,fEnergy,fPSD
*   , namp1,
*   fresp1,namp2,fresp2,ntrial,damp,IslipWeigth,
*   slipWeights,iRow,jColumn,effectivePercent,title)
call openOutputFiles(facc,fpar,fpsa,fEnergy,fPSD)

v=y*beta

soFarWVMs = soFarWVMs+1

dl = FaultLength/nl

dw = FaultWidth/nw

subFaultRidious = (dl+dw)/2.

riseTime = subFaultRidious/v

totalMoment = 10.**(1.5*amag+16.05)

averageSubFaultMoment = totalMoment/(nw*n1)

firstElementF0=4.9e+6*beta*(stress/averageSubFaultMoment)**0.3333

```

```

NoOfEffectiveSubfaults = FaultLength*effectivePercent/100/dl

    if (NoOfEffectiveSubfaults.eq.0)NoOfEffectiveSubfaults = 1
    puslingLength=NoOfEffectiveSubfaults*dl

    call checkFFTpoints(iFFTpoints)
    call createRandomWeight(nl,nw,slipWeights,IslipWeigth)
    call findSubFaultMoment(nl,nw,slipWeights
*       ,totalMoment,weightedMoment)
    call findDistanceAndAzimouth(FaultLat,FaultLon,SiteLat,
*       SiteLon,R,fi2)
    call convertDegreeToRadian(FaultStrike,fi2,dip,FaultDip,pi)
    call findTotalDuration(nl,nw,dl,dw,FaultStrike,fi2,
*       beta,i0,j0,dip,R,h,v,dmin,totalDuration)

    totalPointsOfWave=totalDuration/dt
    if(totalPointsOfWave.gt.maxPointsOfWave)
*       totalPointsOfWave=maxPointsOfWave

    call initializeAveragePSA(nfreq,averagePSA)
    print *, "Program is running. Please Wait!"
    do 3000 iresp=1,ntrial
        call initializeArrays(maxPointsOfWave,iFFTpoints,totalWave,
*           totalEnergy,energy)
        do 2000 i=1,nl
            do 1000 j=1,nw
                subFaultMoment=weightedMoment(i,j)
                NumberOfActiveSubs=NumberOfPulsingSubs(i0,j0,i,j
*           ,nl,nw,NoOfEffectiveSubfaults)
                f0=firstElementF0*((NumberOfActiveSubs)**(-1.0/3.0))
                actualSlip(i,j)=1.e-22*subFaultMoment/
*           (rho*beta**2.*dl*dw)
                subfaultDistance=findSubfaultDistance(R,h,FaultStrike,
*           fi2,dip,dl,dw,i,j)

                call computeStochasticWave(wave,subfaultDistance
*           ,NumberOfActiveSubs,energy)
                if(iresp.eq.ntrial)call computeEnergy(i,j,nl,nw,
*           iFFTpoints,dt,totalEnergy,energy,sum)

c           count cumulative number of subsources summed
c           subsourse accelerogram is randomly delayed to simulate complexity
c           in slip process
c           subtract minimum delay to eliminate static time shift, but retain constant
c           static shift of 2 s
                delay=sqrt((dl*(i-i0))**2.+(dw*(j-j0))**2.)/v
                delay=(delay+subfaultDistance/beta)-dmin+2.
                randomDelay=delay+(urand(IslipWeigth))*riseTime

c           shift generated time series by randomDelay and return in array subWave
                call shift (wave,subWave,randomDelay)
c           add current accelerogram to total wave field
                do k=1,maxPointsOfWave
                    totalWave(k)=totalWave(k)+subWave(k)

```



```

        enddo
1000    continue
2000    continue

c ***** end of summation *****
c accelerometer and model parameters are saved only once
  if (iresp.eq.1) then

    call findShortestFaultSistance(FaultLength,FaultWidth,
*      R,h,FaultStrike,fi2,dip,faultDistance)

    peakValue=findPeakValue(maxPointsOfWave,totalWave)
    call writeAcc(facc,fpar,totalWave,peakValue,
*      totalPointsOfWave,title)
    call writeAccInSacFormat(totalWave,peakValue
*      ,totalPointsOfWave,soFarWVMs,amag)
    call writePar (180./pi*FaultStrike,FaultDip,h,FaultLat,
*      FaultLon,SiteLat,SiteLon,FaultLength,
*      FaultWidth,nl,nw,dl,dw,i0,j0,amag,
*      stress,nnTrig,actualSlip,faultDistance,
*      effectivePercent,title,puslingLength)
  endif

  dur=(maxPointsOfWave-1)*dt-5.

  call computeResponse(totalWave,dt,dur,damp,freq1,freq2,
*      nfreq,freq,psa)

  call computeAverageResponse(averagePSA,psa,nfreq,ntrial)
  write (*,(' *** trial',i4)) iresp
3000 continue

  call calculatePSD(totalWave,maxPointsOfWave,dt
*      ,sumOfEnergy,energy,ioPSD)
  call writePSA (freq,averagePSA,nfreq,ntrial,damp,amag,siteLat
*      ,siteLon,h,fi2*180./pi,faultDistance,fpar)
  call closeFiles()

10  format (' *** trial',i4)
100 format(f5.1,2f6.1,2I4,6f8.2)
200 format(f5.1,3i7,2f8.0)
  stop
  end

cccccccccccccccccccc End of Main Program ccccccccccccccccccc
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```

```

subroutine shift (wave,subWave,delay)
dimension wave(*),subWave(*)
common /par/ maxPointsOfWave,iFFTpOints,dt
do i=1,maxPointsOfWave
    subWave(i)=0.
enddo
ish=int(delay/dt)+1
if (ish.gt.maxPointsOfWave+1) return
iend=ish-1+iFFTpOints
if (iend.gt.maxPointsOfWave) iend=maxPointsOfWave
j=0
do i=ish,iend
    j=j+1
    subWave(i)=wave(j)
enddo
return
end

```

```

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
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    real function urand (iy)
c      uniform random number generator. Values of urand are returned
c      in the interval (0,1) (G.E. Forsythe, M.A. Malcolm, C.B. Moler,
c      "Computer Methods for Mathematical Computations", Prentice-Hall, Inc.)
    integer iy,ia,ic,itwo,m2,m,mic
    double precision halfm,datan,dsqrt
    real s
    data m2/0/,itwo/2/
    if(m2.ne.0) go to 20
    m=1
10   m2=m
    m=itwo*m2
    if (m.gt.m2) go to 10
    halfm=m2

```



```

        stop
    endif

    do i=1,iFFTpoints
        seism(i)=0.
        s(i)=cmplx(0.,0.)
        seism(i)=0.0
        energy(i)=0.0
    enddo

c generate Gaussian white noise with zero mean, unit variance. Noise is
c tapered.

    do i=1,nstop
        if (iwind.eq.0) call window(i,1,nstop,ntaper,wind)
        if (iwind.eq.1) call wind2 (i,1,nstop,ntaper,dur,0.2,0.2,wind)
        s(i)=wind*cmplx(ggnqf()),0.)
    enddo

c transform to frequency domain

    call fork (iFFTpoints,s,-1.)

c multiply spectrum by an w-squared spectral shape after normalizing to
c square of unit spectral amplitude

    call avg (nnyq,s,avamp2)
    avamp=sqrt(avamp2)
    do i=1,nnyq
        f=(i-1)*df
        energy(i)=sourceSpectra(f,subfaultDistance,const,
*           NumberOfActiveSubs)**2.0
        s(i)=sourceSpectra(f,subfaultDistance,const,
*           NumberOfActiveSubs)*s(i)/avamp
        if (i.ne.1) s(iFFTpoints+2-i)=conjg(s(i))
    enddo
    s(nnyq)=cmplx(real(s(nnyq)),0.)

c transform back to time domain
    call fork(iFFTpoints,s,1.)
    afact=sqrt(float(iFFTpoints))/tmax
    do i=1,iFFTpoints
        seism(i)=afact*real(s(i))
    enddo
    return
end

cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
cccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccccc
    subroutine durcmp (subfaultDistance,dur)
c computes duration dur of soubsource time histories
    common /sub/subFaultMoment,f0,rho,beta,iKapa,fmax,Q0,eta,riseTime,
*   rmin,rd1,rd2,durmin,b1,b2,b3,igeom,rg1,rg2,pow1,pow2,pow3,
*   iwind,namp1,namp2
    if (subfaultDistance.le.rmin) dur=riseTime+durmin
    if (subfaultDistance.gt.rmin.and.subfaultDistance.le.rd1)

```


c bounds we do a quick cosine taper down to 0

pi=3.141592654

```
if(i.lt.nstart.or.i.gt.nstop) return
```

c Apply Sargoni and Hart window

$$b = -\epsilon \cdot \log(\eta) / (1 + \epsilon \cdot (\log(\epsilon) - 1))$$
$$a = (2.7182818 / (\epsilon_{ps} \cdot t_w))^{**b}$$
$$t = (tw / \text{float}(nstop - nstart - 2 * ntaper)) *$$
$$\text{wind} = a * t ** b * \exp(-c * t)$$

else

c Cos. taper goes from 0 to 1 from `nstart` to `nstart+ntaper`, from

1 to 0 from nstop-ntaper to nstop.

```
if (i.lt.(nstart+ntaper)) then
```

$$wf=a*t1**b*\exp(-c*t)$$

```

else

```

```
wind=abs(sin((float(nstop)/float(nstart))
```

```
Wind=abs(sin((float(nstop-1)/float(nlaper))*pi/2.))*Wl
endif
```

end
return

and dif

endit
and

end

[illegible]

```
subroutine computeResponse(a,dt,dur,damp,freq1,freq2,
```

* Nfreq, freq.psa)

c calculates response spectrum from acceleration time history

dimension Freq(*),Omega(100),psa(*),a(*)

real pi,freq1,freq2,damp,Maxtim

pi=3.141593

```
write (6,*)
```

stop

c Convert % damping to fraction

```
beta=damp*0.01
```

c Add 5 sec. to dur for shake-down

```
maxtim=dur+5.
```

$$n = \text{ifix}(\text{dur}/\text{dt})$$

```
ntime=ifix(maxtim/dt)
```