Finite fault stochastic modeling of the 1999

Chi-Chi Taiwan Earthquake

by

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ABSTRACT

Ground motion prediction plays an important role in seismic hazard evaluation and mitigation. Among various techniques, the stochastic simulation method is a simple, powerful and widely used way to characterize the behavior of ground motions of a broad range of earthquake magnitudes and distances. By comparing the response spectra of observed and simulated ground motions, the source parameters of the earthquake, the propagation properties of the crust and the site amplification behavior may be inferred. This information allows us to better predict future ground motions and ultimately improve building codes.

In this study, the revised Finite Fault Stochastic Simulation technique proposed by Motazedian (2002) and Motazedian and Atkinson (2005) is used to model over 400 ground motion records from the 1999 M_W 7.6 Chi-Chi Taiwan earthquake, at near-fault to regional distances. The geometric and anelastic attenuation properties of the crust, site amplifications and duration are empirically calculated from the recorded seismic data.

With the specified path and site model for the Chi-Chi earthquake, stochastic simulation is conducted first on rock stations for model calibration, and then on soil stations using the calibrated model. Based on comparisons of simulations and data, I conclude that the stress drop of the Chi-Chi earthquake was 40 bars, which is relatively low compared with earthquakes of similar magnitude in other regions (eg. 50-70 bars in California). Regarding site effects, I conclude that the H/V (horizontal/vertical component) ratio works well as a site amplification term, and that obvious nonlinear soil response was observed on soil stations during the Chi-Chi earthquake.

Furthermore, there are marked basin effects in the Taipei region for ground motions of intermediate frequency (around 1 Hz). This could be an important contributing reason for building damage in the Taipei area during the Chi-Chi earthquake.

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LIST OF ACRONYMS

This section contains the definition of the acronyms used in the manuscript.

PGA: Peak Ground Acceleration

PGV: Peak Ground Velocity

Faccn: Fourier Acceleration Amplitude

PSA: Pseudo Spectrum Acceleration (5% damping)

NEHRP: National Earthquake Hazard Reduction Program

USGS: United States Geological Survey

CWB: Central Weather Bureau (Taiwan)

TSMIP: Taiwan Strong-Motion Instrumentation Program

SMSIM: **S**tochastic **M**odel **SIM**ulation

FINSIM: **FIN**ite fault stochastic **SIM**ulation

EXSIM: **EX**tended fault stochastic **SIM**ulation

FFT: Fast Fourier Transformation

IFFT: Inverse Fast Fourier Transformation

M_W : Moment Magnitude

E-W: East-North direction

N-S: North-South direction

U-D: Vertical direction

NCREE: National Center for Research on Earthquake Engineering (Taiwan)

H/V: Horizontal to Vertical ratio of the Fourier acceleration amplitudes

Chapter 1

INTRODUCTION

1.1 Purpose of Study

The September 21, 1999, Chi-Chi earthquake ($M_W = 7.6$) is one of the largest earthquakes to strike Taiwan this century. During this earthquake, many strong motion records were collected, greatly increasing the world's near-fault strong motion database. The Chi-Chi database, especially the rich near source records, offers us a good opportunity to investigate the earthquake's source parameters, the path and the site amplification effects, including the non-linear soil response.

In engineering, the peak value of ground acceleration or velocity (PGA or PGV) is often used to conduct some preliminary analysis. However, the PGA or PGV of the shaking cannot adequately characterize the ground motion, since the duration and the frequency content of the shaking are the important factors that control the earthquake damage. An earthquake with low peak ground motion amplitude but longer duration may release more energy than the one with large peak value but shorter duration. The response spectrum of the shaking, describing the response of a single-degree-of-freedom to the motion as a function of natural frequency, is a useful description as it conveys information on the frequency content of the ground motion, and is somewhat influenced by the duration.

According to Taiwan's Interior Department records, the death toll in the Chi-Chi earthquake was 2,470 and 11,305 people were injured (Shin and Teng, 2001).

Thousands of houses collapsed making more than 100,000 people homeless. Among several factors leading to the high casualty rate in the Chi-Chi earthquake, buildings collapsing in the metropolitan area is a key one. Underestimation of seismic hazard in the building code at least partly explains these collapses. Understanding the source characterization of the earthquake, the propagation properties of the crust in Taiwan Island and the site amplification behavior may help us to improve the building code for this region.

In this study, I use the extended fault stochastic simulation method developed by Motazedian (2002) and Motazedian and Atkinson (2005) to model ground motions of the $M_W = 7.6$ Chi-Chi main shock. By calibrating the simulation parameters to reproduce the ground motion, we can determine the contribution of the source, propagation path and site parameters to the ground motion. Furthermore, by analyzing the simulated results, we may determine the slip distribution model, the directivity effect, the basin effect and the non-linear response of the soil stations. Better understanding of these effects improves our ability to predict ground motion for future large earthquakes, hence improve building codes.

1.2 Organization of Work

This study focuses on the source characterization of the 1999 Chi-Chi earthquake, seismic wave path parameters of Taiwan Island and site amplification of the strong motion stations. These effects are discussed in six chapters. In Chapter 1, the purpose of the project and the outline of the tasks is presented. Chapter 2 overviews and compares the theoretical background of the point source stochastic simulation technique (SMSIM (Boore, 1996)), the finite fault stochastic simulation method (FINSIM (Beresnev and Atkinson, 1998a)) and the extended fault stochastic

simulation approach (EXSIM (Motazedian and Atkinson, 2005)), which is adopted in this study. Chapter 3 describes the strong motion seismic network in Taiwan, the available dataset used in this study and the procedures of the data processing. Chapter 4 presents taken steps to obtain the source parameters (fault geometry, earthquake location and ground motion duration), the path (geometric attenuation spreading and Q model), and the site effects (site amplification function and the kappa factor). Chapter 5 discusses the input parameters for ground motion simulation at rock stations, the process of model calibration, the parameters determined by the simulation and the simulation results for both rock and soil stations. Chapter 6 presents the conclusions.

1.3 Contribution

The author, under the supervision of his advisors, has made the following contributions in this study:

1. Data processing of 441 strong motion three-component recordings of the Chi-Chi mainshock.
2. Characterizing the seismic source and path parameters of the 1999 Chi-Chi earthquake, including calculating the kappa value for all of the stations (two horizontal and vertical components), and the regression of ground motions to determine the geometric spreading attenuation and Q model for the main shock.
3. Calculating the site amplification function for rock and soil stations based on the shear wave velocity information provided by National Center for Research on Earthquake Engineering of Taiwan.

4. Calculating H/V ratio and evaluating its accuracy as a site amplification function.
5. Determining stress drop and pulsing percentage (two free source parameters), based on extended fault stochastic simulation techniques.
6. Analyzing the nonlinear soil response by applying the calibrated model parameters (from NEHRP class C stations) to the soil stations (NEHRP class D sites) using the empirical correction function.
7. Analyzing the basin effect of the soil stations in the Taipei basin area.

Chapter 2

LITERATURE SURVEY

2.1 Overview

The main modeling technique used in this study is the stochastic model, which is reviewed here. In stochastic simulation of ground motions, a Gaussian noise signal with zero mean and unit variance is first generated in the time domain as shown in Figure 2.1. Then, a window such as the Saragoni-Hart taper window (Figure 2.2) with a specified duration time is applied to the noise signal. Figure 2.3 shows the tapered Gaussian noise. Then, the tapered noise signal is transformed by FFT (Fast Fourier Transformation) from the time domain to the frequency domain to obtain the Fourier amplitude acceleration spectrum of the noise signal (Figure 2.4). To model a specific earthquake magnitude at a given distance, the Brune model spectrum (Figure 2.5) is often calculated (Equation 2.10) and multiplied with the spectrum of the noise signal (Boore, 1983). Figure 2.6 is the spectrum of a specified earthquake at a target distance based on the stochastic simulation method. Finally, the simulated spectrum is transformed back to the time domain by IFFT (Inverse Fast Fourier Transformation) to get the seismogram, as shown in Figure 2.7. When using the above procedure to generate the simulated seismogram, the parameters chosen to specify the Brune spectrum model as a function of magnitude and distance are the key factors. In this study, most of the efforts are based on how to adjust parameters to specify the seismological model, using regional empirical parameters and regression

analysis of the recorded strong motion data. In the following section, the theoretical background of the stochastic simulation technique is presented in more detail. Its application to the Chi-Chi earthquake is then introduced.

2.2 Stochastic Simulation

2.2.1 Point Source Stochastic Simulation

The stochastic simulation method is a simple, powerful and widely used technique to predict ground motions (Boore, 1983; Boore and Atkinson, 1987; Atkinson and Boore, 1997; Beresnev and Atkinson, 1997, 1998a, 1999; Atkinson and Silva, 2000; Castro *et al.*, 2001; Roumelioti and Kiratzi, 2002; Roumelioti and Beresnev, 2003). It is particularly useful to simulate the higher-frequency ground motion which is of interest to most engineers ($f > 0.2$ Hz) (Boore, 2003). This method assumes that higher-frequency earthquake ground motions can be represented as a band-limited Gaussian noise which has an ω^2 mean spectrum (Beresnev and Atkinson, 1998b), sometimes referred to as a Brune spectrum (Brune, 1970). Various factors affecting ground motions ($FA(M_0, R, f)$) can be simply expressed as Equation 2.1, which is the product of the source term ($E(M_0, f)$), the path term ($P(R, f)$) and the site term ($G(f)$), in the frequency domain (Boore, 2003):

$$FA(M_0, R, f) = E(M_0, f)P(R, f)G(f) \quad (2.1)$$

where f is frequency in Hertz, M_0 is the seismic moment introduced by Aki (1966) and R is the hypocentral distance.

The spectrum of ground motions at a site is the combined effects of the source, the path and the site. In the following sections, these factors will be discussed in

more detail.

The source effects In the stochastic simulation technique, the most frequently used earthquake source model is the ω -square shape spectrum (Aki, 1967; Brune, 1970). Apart from the widely used ω -square model, there are many other models used in stochastic simulation (Boatwright and Choy, 1992; Atkinson and Boore, 1995; Frankel *et al.*, 1996; Haddon, 1996; Atkinson and Silva, 2000). The earthquake source spectra for all of the models can be written in a general form as Equation 2.2.

$$E(M_0, f) = CM_0S(f, f_0) \quad (2.2)$$

where C , f_0 and M_0 are a constant defined in Equation 2.3, corner frequency and seismic moment, respectively. $S(f, f_0)$ is one of the above-mentioned spectrum models.

$$C = \frac{R_{\theta\phi} \cdot FS \cdot PRTITN}{4\pi\rho\beta^3} \quad (2.3)$$

where $R_{\theta\phi}$ is the radiation pattern, FS is the amplification due to the free surface, $PRTITN$ is the reduction factor that accounts for the partitioning of energy into two horizontal components($1/\sqrt{2}$), ρ and β are the density and shear wave velocity, respectively (Boore, 1983).

Among source spectra models used in the stochastic simulation, the ω^2 model ($S(f, f_0)$) introduced by Aki (1967) and Brune (1970) is used in this study to characterize the spectrum of subfaults that make up an extended fault plane. Equation 2.4 is the functional form of the Brune source spectrum model (Brune, 1970).

$$S(f, f_0) = \frac{f^2}{1 + (f/f_0)^2} \quad (2.4)$$

where f_0 can be calculated by Equation 2.5 (Boore, 1983):

$$f_0 = 4.9 \times 10^6 \beta (\Delta\sigma / M_0)^{1/3} \quad (2.5)$$

where β in km/s, M_0 in dyne-cm, $\Delta\sigma$ in bars.

The corner frequency (f_0) is a function of seismic moment, as illustrated in Figure 2.8. Assuming self-similarity in the source, it can be shown that $M_0 f_0^3 = \text{constant}$ (Aki, 1967; Boore, 2003).

The path effects The simplest path effects function, $P(R, f)$ (Equation 2.6), is the product of the geometrical spreading function $Z(R)$ and the anelastic attenuation which is a function of crustal quality factor, Q , (Boore, 2003):

$$P(R, f) = Z(R) \exp[-\pi f R / Q(f) \beta] \quad (2.6)$$

The geometrical spreading function $Z(R)$ can be assigned with various forms. The simplest form for $Z(R)$ is $Z(R) = \frac{1}{R^n}$. Alternatively, a hinged linear form in which n varies with distance may also be used, as described by Atkinson (2004). The anelastic attenuation function is discussed in more detail in Chapter 4.

The site effects The site effects, defined as Equation 2.7, are comprised of two separate parts: site amplification ($A(f)$) and the high frequency diminution operator ($D(f)$).

$$G(f) = A(f)D(f) \quad (2.7)$$

The site amplification ($A(f)$) as a function of frequency can be calculated using the quarter wavelength approximation approach (Boore and Joyner, 1997). The high fre-

quency diminution operator ($D(f)$) accounts for the path-independent loss of high-frequency in the ground motions (Boore, 2003). Some researchers (Papageorgiou and Aki, 1983) attribute $D(f)$ to source processes while others suggest it is a site effect near the recording station (Hanks, 1982). The form of $D(f)$ is typically represented as a 4th order butterworth filter (Equation 2.8), or an exponential filter (Equation 2.9) (Boore, 1983, 2003).

$$D(f) = [1 + (f/f_{max})^8]^{-1/2} \quad (2.8)$$

$$D(f) = \exp(-\pi\kappa_0 f) \quad (2.9)$$

where f_{max} is the high-cut frequency introduced by Hanks (1982), and κ_0 is the “kappa” parameter introduced by Anderson and Hough (1984).

After separate discussion of the source, path and site effects, in the following sections, their combined effects will be illustrated. Equation 2.10 presents the acceleration spectrum of the shear wave with seismic moment M_0 at hypocentral distance R from a point source earthquake.

$$FA(M_0, R, f) = CM_0 \frac{(2\pi f)^2}{1 + (f/f_0)^2} \exp(-\pi f \kappa_0) \frac{\exp(-\pi f R/Q\beta)}{R} A(f) \quad (2.10)$$

where $CM_0 \frac{(2\pi f)^2}{1 + (f/f_0)^2}$ is the source term discussed above in Equation 2.2, $\frac{\exp(-\pi f R/Q\beta)}{R}$ is the path term in which $\frac{1}{R}$ is the geometric spreading function and $\exp(-\pi f R/Q\beta)$ accounts for the anelastic attenuation effect, and $\exp(-\pi f \kappa_0)A(f)$ is the site term for the near surface high frequency diminution and site amplification.

Figure 2.9 presents the shape of the source term, the effects of the path term on the source term and the combined effects of the path and high-frequency diminution

operator ($\exp(-\pi f \kappa_0)$). The top line is the source spectra with a specified Brune model at distance R ($R=1$ in this example). The middle line is the product of the source term and the path term (only the anelastic attenuation affects the shape of the spectrum in this simple example). The bottom line is the product of the source term, the path term and $\exp(-\pi f \kappa_0)$. In this case, only the high-frequency diminution operator is included, and site amplification, $A(f)$, is not considered. It is assumed to be negligible for a very-hard rock site, as an example.

2.2.2 Finite Fault Stochastic Simulation

When the earthquake magnitude is small to moderate ($M_W < 6$), the earthquake can be treated as a point source. However, for large events ($M_W > 6$), the point source stochastic simulation may fail due to the effects of the rupture geometry, heterogeneity of the slip and directivity (Beresnev and Atkinson, 1998b). To overcome this limitation, Schneider *et al.* (1993), Beresnev and Atkinson (1998a) and Beresnev and Atkinson (1998b) extended the point source stochastic simulation technique to the finite-fault simulation. A rectangular fault plane is subdivided into several smaller subfaults. Each subfault is treated as a point source with an ω^2 spectrum (Equation 2.2). When the earthquake is triggered at the hypocenter, the rupture propagates radially from the hypocenter along the fault plane. As the rupture propagates, each subfault is triggered as a point source. The seismic waves generated by every subfault are summed at the target recording station with proper time delay defined as Equation 2.11.

$$t = \frac{r_2}{V} + \frac{r_1}{\beta} \quad (2.11)$$

where r_1 , r_2 , V and β are the distance between the mid-point of the subfault and the recording site, the distance between the hypocenter and the subfault middle, the

fault rupture velocity and the shear wave velocity, respectively.

According to the seismic moment conservation theory (similar to the energy conservation theory), the seismic moment of the whole fault plane (M_0) is the sum of the seismic moments of all subfaults (m_0). In the case of identical subfaults, the total seismic moment is given by the Equation 2.12

$$M_0 = N \cdot m_0 \quad (2.12)$$

where N is the number of the subfaults.

The finite fault stochastic simulation technique was implemented in the computer program FINSIM by Beresnev and Atkinson (1998a), including fault geometry, slip distribution, stress drop, path effects and duration (Beresnev and Atkinson, 1998b). FINSIM has been extensively validated via many real recorded earthquakes, including Michoacan, Mexico (1985); Valparaiso, Chile (1985); Saguenay, Quebec (1988) and Northridge, California (1994).

2.2.3 Refinements to the Finite Fault Stochastic Simulation

The above finite fault stochastic simulation method calculate the corner frequency of each subfault identically using Equation 2.13

$$f_{0ij} = 4.9 \times 10^6 \beta (\Delta\sigma / M_{0ij})^{1/3} \quad (2.13)$$

Where f_{0ij} , $\Delta\sigma$ and M_{0ij} are the corner frequency, the stress drop in bars and the moment of the ij^{th} subfault in dyne-cm respectively.

A conceptual drawback of FINSIM is that the simulated ground motions are dependent on the subfault size (Beresnev and Atkinson, 1998a). Motazedian (2002)

and Motazedian and Atkinson (2005) noted that this dependency on subfault size produces different radiated energy from the entire fault using different subfault sizes. In order to eliminate these shortcomings, the dynamic corner frequency concept, in which the corner frequency is expressed as a function of time, was proposed by Motazedian (2002) and Motazedian and Atkinson (2005), and implemented in the program EXSIM (Extended Fault Simulation). The concept of pulsing percentage, in which only some parts of the fault is active at any moment in time, was also introduced in EXSIM to mimic the rupture process of real earthquakes better. In EXSIM, the corner frequency of the subfault is defined in Equation 2.14. As the rupture propagates, it activates more subfaults, which contribute to the changing frequency content of the ground motion. The corner frequency of the active subfaults decreases to lower frequency because the corner frequency is inversely proportional to the ruptured area. The value of the corner frequency is not a static variable during the motion but has a dynamic value that varies with time in the rupture process. Thus, the corner frequency of Equation 2.13 can be rewritten as:

$$f_{0ij}(t) = N_R^{-1/3}(t) 4.9 \times 10^6 \beta (\Delta\sigma / M_{0ave})^{1/3} \quad (2.14)$$

where $f_{0ij}(t)$ becomes a function of time and controlled by $N_R^{-1/3}(t)$, which is the cumulative number of ruptured subfaults at time t . $M_{0ave} = M_0/N$ is the average seismic moment of subfaults.

The Fourier acceleration spectrum of the ij^{th} subfault using the dynamic corner frequency can be written as:

$$FA_{ij}(f) = CM_{0ij}H_{ij}(2\pi f)^2/[1 + (f/f_{0ij}(t))^2] \quad (2.15)$$

where H_{ij} is a scaling factor to conserve the high-frequency spectral level of subfaults, C is the constant defined in Equation 2.3, M_{0ij} is the moment of the ij^{th} subfault, and $f_{0ij}(t)$ is the dynamic corner frequency of the ij^{th} subfault (Motazedian and Atkinson, 2005).

From Equation 2.15, the introduction of the dynamic corner frequency tends to decrease the level of the acceleration spectrum but this is counteracted by H_{ij} , keeping the total radiated energy from the subfault constant (Motazedian, 2002).

The subfaults are not always active during the rupture. When the rupture triggers a subfault, the subfault is active for a while and stops after a limited time, after which it does not contribute energy to the ground motion any more. In EXSIM, the pulsing percentage concept is used to define the percentage of active subfaults during the rupture and constrain the lower bounds of the dynamic corner frequency. The dynamic corner frequency, starting from the corner frequency of one subfault, progresses to lower values with time. When the number of activated subfaults reaches the number of subfaults defined by the pulsing percentage, it becomes a constant.

2.3 Background of the Chi-Chi Earthquake

2.3.1 Tectonics and Seismicity of Taiwan

Regional Tectonics Taiwan, located on the convergent plate boundary of the Eurasian continental plate and the Philippine oceanic plate, is a part of the pan-Pacific seismic belt. As a result of the collision between the above mentioned two plates, a transitional zone formed along Taiwan Island. The northeastern part of Taiwan Island belongs to the Ryukyu Arc system where the Philippine plate is being subducted under the Eurasian plate. To the south of Taiwan, the Philippine plate is overriding the Eurasian plate along the Manila trench (Figure 2.10). With a 7 cm/yr.

convergence rate in a northwest direction (Figure 2.11), Taiwan Island experiences active tectonic movements leading to frequent earthquakes.

Seismicity and Seismic hazard The seismicity of Taiwan island is very high. Within the past 100 years (1900-1999), there were at least 86 destructive earthquakes with Richter magnitude larger than 5, including 23 events above magnitude 7 (Central Weather Bureau (Taiwan), 2006). Because of this extensive seismic activity, Taiwan's 22 million people are exposed to high seismic hazard. Figure 2.12 shows its destructive earthquakes from 1900 to 1999.

2.3.2 Geological Setting

Figure 2.13 is a map showing the geological provinces in Taiwan. "The main island of Taiwan comprises in part of a metamorphic basement covered by Cenozoic deposits to a thickness of more than 10,000 meters. The north-south axis of deposition has shifted progressively westward with successive orogenic episodes. A considerable part of the Tertiary sediments of Taiwan have been subjected to different grades of induration or metamorphism. Large igneous intrusions are rare, but there are several important volcanic fields in northern Taiwan, eastern Taiwan, and the Taiwan Strait" (CENTRAL GEOLOGICAL SURVEY (MOEA), 2006). In this study, the rock stations include limestone, igneous or metamorphic rocks comprising hard volcanic deposits, and Miocene or older strata; the soil sites includes fluvial terraces, stiff clays and sandy gravel deposits (Roumelioti and Beresnev, 2003).

Figure 2.1. Gaussian noise (step 1 of stochastic simulation)

Figure 2.2. Saragoni-Hart taper window (step 2 of stochastic simulation)

Figure 2.3. Tapered Gaussian noise (step 3 of stochastic simulation)

Figure 2.4. Fourier spectrum of the tapered noise (step 4 of stochastic simulation)

Figure 2.5. Brune source spectrum (step 5 of stochastic simulation)

Figure 2.6. Simulated Fourier spectrum (step 6 of stochastic simulation)

Figure 2.7. Simulated seismogram (step 7 of stochastic simulation)

Figure 2.8. Comparison of corner frequency for Moment Magnitude 5, 6 and 7 at distance 50 km and stress drop=40 bars

Figure 2.9. The shape of source spectra and the effects of the path term and kappa factor.

Figure 2.10. Tectonic structure of Taiwan

Figure 2.11. Tectonics of the 21 September Chi-Chi Taiwan Earthquake (The Institute of Earth Sciences, Academia Sinica (Taipei), 2006)

Figure 2.12. Destructive earthquakes in Taiwan (1900-1999) (Central Weather Bureau (Taiwan), 2006)

Figure 2.13. Generalized Geologic map of Taiwan (reduced from the 1:250,000 scale geologic map of the Central Geologic Survey). Inset block shows the extent of geologic maps with different scales used in this study. Green area represents the 1:50,000 geologic maps from the Central Geological Survey. Blue area represents the 1:100,000 geologic maps from the Chinese Petroleum Company. Brown area represents 1:250,000 geologic maps from the Central Geologic Survey. After Lee. *et al.*, 2001a.

Chapter 3

AVAILABLE DATA AND PROCESSING PROCEDURES

3.1 Introduction

This chapter first describes the seismic network of Taiwan and the dataset used in the study. The seismic database was obtained from Lee *et al.* (2001b). All of the records were retrieved from three-components accelerographs. Data quality control was first applied to the whole dataset to select the most appropriate records for further processing. Then, the envelope function was calculated for each record. With the help of the envelope function, the shear wave window of the accelerogram was defined and then tapered by a boxcar window function. Finally, the Fourier amplitude acceleration spectrum and pseudo acceleration spectrum were computed.

3.2 Seismic Network and Data Set

The Central Weather Bureau (CWB) of Taiwan hosts the Taiwan Strong-Motion Instrumentation Program (TSMIP) which consists of a total of 640 digital accelerographs deployed at “free-field” sites. Among these 640 accelerographs, 439 of them are A800, A900 & A900A type manufactured by Geotech Instruments; 163 of them are IDS & IDSA type from Terra Tech; and 38 of them are ETNA & K2 type made by Kinometrics (Lee *et al.*, 2001b). The installation of the network was completed in 1996. During the 1999 Chi-Chi earthquake TSMIP recorded the most extensive set of strong-motion data from a single event in the history of seismology. 441 digital records

of the main shock were re-processed by Lee *et al.* (2001b) after the pre-publication of the Chi-Chi main shock data (Lee *et al.*, 1999). Comparing with the previous publication, significant improvements were achieved by the re-processing in the following aspects.

1. The coordinates of 85% of the stations have been verified and confirmed.
2. DC offset was removed by using the computation of the pre-event signal to help define the baseline.
3. Timing correction was applied to stations with a GPS timing device.

3.3 Data Processing Procedures

The seismic data used in this study are based on the most recently published data by Lee *et al.* (2001b). The general data processing procedure is demonstrated in a flow-chart (Figure 3.1), and described as follows.

- Data Quality Control

411 out of 441 seismograms (about 95%) are processed and used in this study. According to Lee *et al.* (2001b), all of the 441 seismograms are classified into 4 categories: class A, B, C and D based on their quality. Data belonging to class A category are the most reliable while class D data have the poorest quality, due to missing portions of the trace, incorrect recording time or signal glitches. The incorrect or incomplete recording time is the most significant problem in dataset, leading to several records that cannot be used. Although there are many inherent deficiencies for class D data, some of them were selected for our database based on the following criteria: no missing trace portion, all three components of the record are complete without timing error, and there

are no obvious saturation effects. All of the used seismic stations are listed in Table 3.1 and shown in Figure 3.2, where the stations were classified as rock sites (square) or soil sites (up-triangle) according to the shear wave velocity in the top 30 meters.

Table 3.1: Stations used in this study

Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V _{s30}	PEER	RSS	Geo
ALS	23.5103	120.8052	A800	2048	38.8	10.8	553.4	C	R	C
CHK	23.0992	121.3653	A800	2048	102.2	63.53	304.7	D	S	D
CHY	23.4977	120.4245	A800	2048	55.5	30.04*	N/A	N/A	N/A	D
CHY002	23.7192	120.4125	IDSA	16384	42.4	24.98	235.1	D	S	E
CHY004	23.6013	120.1715	IDSA	16384	70.2	47.34	271.3	D	R	E
CHY006	23.5815	120.552	IDSA	16384	39.9	9.77	438.2	C	R	D
CHY008	23.4853	120.2692	IDSA	16384	68.2	40.44	210.7	D	S	E
CHY010	23.4653	120.544	IDSA	16384	50.9	19.96	518.7	C	R	D
CHY012	23.3328	120.1523	IDSA	16384	88.2	59.05	198.4	D	S	E
CHY014	23.2963	120.5828	IDSA	16384	66.3	34.18	528.8	C	R	D
CHY015	23.355	120.4052	IDSA	16384	68.9	38.14	228.7	D	S	D
CHY016	23.2212	120.1532	IDSA	16384	96.8	66.65	200.9	D	S	E
CHY017	23.2147	120.268	IDSA	16384	89.8	59.09	190.6	D	S	E
CHY019	23.1795	120.4778	IDSA	16384	82.2	50.53	466	C	R	D
CHY022	23.0457	120.4615	IDSA	16384	96.6	64.15	472.1	C	R	C
CHY023	22.9655	120.28	IDSA	16384	112.4	81.28	249.1	D	S	D
CHY024	23.757	120.6062	A900	16384	22.8	9.64	427.7	C	S	D
CHY025	23.7795	120.5137	A900	16384	30.5	19.09	277.5	D	S	E
CHY026	23.7987	120.4113	A900	16384	40.1	29.53	226	D	S	E
CHY027	23.752	120.2468	A900	16384	57.6	42	210	D	R	E
CHY028	23.632	120.6052	A900	16384	32.1	3.14	542.6	C	R	D
CHY029	23.6135	120.5282	A900	16384	38.9	10.97	544.7	C	R	C
CHY032	23.5799	120.2944	A900	16384	60.1	35.44	192.7	D	S	E
CHY033	23.5407	120.2153	A900	16384	69.3	43.83	197.6	D	S	E
CHY034	23.5212	120.5443	IDSA	16384	45.7	14.82	378.8	C	R	D
CHY035	23.52	120.584	A900A	16384	43.6	12.65	523.7	C	R	D
CHY036	23.6073	120.4788	A900	16384	43.1	16.06	233.1	D	R	D
CHY039	23.5207	120.344	A900	16384	59.8	31.88	201.2	D	S	E
CHY041	23.4388	120.5957	A900	16384	51.1	19.83	492.3	C	R	D
CHY042	23.3583	120.5833	A900	16384	59.8	28.17	605.6	C	S	?
CHY044	23.3832	120.1635	A900	16384	83.7	55.14	194.5	D	S	E
CHY046	23.4765	120.4632	A900	16384	54.6	24.11	444.6	C	R	C
CHY047	23.4938	120.4468	IDSA	16384	54.2	24.14	282.5	D	S	D
CHY050	23.2803	120.4083	A900	16384	75.6	44.76	421.7	C	R	C
CHY052	23.2878	120.501	IDSA	16384	70.3	39.02	547.8	C	R	C
CHY054	23.3077	120.3097	A900	16384	79	48.49	172.1	E	R	E
CHY055	23.2698	120.2705	IDSA	16384	84.8	54.31	225.8	D	S	E
CHY057	23.1495	120.4098	A900	16384	88.2	56.93	411.5	C	R	C
CHY058	23.1725	120.3192	A900	16384	90.6	59.8	233	D	S	D
CHY059	23.184	120.1025	A900	16384	103.3	73.27	191.1	D	S	E
CHY060	23.1243	120.2392	A900A	16384	99.6	68.86	228.9	D	S	E
CHY061	23.0768	120.5107	A900	16384	91.7	58.75	478.5	C	R	C
CHY063	23.027	120.3402	A900	16384	103.5	72.23	246.9	D	R	D
CHY065	22.906	120.345	A900	16384	115.5	83.43	332	D	R	D

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Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V ₈₃₀	PEER	RSS	Geo
CHY066	22.9205	120.2078	IDSA	16384	120.4	89.48	212	D	S	E
CHY067	22.999	120.1837	IDSA	16384	114.3	83.56	228	D	S	E
CHY069	22.9737	120.1815	A900	16384	116.8	86.02	198	D	S	E
CHY070	22.9651	120.2286	A900	16384	115	83.61	274.1	D	S	D
CHY071	23.0648	120.1645	A900	16384	109.4	78.74	198	D	S	E
CHY074	23.5103	120.8052	A900A	16384	38.8	10.8	553.4	C	R	C
CHY075	23.5672	119.5552	A900A	16384	131	115.8*	409.9	C	N/A	B
CHY076	23.638	120.2217	A900A	16384	63.8	42.16	169.8	E	S	E
CHY078	23.0402	120.2283	A900A	16384	108	77.2	160.7	E	S	D
CHY079	23.1848	120.528	A900A	16384	79.8	47.53	519.7	C	R	C
CHY080	23.5972	120.6777	A900A	16384	31.7	2.69	611.1	C	R	?
CHY081	23.2703	120.4965	A900A	16384	72.3	41.67	548.6	C	R	C
CHY082	23.7237	120.2975	A900	16384	53.4	36.11	193.7	D	R	E
CHY086	23.351	120.5932	A900A	16384	60.2	28.42	598.7	C	R	?
CHY087	23.3845	120.519	A900	16384	60	28.91	523.9	C	R	C
CHY088	23.3462	120.4293	A900	16384	68.3	37.48	353.7	D	R	D
CHY090	23.2673	120.2163	A900	16384	88.6	58.43	198	D	S	E
CHY092	23.7913	120.4783	IDSA	16384	33.6	22.7	253.7	D	S	E
CHY093	23.6538	120.1472	IDSA	16384	70.3	49.83	190.5	D	R	E
CHY094	23.7935	120.3205	IDSA	16384	49.4	37.12	221.9	D	R	E
CHY096	22.983	120.2327	IDSA	16384	113.1	82.26	282.5	D	S	D
CHY099	23.1373	120.2802	IDSA	16384	96	65.28	228.8	D	S	D
CHY100	23.2272	120.3418	IDSA	16384	84.3	53.46	230.1	D	S	D
CHY101	23.6862	120.5622	A900A	16384	30.9	9.96	258.9	D	S	D
CHY102	23.2455	120.6138	A900A	16384	70.7	37.72	592.4	C	R	B
CHY104	23.6695	120.4648	IDSA	16384	40.1	18.04	223.2	D	S	E
CHY107	23.2988	120.2897	IDSA	16384	81.1	50.62	175.7	E	R	E
CHY109	23.2517	120.5295	A800	2048	72.8	41.03	525.8	C	R	C
CHY110	23.2517	120.5295	A800	2048	72.8	41.03	521.5	C	R	C
CHY111	23.7912	120.2273	IDSA	16384	58.8	48.02*	276.3	D	N/A	E
CHY112	23.7035	120.183	IDSA	16384	65.2	52.03*	239.7	D	N/A	E
CHY114	23.0372	120.1187	IDSA	16384	114.7	86.65*	225	D	N/A	E
CHY115	23.1543	120.0967	IDSA	16384	106.1	79.23*	225	D	N/A	E
CHY116	23.0775	120.1082	IDSA	16384	111.8	125.03	198	D	S	E
ENA	24.428	121.7407	A800	2048	114.5	66.88	510.2	C	R	B
ESL	23.8137	121.4328	A800	2048	64.7	44.54	497.3	C	R	D
HSN	24.8022	120.9695	A800	2048	105.7	55.49	304.7	D	S	D
HWA	23.977	121.605	A800	2048	83	55.59	238.7	D	R	D
HWA002	23.6012	121.5122	IDS	16384	78.1	56.93	391.2	C	R	C
HWA003	23.4768	121.497	IDS	16384	82.9	56.14	393.8	C	S	D
HWA005	23.6608	121.414	IDS	16384	66.4	47.58	482.9	C	R	D
HWA006	23.6732	121.4173	IDS	16384	66.3	47.86	484.6	C	R	D
HWA007	23.9877	121.6173	A900	16384	84.4	56.3	249.1	D	S	D
HWA009	23.9925	121.6165	A900	16384	84.5	56.06	313.8	D	R	D
HWA011	23.9962	121.5858	A900	16384	81.5	53.19	236.6	D	S	D
HWA012	23.993	121.6233	A900	16384	85.1	56.65	270.1	D	S	D
HWA013	23.978	121.591	A900	16384	81.6	54.32	227.2	D	S	D
HWA014	23.9732	121.5993	A900	16384	82.4	55.24	225.1	D	S	D
HWA015	23.9757	121.553	A900A	16384	77.8	51.12	322.9	D	S	D
HWA016	23.9648	121.56	A900	16384	78.3	52.18	332	D	S	D
HWA017	23.9497	121.5392	A900	16384	76	51.11	435.8	C	S	D
HWA019	23.977	121.605	A900A	16384	83	55.59	238.7	D	S	D
HWA020	23.8137	121.4328	A900A	16384	64.7	44.54	497.3	C	R	D
HWA022	24.2675	121.7325	A900A	16384	105.1	62.07	386.1	C	R	C
HWA023	24.08	121.5955	A900A	16384	84.6	51.15	438.3	C	R	B

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Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V ₃₀	PEER	RSS	Geo
HWA024	23.3522	121.297	A900A	16384	75.8	43.15	559.5	C	R	B
HWA025	24.163	121.6447	A900A	16384	92.3	53.79	409.8	C	R	D
HWA026	24.1185	121.6165	A900A	16384	87.9	51.96	457.5	C	R	B
HWA027	24.055	121.591	A900A	16384	83.4	51.62	274.1	D	R	D
HWA028	24.0172	121.6013	A900A	16384	83.5	53.84	236.6	D	S	D
HWA029	23.9373	121.5702	A900A	16384	78.9	54.29	291.2	D	S	D
HWA030	23.7852	121.4488	A900A	16384	66.7	46.95	480.9	C	R	D
HWA031	23.7653	121.4922	A900A	16384	71.4	51.46	461.9	C	S	D
HWA032	23.7108	121.412	A900A	16384	64.6	47.16	492.2	C	R	D
HWA033	23.6867	121.4747	A900A	16384	71.5	53.21	395.6	C	R	C
HWA034	23.5905	121.3772	A900A	16384	66.1	44.32	379.2	C	R	D
HWA035	23.732	121.4362	A900A	16384	66.4	48.35	482.4	C	R	D
HWA036	23.4995	121.367	A900A	16384	70.3	43.8	474.1	C	S	D
HWA037	23.4542	121.384	A900A	16384	74.7	46.2	469.3	C	R	D
HWA038	23.4615	121.3445	A900A	16384	71	42.54	525.2	C	R	C
HWA039	23.3845	121.3523	A900A	16384	77.2	45.89	491.7	C	R	D
HWA041	23.2675	121.2942	A900A	16384	82.8	47.76	496.4	C	S	D
HWA043	23.7092	121.54	A900A	16384	77.3	58.05	225.1	D	R	D
HWA044	23.6538	121.5268	A900A	16384	77.6	58.22	393.8	C	R	D
HWA045	24.3095	121.7405	IDS	16384	107.8	63.43	252.2	D	R	D
HWA046	24.1492	121.6213	IDS	16384	89.5	51.8	460.9	C	R	B
HWA048	24.0113	121.5715	IDS	16384	80.4	51.41	270.1	D	R	D
HWA049	23.9952	121.5577	IDS	16384	78.6	50.76	377.5	C	R	D
HWA050	23.9897	121.584	IDS	16384	81.1	53.27	234.7	D	R	D
HWA051	23.8703	121.548	IDS	16384	76.2	53.56	345.2	D	R	D
HWA055	23.3232	121.3323	IDS	16384	80.6	47.46	492.1	C	R	D
HWA056	24.1795	121.5077	A900A	16384	80.3	41.1	511.3	C	R	B
HWA057	24.16	121.61	A900A	16384	88.9	50.6	581.3	C	R	N/A
HWA058	23.9672	121.484	A900A	16384	70.7	45.77	542.1	C	R	N/A
HWA059	23.8713	121.5005	A900A	16384	71.4	49.15	400.4	C	R	N/A
HWA060	23.8703	121.59	A900A	16384	80.5	57.51	402.4	C	R	N/A
HWA2	23.977	121.605	A900A	16384	83	55.59	238.7	D	R	N/A
ILA001	24.8827	121.836	IDS	16384	154.5	103.2	382.8	C	R	D
ILA002	24.845	121.7973	IDS	16384	148.8	97.58	225.6	D	S	D
ILA003	24.7982	121.7813	IDS	16384	143.9	92.81	263.8	D	S	E
ILA004	24.745	121.7828	IDS	16384	139.9	88.89	124.3	E	S	E
ILA005	24.6978	121.8052	IDS	16384	138	87.2	239.3	D	S	D
ILA006	24.6412	121.825	IDS	16384	135.4	85.07	279.4	D	S	D
ILA007	24.5943	121.8462	IDS	16384	133.8	84.07	384	C	S	D
ILA008	24.7088	121.7628	IDS	16384	135.6	84.8	226	D	R	E
ILA010	24.619	121.7812	IDS	16384	130.4	80.18	383.1	C	R	C
ILA012	24.7807	121.7335	IDS	16384	139.2	88.18	233	D	S	D
ILA013	24.735	121.7294	IDS	16384	135.3	84.12	215	D	S	D
ILA014	24.6945	121.7202	IDS	16384	131.4	80.67	300.8	D	R	D
ILA015	24.7807	121.6912	IDS	16384	136.3	85.4	493.2	C	R	B
ILA016	24.749	121.684	IDS	16384	133.2	82.36	271.1	D	S	D
ILA021	24.7135	121.644	IDS	16384	127.6	76.9	453.2	C	S	D
ILA024	24.6448	121.588	IDS	16384	118.2	67.81	536.6	C	S	B
ILA027	24.6893	121.7603	A800	2048	134	83.23	215	D	S	D
ILA030	24.7278	121.755	A900	16384	136.5	85.62	201	D	S	E
ILA031	24.5995	121.8337	A900	16384	133.2	83.31	649.2	C	R	B
ILA032	24.6242	121.8272	A800	2048	134.4	84.22	295.5	D	S	D
ILA035	24.8241	121.7603	A800	2048	144.6	93.43	236.6	D	S	D
ILA036	24.7883	121.7513	A900	16384	141.1	89.98	225.6	D	S	D
ILA037	24.7455	121.7142	A900	16384	135	84.11	210.2	D	S	D

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Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V _{s30}	PEER	RSS	Geo
ILA039	24.765	121.7212	A800	2048	137.1	86.11	227.2	D	S	D
ILA041	24.7233	121.7917	IDS	16384	138.9	87.97	196.9	D	S	E
ILA042	24.6903	121.792	A900	16384	136.4	85.68	209.4	D	S	E
ILA043	24.629	121.7347	A800	2048	127.6	77.17	408.7	C	R	C
ILA044	24.656	121.755	IDS	16384	131.1	80.53	158.1	E	S	D
ILA046	24.666	121.7338	A900	16384	130.2	79.62	396.9	C	S	D
ILA048	24.7663	121.7612	IDS	16384	140	88.95	199.6	D	S	E
ILA049	24.7655	121.748	A900A	16384	139	87.98	215	D	S	D
ILA050	24.428	121.7407	A900A	16384	114.5	66.88	479.8	C	R	B
ILA051	24.7212	121.667	A900A	16384	129.8	79.03	484.3	C	S	B
ILA052	24.6092	121.8488	A900A	16384	135	85.13	424.2	C	R	B
ILA054	24.9732	121.9183	IDSA	16384	167.5	116.01	408.7	C	S	B
ILA055	24.7387	121.8083	IDSA	16384	141.3	90.3	266.8	D	S	E
ILA056	24.7622	121.8088	IDSA	16384	143.1	92.04	223.7	D	S	E
ILA059	24.6667	121.8205	IDSA	16384	136.8	86.33	236.8	D	R	E
ILA061	24.5233	121.825	IDSA	16384	127.5	78.55	236.6	D	S	D
ILA062	24.4677	121.7933	IDSA	16384	121.3	73.22	270.1	D	R	D
ILA063	24.6157	121.518	IDSA	16384	111	61.06	565.1	C	R	B
ILA064	24.477	121.7787	IDSA	16384	120.7	72.33	398	C	S	D
ILA066	24.4473	121.7707	IDSA	16384	118.2	70.35	295.6	D	R	D
ILA067	24.44	121.3728	A900A	16384	86.7	38.82	610.6	C	R	N/A
KAU001	23.1618	120.6355	IDSA	16384	79.2	44.93	542.3	C	R	D
KAU003	22.628	120.2573	IDSA	16384	147.3	114.44	913.8	B	S	D
KAU006	22.591	120.3173	A900A	16384	149	114.92	218.5	D	S	E
KAU007	22.6462	120.3585	A900	16384	141.8	107.57	246.2	D	S	D
KAU008	22.6295	120.3672	A900A	16384	143.3	108.75	285.9	D	S	D
KAU010	22.7873	120.279	A900	16384	130.2	98.16	198	D	S	E
KAU011	22.7613	120.2558	A900	16384	133.8	101.85	155.3	E	S	E
KAU012	22.8797	120.3707	A900	16384	117.1	84.61	402.4	C	S	D
KAU015	22.656	120.3317	A900	16384	141.7	107.97	309.2	D	S	D
KAU017	22.509	120.3862	A900	16384	155.5	126.55*	284.7	D	N/A	E
KAU018	22.891	120.4738	A900	16384	112.4	78.41	420.6	C	S	D
KAU020	22.902	120.5352	A900	16384	109.5	74.48	373.3	C	S	D
KAU022	22.6707	120.491	A900	16384	135.5	98.88	199	D	S	E
KAU030	22.6108	120.5588	A900	16384	140.6	102.09	198.1	D	S	E
KAU032	22.5462	120.4528	A900	16384	149.8	112.81	198	D	S	E
KAU037	22.2617	120.6432	A900	16384	177.8	136.47	283.2	D	S	D
KAU044	22.4397	120.5028	A900	16384	160.2	121.61	198	D	S	E
KAU045	22.5678	120.308	A900A	16384	151.7	119.22	150.1	E	N/A	E
KAU047	23.0817	120.5827	A900A	16384	89	54.95	533	C	R	B
KAU048	22.7252	120.4908	A900A	16384	129.6	93.61	286.8	D	S	D
KAU050	23.1625	120.7573	A900A	16384	77.4	40.49	596.6	C	R	B
KAU054	23.2777	120.7128	A900	16384	65.1	30.85	553.8	C	R	C
KAU055	22.5747	120.3353	A900A	16384	150.1	120.96*	225.6	D	N/A	E
KAU056	22.5538	120.3437	A900A	16384	152	122.92*	225.6	D	N/A	E
KAU057	22.6342	120.2633	A900A	16384	146.5	113.54	491.7	C	S	C
KAU062	22.6237	120.2843	A900A	16384	146.7	113.46	198	D	S	E
KAU063	22.9053	120.1732	A900A	16384	123.6	92.83	198	D	S	E
KAU064	22.7852	120.2385	A900A	16384	132.2	100.51	198	D	S	E
KAU066	22.7303	120.3412	A900A	16384	133.6	100.38	198	D	S	E
KAU069	22.8873	120.6567	A900A	16384	108.7	70.71	524.6	C	R	B
KAU073	22.5348	120.5362	A900A	16384	149.2	110.67	198	D	S	E
KAU074	22.574	120.5663	A900A	16384	144.4	105.59	198.1	D	S	E
KAU075	22.4903	120.499	A900A	16384	154.8	116.57	198	D	S	E
KAU077	22.747	120.7233	A900A	16384	123.5	82.96	603.9	C	R	B

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Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V ₃₀	PEER	RSS	Geo
KAU078	22.7112	120.6412	A900A	16384	128.3	88.99	503.9	C	R	B
KAU081	22.0095	120.7367	A900A	16384	205.1	162.43	249.1	D	S	D
KAU083	22.5673	120.4475	A900A	16384	147.7	110.95	198	D	S	E
KAU085	22.8858	120.3222	IDSA	16384	118.4	86.54	260.8	D	R	D
KAU086	22.795	120.295	IDSA	16384	128.8	96.59	198	D	S	E
KAU087	22.6128	120.3113	IDSA	16384	146.9	113.13	198	D	S	E
KAU088	22.6461	120.311	IDSA	16384	143.5	110.22	198	D	S	E
KAU089	22.4802	120.4028	IDSA	16384	158.1	129.26*	189.9	D	N/A	E
NCU	24.97	121.1867	A800	2048	129	80.44	492.2	C	R	?
NSK	24.6755	121.3583	A800	2048	106.6	58.09	598.5	C	R	B
NST	24.6312	121.0005	A800	2048	87.8	38.43	495.5	C	R	D
NSY	24.4162	120.7607	A800	2048	61.7	13.15	599.6	C	R	C
PNG	23.5672	119.5552	A800	2048	131	110.31	409.9	C	R	B
SGS	23.0817	120.5827	A800	2048	89	60.29*	N/A	N/A	N/A	B
SSD	22.746	120.632	A800	2048	124.6	85.75	499.1	C	R	C
STY	23.1625	120.7573	A800	2048	77.4	40.49	596.6	C	R	B
TAP	25.0392	121.5225	A800	2048	149.8	100.03	198	D	S	E
TAP003	25.0863	121.45	ETNA	4194304	151	102.39	212.4	D	S	E
TAP005	25.1077	121.507	ETNA	4194304	155.7	106.87	198	D	S	E
TAP006	25.0947	121.5093	ETNA	4194304	154.5	105.66	198	D	S	E
TAP007	25.0758	121.5083	ETNA	4194304	152.6	103.73	198	D	S	E
TAP008	25.0758	121.5273	ETNA	4194304	153.5	104.52	198	D	S	E
TAP010	25.0677	121.4813	ETNA	4194304	150.5	101.33	226.4	D	S	E
TAP012	25.0563	121.5078	ETNA	4194304	150.7	101.76	198	D	S	E
TAP013	25.0572	121.5253	ETNA	4194304	151.6	102.59	198	D	S	E
TAP014	25.0578	121.5442	ETNA	4194304	152.6	103.45	198	D	S	E
TAP017	25.0528	121.448	ETNA	4194304	147.5	98.93	198	D	S	E
TAP020	25.0388	121.5263	ETNA	4194304	149.9	100.8	198	D	S	E
TAP021	25.0378	121.5432	ETNA	4194304	150.7	101.43	198	D	S	E
TAP024	25.0203	121.4652	ETNA	4194304	145.1	96.39	195	D	S	D
TAP026	25.017	121.5027	ETNA	4194304	146.6	97.64	198	D	S	E
TAP028	25.0045	121.5073	ETNA	4194304	145.6	96.6	227.2	D	S	D
TAP032	25.0007	121.4748	A900	16384	143.7	94.84	385	C	S	D
TAP034	24.955	121.5303	A900	16384	142.1	92.73	408.7	C	R	B
TAP035	24.9239	121.5399	A900	16384	139.7	89.91	438.1	C	R	B
TAP036	24.9043	121.5447	A900	16384	138.2	88.45	487.2	C	S	B
TAP041	25.183	121.4167	A900	16384	159.3	110.9	225.6	D	S	D
TAP042	25.1255	121.4532	A900	16384	155	106.48	225.3	D	S	D
TAP043	24.9913	121.41	A900	16384	139.7	91.19	234.7	D	R	D
TAP046	25.1037	121.7683	A900	16384	169.2	118.34	410.9	C	S	D
TAP047	24.9538	121.3375	A900	16384	132.8	84.46	388.1	C	R	D
TAP049	25.148	121.4365	A900	16384	156.6	108.1	419.5	C	S	D
TAP051	25.1008	121.4403	A900	16384	152	103.46	403.2	C	R	B
TAP052	25.0817	121.3828	A900	16384	147.6	99.24	527.7	C	R	C
TAP053	24.959	121.5143	A900	16384	141.7	92.42	394.7	C	R	D
TAP059	25.1565	121.6855	A900	16384	169.3	119.3	478.2	C	R	B
TAP060	25.1572	121.7237	A900	16384	171.5	121.15	439.6	C	S	B
TAP065	25.1488	121.7668	A900A	16384	173.1	122.48	1023.5	B	S	?
TAP066	25.1865	121.5202	A900A	16384	164.1	115.34	662.8	C	S	C
TAP067	24.9802	121.5802	A900A	16384	147.2	97.39	552.9	C	R	B
TAP069	25.0082	121.9882	A900A	16384	175.2	123.57	519	C	S	B
TAP072	24.9913	121.65	IDSA	16384	152.1	101.74	529.5	C	R	B
TAP075	25.0288	121.728	IDSA	16384	160	109.27	552.5	C	S	B
TAP077	25.0643	121.8437	IDSA	16384	170.3	119	1022.8	B	S	D
TAP078	25.0354	121.8595	IDSA	16384	168.8	119.97	501.9	C	S	B

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Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V ₃₀	PEER	RSS	Geo
TAP079	25.0237	121.906	IDSA	16384	170.9	119.36	413.2	C	S	B
TAP081	25.0182	121.9808	IDSA	16384	175.5	123.86	397.9	C	S	B
TAP083	25.2595	121.4938	IDSA	16384	170.2	121.7	404.1	C	S	D
TAP084	25.2252	121.6295	IDSA	16384	173	123.71	224.2	D	S	D
TAP086	24.9527	121.5677	A900	16384	143.9	94.16	489.5	C	R	C
TAP087	25.1008	121.4177	A900A	16384	151	102.56	434.5	C	S	C
TAP088	25.0385	121.5762	ETNA	4194304	152.4	93.26*	418	C	N/A	D
TAP089	25.027	121.5595	ETNA	4194304	150.5	91.31*	440.2	C	N/A	D
TAP090	25.0573	121.5945	ETNA	4194304	155.2	105.56	324.4	D	S	E
TAP094	25.141	121.4758	ETNA	4194304	157.5	108.96	255.4	D	S	D
TAP095	25.1353	121.4913	ETNA	4194304	157.7	109.01	198	D	S	E
TAP097	25.0207	121.5299	IDSA	16384	148.3	99.17	198	D	S	E
TAP098	25.103	121.5395	ETNA	4194304	156.8	107.75	457.6	C	S	C
TAP100	25.0351	121.5139	ETNA	4194304	148.9	100.13	198	D	S	E
TAP103	25.071	121.781	A900A	16384	167	116.02	429.5	C	R	C
TAP104	25.158	121.7202	ETNA	4194304	171.4	112.22*	396.1	C	N/A	B
TCU	24.1475	120.676	A800	2048	34.2	5.18	472.8	C	R	D
TCU003	25.0473	121.1357	A900	16384	135.8	86.57	517.3	C	S	D
TCU006	24.9118	121.1405	A900	16384	121.5	72.61	505.5	C	S	D
TCU007	25.0015	121.3097	A900	16384	136.6	88.2	462.8	C	S	D
TCU008	25.0092	121.2062	A900	16384	133.8	85.09	457.6	C	S	C
TCU010	25.0003	121.1533	A900	16384	131.3	82.27	469.9	C	S	C
TCU014	25.0463	121.3075	A900	16384	141.1	92.7	473.4	C	R	D
TCU015	24.7572	120.9345	A900	16384	100.3	49.81	416.3	C	S	C
TCU017	24.7808	121.0068	A900	16384	104.1	54.28	558.8	C	S	?
TCU018	24.88	121.0535	A900	16384	115.8	66.25	475	C	R	C
TCU026	24.7757	121.075	A900	16384	105.2	56.12	472.9	C	R	D
TCU029	24.5588	120.7492	A900	16384	77.5	28.05	410.9	C	R	C
TCU031	24.5615	120.701	A900	16384	78.3	30.18	393.8	C	S	D
TCU033	24.6855	120.8623	A900	16384	91.6	40.89	423.4	C	S	D
TCU034	24.639	120.8568	A900	16384	86.4	35.69	392.1	C	R	C
TCU035	24.6157	120.7877	A900	16384	83.7	31.1*	227.9	D	N/A	D
TCU036	24.4488	120.6963	A900	16384	66	19.84	489.3	C	S	D
TCU038	24.4912	120.663	A900	16384	71.2	25.44	225.6	D	S	D
TCU039	24.4917	120.7837	A900	16384	70	19.9	540.7	C	S	C
TCU040	24.4497	120.6455	A900	16384	67.1	22.08	362	C	S	E
TCU042	24.5542	120.8077	A900	16384	76.9	26.32	412.6	C	R	D
TCU045	24.5412	120.9137	A900	16384	76.3	26	704.6	C	R	C
TCU046	24.4683	120.8543	A900	16384	67.6	16.74	465.5	C	R	B
TCU047	24.6188	120.9387	A900	16384	85.2	35	520.4	C	R	C
TCU048	24.18	120.5888	A900	16384	41.4	13.55	508.5	C	S	C
TCU049	24.179	120.6902	A900	16384	37	3.78	487.3	C	R	D
TCU050	24.1815	120.6338	A900	16384	39.4	9.51	462.5	C	S	D
TCU051	24.1603	120.6518	A900	16384	36.5	7.66	459.1	C	S	D
TCU052	24.198	120.7393	A900	16384	37.9	0.66	393.2	C	S	D
TCU053	24.1935	120.6688	A900	16384	39.2	5.97	454.5	C	R	D
TCU054	24.1612	120.675	A900	16384	35.7	5.3	460.7	C	S	D
TCU055	24.1392	120.6643	A900	16384	33.8	6.36	437.8	C	S	D
TCU056	24.1588	120.6238	A900	16384	37.6	10.5	429.6	C	S	D
TCU057	24.1732	120.6107	A900	16384	39.6	11.84	466.8	C	R	C
TCU059	24.2687	120.5637	A900	16384	51.2	17.13	226.5	D	S	D
TCU060	24.2247	120.644	A900	16384	43.3	8.53	490.1	C	S	D
TCU061	24.1355	120.549	A900	16384	39.7	17.19	309.2	D	S	D
TCU063	24.1083	120.6158	A900	16384	33.2	9.8	282.5	D	S	D
TCU064	24.3457	120.61	A900	16384	57.1	16.62	345.2	D	S	D

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Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V ₃₀	PEER	RSS	Geo
TCU065	24.0588	120.6912	A900	16384	24.6	0.59	305.9	D	R	D
TCU067	24.0912	120.72	A900	16384	26.8	0.64	433.6	C	S	D
TCU068	24.2772	120.7658	A900	16384	46.3	0.32	487.3	C	S	D
TCU070	24.196	120.5403	A900	16384	45.6	19.02	401.3	C	S	C
TCU071	23.9855	120.7883	A900	16384	13.9	5.31	624.8	C	R	D
TCU072	24.0407	120.8488	A900	16384	20.6	7.03	468.1	C	R	D
TCU074	23.9622	120.9618	A900	16384	20	13.46	549.4	C	R	D
TCU075	23.9827	120.6778	A900	16384	18.4	0.91	573	C	S	D
TCU076	23.9077	120.6757	A900	16384	13.7	2.76	615	C	R	D
TCU078	23.812	120.8455	A900	16384	7.1	8.2	443	C	R	D
TCU079	23.8395	120.8942	A900	16384	9.9	10.97	364	C	R	D
TCU081	24.8022	120.9695	A900A	16384	105.7	55.49	291.2	D	S	D
TCU082	24.1475	120.676	A900A	16384	34.2	5.18	472.8	C	S	D
TCU083	24.97	121.1867	A900A	16384	129	80.32	490.6	C	R	?
TCU084	23.883	120.8998	A900A	16384	10.5	11.24	607.2	C	R	?
TCU085	24.6755	121.3583	A900A	16384	106.6	58.09	598.5	C	R	B
TCU087	24.3482	120.7733	A900A	16384	54.1	7	530.3	C	R	C
TCU088	24.2533	121.1758	A900A	16384	58	18.16	616	C	S	B
TCU089	23.9037	120.8565	A900A	16384	7.5	8.88	599.5	C	R	C
TCU092	25.0117	121.2792	A900	16384	136.5	88.07	477.8	C	S	D
TCU094	24.7695	121.0488	A900	16384	103.8	54.53	589.8	C	S	C
TCU095	24.6917	121.0135	A900	16384	94.6	45.18	446.6	C	R	C
TCU096	24.7957	120.9558	A900	16384	104.8	54.46	399.4	C	S	D
TCU098	24.7433	120.899	A900	16384	98.3	47.67	226	D	R	D
TCU100	24.1858	120.6153	A900	16384	40.6	11.39	466.8	C	R	C
TCU101	24.242	120.7092	A900	16384	43.3	2.13	499.7	C	S	D
TCU102	24.2493	120.7208	A900	16384	43.8	1.51	714.3	C	S	D
TCU103	24.3098	120.7072	A900	16384	50.7	6.1	494.1	C	S	D
TCU104	24.2455	120.6018	A900	16384	47.2	12.89	513.9	C	R	C
TCU105	24.239	120.559	A900	16384	48.6	17.18	395.6	C	R	C
TCU106	24.0833	120.5518	A900A	16384	35.3	14.99	391.2	C	S	D
TCU107	24.0727	120.5402	A900	16384	35.4	16.01	390.4	C	S	D
TCU109	24.0848	120.5713	A900	16384	34	13.08	406.6	C	S	D
TCU110	23.9622	120.5695	A900	16384	26	11.6	212.7	D	S	E
TCU111	24.1137	120.4872	A900	16384	42.4	22.14	237.5	D	S	E
TCU112	24.0557	120.424	A900	16384	43.9	27.5	198	D	S	E
TCU113	23.8928	120.3865	A900	16384	42.2	31.07	230.3	D	R	E
TCU115	23.9595	120.4693	A900	16384	35.4	21.78	215.3	D	R	E
TCU116	23.8568	120.5803	A900	16384	22.3	12.4	493.1	C	S	E
TCU117	24.1335	120.4598	A900	16384	45.9	25.44	198	D	S	E
TCU118	24.0027	120.4235	A900	16384	41.4	26.84	198	D	S	E
TCU119	23.9242	120.3122	A900	16384	50.1	37.95	198	D	R	E
TCU120	23.9803	120.613	A900	16384	23.2	7.41	459.3	C	S	C
TCU122	23.8128	120.6097	A900	16384	20	9.35	475.5	C	R	D
TCU123	24.0187	120.5437	A900	16384	31.4	14.93	236.6	D	S	D
TCU128	24.4162	120.7607	A900A	16384	61.7	13.15	599.6	C	S	C
TCU129	23.8783	120.6843	A900A	16384	11.9	1.84	664.4	C	R	D
TCU131	24.5673	120.8165	A900A	16384	78.3	26.15*	361.9	C	N/A	D
TCU136	24.2603	120.6518	IDS	16384	46.8	8.29	509.2	C	S	C
TCU138	23.9223	120.5955	IDS	16384	21.9	9.79	652.8	C	R	D
TCU140	23.9578	120.3593	IDS	16384	46.1	32.97	198	D	R	E
TCU141	23.8338	120.464	IDS	16384	34.3	24.21	206.5	D	S	E
TCU145	23.98	120.3368	IDS	16384	48.9	35.34	198	D	R	E
TCU147	24.8592	121.2475	A900	16384	119.6	71.27	537.9	C	S	N/A
TTN	22.754	121.1465	A800	2048	127.6	83.31	228	D	S	D

Continued...

Station	Latitude	Longitude	Model	Count/G	EpiDist	Drup	V ₃₀	PEER	RSS	Geo
TTN001	23.3178	121.4425	IDS	16384	89	56.56	412.6	C	S	D
TTN002	22.9738	121.2968	IDS	16384	110.6	68.71	413	C	R	D
TTN003	22.6178	120.9975	IDS	16384	139.1	94.99	255.4	D	S	D
TTN004	22.9102	121.1287	IDS	16384	110.5	66.87	487.7	C	S	D
TTN007	22.7647	121.1427	A900	16384	126.3	82.1	234.7	D	S	D
TTN008	22.7602	121.1517	A900	16384	127	82.83	226.5	D	S	D
TTN009	22.7488	121.1442	A900	16384	128	83.78	226.5	D	S	D
TTN010	22.74	121.1135	A900	16384	128.2	83.88	241	D	S	D
TTN012	22.7662	121.133	A900	16384	125.9	81.67	243.5	D	S	D
TTN014	23.0992	121.3653	A900A	16384	102.2	63.53	304.7	D	S	D
TTN015	22.754	121.1465	A900A	16384	127.6	83.31	228	D	S	D
TTN018	22.8207	121.0717	A900A	16384	118.5	74.45	516.2	C	R	C
TTN020	23.1268	121.2057	A900A	16384	91.2	50.69	502.7	C	R	D
TTN022	23.0973	121.2105	A900A	16384	94.4	53.34	502.6	C	S	D
TTN023	23.053	121.1557	A900A	16384	96.5	54.29	500.9	C	S	D
TTN024	22.9725	121.1083	A900A	16384	103.3	60.01	562.8	C	R	B
TTN025	22.9045	121.072	A900A	16384	109.5	65.79	531.7	C	R	C
TTN026	22.863	121.083	A900A	16384	114.2	70.33	525.4	C	R	C
TTN027	22.8078	121.086	A900A	16384	120.2	76.13	495.9	C	S	D
TTN028	22.779	121.0543	A900A	16384	122.6	78.48	486.7	C	R	B
TTN031	23.3563	121.4603	A900A	16384	87.5	56.3	340.9	D	R	D
TTN032	23.2462	121.4055	A900A	16384	91.9	57.65	406.6	C	S	D
TTN033	23.193	121.3878	A900A	16384	95.2	59.43	225.6	D	S	D
TTN036	22.7988	121.1855	A900A	16384	124	80	398.5	C	S	C
TTN040	23.1512	121.198	IDS	16384	88.5	48.33	533.9	C	R	B
TTN041	23.1342	121.1177	IDS	16384	86.7	45.35	418.2	C	R	B
TTN042	23.0007	121.2767	IDS	16384	107	65.25	443.7	C	S	D
TTN044	23.0068	121.1655	IDS	16384	101.7	58.97	517.6	C	R	C
TTN045	22.9757	121.1478	IDS	16384	104.2	61.16	498.3	C	S	D
TTN046	22.9658	121.232	IDS	16384	108.5	65.9	512.9	C	R	C
TTN048	22.773	121.0827	IDS	16384	123.9	79.69	451.1	C	S	D
TTN050	22.674	121.0293	IDS	16384	133.5	89.28	388.1	C	R	D
TTN051	23.1887	121.0168	A900A	16384	77.6	36.7	608.8	C	R	N/A
WGK	23.6862	120.5622	A800	2048	30.9	9.96	258.9	D	S	D
WNT	23.8783	120.6843	A800	2048	11.9	1.84	664.4	C	R	D
WSF	23.638	120.2217	A800	2048	63.8	42.16	169.8	E	S	E
WTC	23.8635	120.2812	A800	2048	52.8	42.25	198	D	S	E

NOTES:

- Station: Accelerograph's station name.
- Latitude: Station latitude in degrees North (Lee *et al.*, 2001b).
- Longitude: Station longitude in degrees East (Lee *et al.*, 2001b).
- Model: Instrument model of the accelerograph (Lee *et al.*, 2001b).
- Count/G: Factor to convert acceleration data in digital counts to G (Lee *et al.*, 2001b).
- EpiDist: Distance (km) from Chi-Chi epicenter (23.8603 deg N, 120.7995 deg E) (Lee *et al.*, 2001b).
- Drup: Closest distance (km) to the rupture surface (PEER, 2005); the distance with star is from Lee *et al.* (2001b).

- V_{s30} : Shear wave velocity at top 30 meters (PEER, 2005).
- PEER: Site classification based on the V_{s30} from PEER (2005).
- RSS: Site classification based on the Response Spectral Shape method by Phung *et al.* (2004). "R" means rock sites and "S" means soil sites.
- Geo: Site classification mainly based on the geological and geomorphologic data by (Lee *et al.*, 2001a).
- "B", "C", "D" and "E" are the site class according to NEHRP classification scheme;
- "?" means questionable sites while "N/A" means no information available.

- Envelope calculation

In order to better identify the onset of P-wave and S-wave phases, the envelope function is calculated for every record. The envelope function $E(t)$ of a seismogram $s(t)$ is defined as the absolute value of the complex envelope function in Equation 3.1

$$E(t) = |s(t) - iH[s(t)]| \quad (3.1)$$

where $H[s(t)]$ is the Hilbert transformation of the function $s(t)$ (Pacor *et al.*, 2005). According to Bracewell (2000), the Hilbert transformation of a real-valued function $s(t)$ is defined in Equation 3.2

$$H[s(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{s(t') dt'}{t' - t} \quad (3.2)$$

$$= -\frac{1}{\pi t} * s(t) \quad (3.3)$$

where '*' denotes convolution operator.

The envelope function of $s(t)$ which we denote as $E(t)$ can be represented in Equation 3.4:

$$E(t) = |s(t) - iH[s(t)]| = \sqrt{s^2(t) + H^2[s(t)]} \quad (3.4)$$

- Windowing the Shear Wave Signal

Because the shear waves contribute most energy to the signal, in engineering seismology the portion of the seismogram we are interested in is the shear wave window. The simulated waveform from EXSIM is also the shear wave window. Thus, the definition of the shear wave window is important. The arrival time of the P wave has already been picked by Lee *et al.* (2001b) for each record.

First, the start and end time of shear wave window are picked visually with the assistance of the calculated envelope of the seismogram. Figure 3.3 presents a sample seismogram for station ALS. In order to identify the ending of the shear wave window more accurately, I use 90% of the whole seismic record energy defined as $E = \frac{1}{2} \cdot |\text{amp}|^2$ as a criteria to cut the extra noise signal. If the calculated time (90% energy of the total seismic record) is earlier than the ending time picked visually, it is then used as the ending time of the shear wave window. Otherwise, the ending time of the record picked visually is kept. The defined shear wave window is then used to compute the duration function later in Chapter 4.

- Remove Linear Trend and DC

The baseline of the recorded seismogram may move upward or downward in the latter part of the seismogram. Correction of records for any baseline or linear trend has been done by Lee *et al.* (2001b).

- Taper Function

In order to decrease the signal leakage (Gibbs phenomenon) when the Fourier transformation is applied on the windowed seismogram, a taper function is applied on the windowed seismogram. Generally, there are several commonly used taper functions available, such as: Hanning and Hamming windows, shown in Figure 3.4. However, the implementation of these window functions may lead to loss of energy since they cut off some part of the seismogram. To avoid this, a simple boxcar taper window (shown in the Figure 3.4 as well) is used for all of the data, in which 5% of the signal is tapered at each end.

- Instrument Response

Accelerographs generally have flat response in the frequency range from 0 to 50 Hz. Because the frequency range of this research is from 0.1Hz to 20Hz, there is no need for instrument response correction, other than calibration to the flat response level.

- Output

The corrected seismic data are transformed to the frequency domain using Fast Fourier transformation. Since there are only two types of sampling rate for the seismic instrumentation of the TSMIP (200 samples/sec and 250 samples/sec), the lowest Nyquist frequency can reach up to 100 Hz, which extends well beyond our range of interest (0.1 Hz -20 Hz). The computed Fourier spectrum is then log smoothed for later analysis (attenuation regression, kappa calculation and H/V ratio computation). Twenty four log-spaced points have been generated between 0.1 Hz and 20 Hz; the range between two contiguous points is treated as one frequency bin. The Fourier amplitude acceleration spectrum within each bin is averaged to represent the Fourier amplitude for such bin. 5% damped pseudo acceleration spectra (PSA) are calculated as well for all records.

Figure 3.1. Flow chart for earthquake data processing

Figure 3.2. Stations used in this study; the square represents the rock station while the up-triangle represents the soil station. The line shows the Chi-Chi surface rupture.

Figure 3.3. Sample seismogram with envelope function (dotted lines) and defined shear wave window (box)

Figure 3.4. Commonly used taper functions for data processing

Chapter 4

SEISMIC PARAMETERS OF THE CHI-CHI MAINSHOCK

4.1 Introduction

First, CheLongPu Fault of Taiwan Island (the causative fault of Chi-Chi earthquake) is introduced in this chapter and then other source parameters used in the simulation model are described. The geometrical parameters of the main shock (eg. epicentral location, focus depth, magnitude) from USGS, Harvard University and local authorities are compared to assess the most reasonable values. The shear wave velocity information of the upper 30 meters soil profile is used to classify the stations classes according to the NEHRP classification scheme (Borcherdt, 1995). Then the site amplification functions for both rock and soil stations that have such velocity information are calculated. The high frequency diminution operator, as introduced by Anderson and Hough (1984) is then analyzed.

In the stochastic simulation, the attenuation function is an important factor controlling the shape and amplitudes of seismograms at the recording station. Regression analysis of the main shock data is performed using the PGA data of the rock stations to approximate the geometrical spreading coefficients and a close-in distance saturation term, Δ . Then the quality factor of the crust (Q) attached to this attenuation model is derived by regression analysis of the Fourier acceleration amplitude. The source duration of the motion, which is related to the rise time of the main shock, is calculated. Since it affects the duration time of the simulated seismogram at the

recording stations, the duration model versus distance is derived using the defined shear wave window for each record, as discussed in Chapter 3.

4.2 Geometric Parameters of the Main Shock

4.2.1 Fault Plane

CheLongPu Fault is a major pre-existing fault that ruptured during the 1999 Chi-Chi earthquake. There are several models concerning the fault plane and its slip distribution (Wang *et al.*, 2001; Sokolov *et al.*, 2002; Irikura *et al.*, 2000; Kikuchi *et al.*, 2000). In our simulations, both a random slip distribution model and a pre-determined slip distribution model are considered in order to compare the effects of the different fault rupture processes on the simulation. According to publications about CheLongPu Fault (Wang *et al.*, 2001; Sokolov *et al.*, 2002; Irikura *et al.*, 2000), its strike and dip are 5° and 30° , respectively. The fault plane and the fault grid are shown in Figure 4.1.

The pre-determined fault slip model used in the simulation is shown in Figure 2. (Wang *et al.*, 2001). The slip contour is re-plotted in Figure 4.2 according to the model provided by the author.

4.2.2 Main Shock Location

According to USGS, the epicenter of the main shock was at 23.77N 120.98E with moment magnitude 7.6. It was reported as (24.15N 120.80E with $M_W = 7.6$ at focal depth=21.2km) and (23.85N 120.82E, $M_W = 7.6$, focal depth=8.0km) by Harvard CMT solution and CWB, respectively. I choose the parameters from CWB for use in this study, as they incorporate more local data.

4.3 Site Classification

All of the used 411 stations are classified as rock/soft-rock stations (NEHRP class B & C) or soil stations (NEHRP class D & E) according to the upper 30 meters shear wave velocity information provided by PEER (2005). NEHRP site classification schemes are listed in Table 4.1. The shear wave velocity information was gathered either by near surface geophysical surveys or by borehole geophysical investigations. However, not all of the stations have this information. For the stations for which no geophysical investigations were performed, researchers subjectively assigned the shear wave velocity according to its surface geology condition of each station (PEER, 2005). For stations with no accurate velocity information, the site classification used by Lee *et al.* (2001a) and by Phung *et al.* (2004) are used as a reference. Assigned NEHRP classes for each station are given in Table 3.1.

Table 4.1: NEHRP site classification scheme (Borcherdt, 1995)

Site Class	$\bar{V}_s$	Description
A	>1500 m/s	Hard rock
B	760 to 1500 m/s	Rock
C	360 to 760 m/s	Very dense soil and soft rock
D	180 to 360 m/s	Stiff soil
E	<180 m/s	Soil

For the study database, 4 stations are NEHRP class B; 219 stations are NEHRP class C; 179 stations are NEHRP class D and 9 stations are NEHRP class E sites.

The soft rock stations (NEHRP class C) are used to calibrate the input source model for stochastic simulation (determine the two free parameters: stress drop and pulsing percentage). Then the soil stations are used with the calibrated input model to study the non-linear soil response.

4.4 Kappa Factor

The kappa factor introduced by Anderson and Hough (1984) is used to describe the high frequency diminution filter, defined as $D(f) = A_0 \exp(-\pi\kappa f)$, $f > f_0$ (Equation 2.9), where f_0 is the corner frequency. For all of the stations used, the kappa value is calculated separately for two horizontal components and the vertical component.

In this study, the frequency span to calculate kappa is defined visually for each

record as shown in Figure 4.3. Generally, the corner frequency, f_0 , is always considered to be well below 1 Hz for large earthquakes such as Chi-Chi earthquake and the starting frequency is visually defined at least beyond 1 Hz. The ending frequency to calculate kappa is also visually defined, but not beyond 20 Hz where the noise dominates the signal in most cases. The κ is calculated using the smoothed Fourier acceleration amplitude within the chosen frequency span by linear least square regression method. We have:

$$\log[a(f)] = \log(A_0) - \log(e)\pi k f, \quad f > f_0 \quad (4.1)$$

Re-writing Equation 4.1 as $Y(x) = b + ax$, where f is substituted by x , $Y(x)$ is $\log[a(f)]$ and b is the constant related with source, the slope a is $\pi\kappa\log(e)$.

Thus the kappa value can be derived as:

$$\kappa = a/(\pi\log(e)) \quad (4.2)$$

κ depends on distance ($\kappa = \kappa_0 - CR$) since anelastic attenuation effects are included, the value k_0 (pronounced kappa not), which denotes the zero-distance intercept of kappa, needs to be derived and input to simulations. After calculating the kappa value for all of the stations, the k_0 value can be regressed using least squares method. I regress the k of vertical component, E-W component and N-S component for both rock stations and soil stations. Figure 4.4, Figure 4.5 and Figure 4.6 are the k for rock stations on vertical component, N-S and E-W components while Figure 4.7, Figure 4.8 and Figure 4.9 are for soil stations on vertical component, N-S and E-W components.

According to the regression results, κ_0 is almost the same for the horizontal

components of both rock ($\kappa_0 = 0.064$) and soil ($\kappa_0 = 0.066$) stations in Taiwan. However, κ_0 for vertical components are above 0.05 for both rock and soil stations.

4.5 Wave Propagation Analysis

4.5.1 Attenuation Regression

The ground motion attenuation relationship plays an important role in the stochastic modeling since it shows how the seismic energy decays with distance. The maximum distance to the fault for stations in the dataset is about 160 km and there are only about 60 of 400 stations with rupture-station distances greater than 100 km. The paucity of far field records results in the inapplicability of detailed trilinear or bilinear models which are typical of attenuation over large distances (eg. Atkinson, 2004). We choose a simple function, as given in Equation 4.3, to define the attenuation model:

$$\log (FA) = c_1 + c_2 \cdot \log (R) + c_3 \cdot (R) \quad (4.3)$$

where: FA is the Fourier acceleration amplitude, PGA or PGV depending on the application; R is the distance metric (see below); c_2 is the geometric spreading coefficient; and c_3 is anelastic attenuation coefficient.

A special feature of the Chi-Chi strong motion database is its richness of the near-source records. The shortest rupture-station distance in the dataset is less than 1 km and more than 30 stations have rupture-station distance less than 10 km. Since near-source records attenuate slowly with distance due to the effect of the fault plane, I introduced a close-in distance saturation coefficient (denoted “ Δ ”) to control the shape of the attenuation curve in the near source. Thus the distance metric in Equation 4.3 is: $R = Dist + \Delta$, where Δ is the saturation variable (in km).

According to the assumption that the site amplification for the vertical component is negligible at the rock stations, I first regress the PGA of vertical component for the rock stations to roughly determine the geometric spreading coefficient c_2 and Δ for Equation 4.3. The reason for this step is that in the regression process for Fourier acceleration amplitude, these two coefficients will be used to derive the anelastic coefficient of Equation 4.3 and then to calculate the Q model. In the regression, the geometric spreading coefficient is varied from -0.5 to -1.0 with step 0.1 and the Δ is varied from 1 to 20 in order to find the coefficients which provide the minimum root mean square (rms) of residuals, where the rms is defined as $\sqrt{\frac{\sum_{j=1}^n ((FA_{obs})_j - (FA_{reg})_j)^2}{n}}$, where n is the number of the stations used for regression, $(FA_{obs})_j$ is the Fourier spectrum of the recorded data and $(FA_{reg})_j$ is the Fourier spectrum of the regressed result. The model with minimum rms of residuals has geometrical spreading coefficient -0.9 and $\Delta=7$ km. Figure 4.10 (a) is the regressed result of the attenuation curve for PGA, along with the rock station database. Figure 4.10 (b) is the residual distribution of the regressed result; there is no trend of the residuals, indicating the reasonableness of the chosen attenuation model.

The regressed geometric spreading coefficients are very close to the recent published attenuation relation (Liu and Tsai, 2005) for Taiwan region using a larger small-intermediate magnitude earthquake database. This is very important for the extended fault stochastic simulation method because the moment magnitude of the subfaults are usually low (In most case, it is about moment magnitude 4-5). By contrast, the attenuation model regressed above uses the dataset of a high magnitude earthquake ($M_W = 7.6$), but it may not be suitable for characterizing subfaults or low magnitude earthquakes. The geometric attenuation model is used as a constraint condition for the regression of Fourier acceleration amplitudes to determine Q. Fig-

Figure 4.11 (a) and Figure 4.11 (b) show the regressed curve and residual distribution for Fourier acceleration amplitude at 1 Hz. Figure 4.12 (a) and Figure 4.12 (b) demonstrate the regressed result at 5 Hz. The fit of the regressed curves and lack of trend of the residual distribution indicates that the geometric spreading coefficient and chosen Δ are acceptable.

4.5.2 Q model

The quality factor of crust (Q) is inversely related to the anelastic coefficient c_3 of Equation 4.3. The Q model can be represented as:

$$Q = \frac{\pi \log(e)f}{c_3\beta} \quad (4.4)$$

where Q represents the shear wave Q model of the crust, e is the base of natural logarithm, f is the frequency, β is shear wave velocity of the crust and c_3 is the anelastic coefficient of Equation 4.3. c_3 is a function of frequency and can be empirically determined by least squares. Figure 4.13 is the calculated Q model corresponding to the fixed geometric attenuation model (two exceptional points between 3 Hz and 5 Hz are removed when calculate Q model). The vertical bars are the 95% confidence interval.

4.6 Site Amplification

Site amplification is calculated considered two methods: the H/V ratio and quarter wavelength approximation approaches.

4.6.1 H/V Ratio

The H/V ratio approach was first proposed by Nakamura (1989) for application to micro-tremor measurements, based on the hypothesis that the amplification effects on the vertical component are small enough to be neglected while the observed amplification effects are developed on the horizontal component of ground motions. Lermo and Chavez-Garcia (1994) verified the applicability of the H/V ratio approach to shear waves from earthquakes by using strong motion earthquake data from Mexico earthquakes. Some theoretical justification of the H/V ratio was provided by Lachet and Bard (1994).

According to Nakamura (1989), the site amplification function ($A(f)$) at one station is the ratio of the horizontal Fourier acceleration amplitude (FA_H) to the vertical Fourier acceleration amplitude (FA_V) defined as:

$$A(f) = FA_H/FA_V \quad (4.5)$$

4.6.2 Quarter Wavelength Approximation Approach

The specific site amplification function may be calculated for every station for which the shear wave velocity profile is known. There are 192 stations with such velocity profile provided by National Center for Research on Earthquake Engineering (NCREE) of Taiwan. The station's time-averaged shear wave velocity of the top 30 meter is calculated, and each station is classified into four categories according to the NEHRP site classification scheme of Borchardt (1995). Among the used database, 5 stations are NEHRP class B sites (list in Table 4.2); 65 stations are NEHRP class C sites (list in Table 4.3); 106 stations are NEHRP class D sites (list in Table 4.4) and 16 stations are NEHRP class E sites (list in Table 4.5).

The site amplification is calculated from the seismic impedance using the quarter-wavelength approach which was introduced by Boore and Joyner (1997). For a particular frequency, the amplification is given by the square root of the ratio between the seismic impedance averaged over a depth corresponding to a quarter wavelength and the seismic impedance at the depth of the source (Boore and Joyner, 1997). The algorithm to compute the site amplification is based on Equation 4.6:

$$A[f(z)] = \sqrt{\rho_s \beta_s / \bar{\rho}(z) \bar{\beta}(z)} \quad (4.6)$$

where ρ_s and β_s are the density and the shear wave velocity values in the vicinity of the source, $\bar{\beta}(z)$ is the average velocity to the depth z which can be calculated by $z/S_{tt}(z)$ in which $S_{tt}(z)$ is the S travel time from the surface to depth z , $f(z)$ is the frequency function corresponding to the depth (can be obtained by $1/[4\pi S_{tt}(z)]$), and $\bar{\rho}(z)$ is the travel-time-weighted average density (Boore and Joyner, 1997).

Table 4.2: Stations used to calculate site amplification based on the quarter wavelength approximation method (NEHRP class B sites)

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
KAU003	884.7	B	1.57	1.98
TAP065	1022.0	B	1.51	1.66
TAP071	825.2	B	1.56	1.92
TAP077	976.4	B	1.53	1.76
TAP114	1230.4	B	1.49	1.60

Table 4.3: Stations used to calculate site amplification based on the quarter wavelength approximation method (NEHRP class C sites)

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
CHY006	422.5	C	1.67	2.55
CHY024	403.2	C	1.73	2.80
CHY028	539.1	C	1.05	1.40
CHY029	537.6	C	1.65	2.38
CHY034	374.8	C	1.87	3.29
CHY038	360.2	C	1.85	3.27
CHY041	480.9	C	1.73	2.78
CHY074	514.5	C	1.66	2.51
HWA026	450.8	C	1.73	2.88
HWA033	380.4	C	1.80	3.39
HWA034	373.3	C	1.81	3.17
HWA056	514.2	C	1.67	2.48
ILA020	454.5	C	1.68	2.51
ILA031	641.0	C	1.60	2.20
ILA046	383.3	C	1.85	3.25
KAU039	461.2	C	1.70	2.65
TAP035	392.2	C	1.78	3.42
TAP051	393.0	C	1.81	3.32
TAP056	604.9	C	1.58	2.04
TAP066	642.1	C	1.58	2.02
TAP089	395.6	C	1.71	4.37
TAP103	433.2	C	1.69	2.81
TCU003	504.0	C	1.63	2.33
TCU005	501.5	C	1.65	2.45
TCU009	463.7	C	1.72	2.68
TCU017	563.1	C	1.65	2.42
TCU019	499.4	C	1.70	2.61
TCU021	445.5	C	1.67	2.53
TCU027	661.4	C	1.62	2.23
TCU028	514.7	C	1.68	2.61
TCU030	615.1	C	1.61	2.17
TCU033	408.5	C	1.77	3.14

Continued...

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
TCU037	452.6	C	1.73	2.96
TCU039	543.7	C	1.69	2.54
TCU045	683.6	C	1.56	1.96
TCU046	442.7	C	1.69	3.26
TCU047	510.8	C	1.71	2.75
TCU049	466.3	C	1.70	2.66
TCU052	575.3	C	1.66	2.48
TCU053	449.3	C	1.74	2.74
TCU054	429.7	C	1.73	2.80
TCU067	437.9	C	1.77	2.92
TCU068	480.3	C	1.72	2.87
TCU070	392.9	C	1.80	3.13
TCU071	597.0	C	1.61	2.30
TCU072	459.6	C	1.66	2.68
TCU074	549.9	C	1.68	2.50
TCU075	511.1	C	1.65	2.44
TCU076	562.4	C	1.63	2.29
TCU077	503.5	C	1.65	2.42
TCU078	438.0	C	1.72	2.81
TCU082	464.3	C	1.73	2.77
TCU090	535.3	C	1.64	2.51
TCU094	573.3	C	1.65	2.41
TCU095	443.5	C	1.77	2.99
TCU102	691.1	C	1.59	2.13
TCU103	487.6	C	1.71	2.67
TCU116	458.7	C	1.71	2.71
TCU120	460.0	C	1.03	1.20
TCU128	582.8	C	1.66	2.46
TCU138	600.0	C	1.63	2.26
TCU143	457.0	C	1.71	2.80
TCU147	523.8	C	1.63	2.35
TCU148	497.9	C	1.66	2.52
TTN041	420.8	C	1.76	2.95

Table 4.4: Stations used to calculate site amplification based on the quarter wavelength approximation method (NEHRP class D sites)

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
CHY001	225.1	D	2.34	4.56
CHY002	228.1	D	2.21	3.90
CHY004	269.3	D	2.08	4.06
CHY005	208.1	D	2.45	4.17
CHY007	199.4	D	2.43	4.95
CHY008	207.4	D	2.32	4.37
CHY009	222.4	D	2.45	4.37
CHY012	189.9	D	2.43	5.18
CHY013	212.4	D	2.52	5.09
CHY015	221.6	D	2.62	4.72
CHY016	197.3	D	2.74	4.61
CHY017	188.1	D	2.37	4.94
CHY020	210.0	D	2.53	5.05
CHY021	209.8	D	2.47	4.35
CHY025	274.8	D	2.09	3.65
CHY026	218.3	D	2.41	4.70
CHY027	206.0	D	2.37	4.89
CHY030	205.4	D	2.32	4.64
CHY031	214.2	D	2.55	4.41
CHY032	190.1	D	2.59	4.76
CHY033	191.1	D	2.72	4.83
CHY036	206.1	D	2.31	4.59
CHY037	204.9	D	2.70	5.14
CHY039	187.4	D	2.81	4.72
CHY043	223.1	D	2.49	4.52
CHY044	190.5	D	2.87	4.61
CHY048	233.0	D	1.97	5.07
CHY049	221.9	D	2.57	4.66
CHY051	353.8	D	1.83	3.84
CHY055	218.5	D	2.39	4.44
CHY056	187.0	D	2.87	5.06
CHY059	185.2	D	2.61	4.86

Continued...

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
CHY060	213.2	D	2.18	4.40
CHY066	206.4	D	1.36	5.03
CHY067	224.8	D	2.35	4.81
CHY068	188.6	D	2.44	4.81
CHY073	191.0	D	2.02	4.57
CHY082	191.5	D	2.92	5.28
CHY084	257.8	D	2.15	4.00
CHY092	248.9	D	2.27	4.14
CHY093	189.1	D	2.24	4.99
CHY094	221.5	D	2.57	4.48
CHY095	212.3	D	2.55	4.88
CHY099	209.8	D	2.22	4.42
CHY101	255.0	D	2.09	3.96
CHY103	218.8	D	2.46	4.84
CHY104	219.9	D	2.04	3.77
CHY105	202.1	D	2.37	4.81
CHY106	224.5	D	2.42	4.52
CHY111	268.2	D	2.16	3.73
CHY112	237.3	D	2.45	4.35
CHY113	237.2	D	2.41	4.49
HWA004	312.6	D	1.99	4.16
ILA003	264.8	D	1.96	3.82
ILA005	236.3	D	2.03	4.05
ILA006	274.8	D	1.89	3.56
ILA013	192.5	D	1.93	3.90
ILA014	298.8	D	1.88	3.50
ILA016	268.8	D	1.96	3.63
ILA026	235.1	D	2.22	3.78
ILA027	213.9	D	1.99	4.12
ILA028	215.1	D	2.40	4.97
ILA029	185.1	D	2.55	5.02
ILA030	197.4	D	2.61	4.57
ILA032	296.9	D	1.85	3.37
ILA037	207.2	D	2.34	4.33
ILA038	243.1	D	1.94	3.81
ILA039	222.6	D	1.88	3.54

Continued...

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
ILA041	192.1	D	2.93	4.73
ILA042	206.8	D	2.41	4.89
ILA048	190.9	D	2.39	4.82
ILA049	185.8	D	1.99	4.24
ILA055	263.0	D	2.28	4.05
ILA056	219.7	D	2.50	4.28
ILA059	231.4	D	2.11	4.05
KAU006	214.9	D	2.60	4.87
KAU008	279.6	D	2.08	4.22
KAU013	257.3	D	2.12	4.35
KAU014	243.1	D	2.06	3.68
KAU017	247.9	D	2.31	4.14
KAU020	340.5	D	1.77	3.10
KAU029	352.4	D	1.68	2.55
KAU035	277.4	D	1.96	3.72
KAU037	277.7	D	1.78	3.07
KAU046	192.6	D	2.63	4.76
KAU085	253.9	D	2.05	3.90
KAU089	190.5	D	2.12	4.70
TAP002	358.3	D	1.79	4.20
TAP003	206.9	D	2.70	4.76
TAP009	180.1	D	2.13	4.61
TAP010	217.6	D	2.54	4.69
TAP019	238.4	D	2.16	5.01
TAP024	183.7	D	3.02	5.54
TAP057	351.9	D	1.79	4.25
TAP084	196.4	D	2.25	4.59
TAP090	325.8	D	1.86	3.24
TAP093	186.8	D	2.81	5.48
TCU040	331.1	D	1.82	2.96
TCU065	285.0	D	2.10	4.04
TCU079	340.7	D	1.75	3.49
TCU086	219.8	D	2.50	4.53
TCU110	197.7	D	2.65	4.97
TCU111	230.7	D	2.24	4.63
TCU113	226.2	D	2.44	4.86

Continued...

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
TCU115	181.5	D	2.82	5.10
TCU139	305.8	D	2.01	3.46

Table 4.5: Stations used to calculate site amplification based on the quarter wavelength approximation method (NEHRP class E sites)

Station	$V_{s30}(m/s)$	Class	Amp (1 Hz)	Amp (5 Hz)
CHY003	162.5	E	3.02	5.68
CHY047	144.4	E	2.22	5.22
CHY054	167.3	E	2.88	5.39
CHY076	156.6	E	3.09	6.02
CHY077	117.0	E	3.68	6.04
CHY078	150.7	E	2.55	5.57
CHY107	161.2	E	2.69	5.25
HWA059	144.6	E	2.22	5.23
ILA004	116.1	E	5.31	7.02
ILA044	151.1	E	2.93	5.24
KAU011	135.6	E	3.25	5.10
KAU023	160.3	E	2.23	4.76
KAU045	142.6	E	3.84	5.24
KAU048	168.2	E	1.99	4.46
TAP001	155.3	E	3.31	5.40
TAP022	175.0	E	2.65	5.54

The detailed upper 30 meter shear wave velocity information (provided by NCREE) is stored as an EXCEL file. For those stations with known profiles, velocity information is typically known up to 30 meters. The quarter wavelength approximation method (Boore and Joyner, 1997) is used to calculate the amplification function. Because the quarter wavelength method needs the shear wave velocity information up to the depth of the earthquake source, the formula from Table 1 of Boore and Joyner

(1997) is used to extrapolate from 30 meters to provide the deeper shear wave velocity structure. Three evenly spaced sample depths are chosen for every interval in Table 1 of Boore and Joyner (1997). That is, within the 30 meter to 190 meter interval, three depths are calculated and velocities are estimated using:

$$3.542 \cdot z^{0.407} \quad (4.7)$$

where Z is depth in meter (Boore and Joyner, 1997).

The shear wave velocity of top 30 meters and the extrapolated velocity structure of one rock station is shown as an example in Figure 4.14, while one soil station's velocity structure is shown in Figure 4.15. The density profile is calculated using Equation 3 of Boore and Joyner (1997) ($\rho(z) = 2.5 + [\beta(z) - 0.3] \times \frac{2.8-2.5}{3.5-0.3}$), with the minor modification shown below:

$$\rho(z) = 2.0 + [\beta(z) - 0.3] \times \frac{2.3 - 2.0}{3.5 - 0.3} \quad (4.8)$$

In the above modified equation, the lower and upper limit of the density were assigned as 2.0 and 2.3 respectively, according to the information provided by NCREE (Taiwan), which are compare lower to the California values of 2.5 and 2.8 in the publication of Boore and Joyner (1997).

The shear wave velocity information stored in the EXCEL file is extracted using a Java program (written by myself), which calls the site amplification calculation program by Boore and Joyner (1997) as a black-box within Java. To meet the requirement of the site amplification program, the input velocity files were designed using the following assumptions:

1. The shear wave velocity increases with depth

2. Deeper layers with slower velocity will be ignored

A sample input file for the site amplification program is shown in Table 4.6.

The calculated site amplification function of all stations is averaged for rock stations and soil stations. The averaged result of the rock stations (NEHRP class C) and soil stations (NEHRP class D); the site amplification function based on H/V ratio approach and the site amplification of California (Boore and Joyner, 1997) are compared in Figure 4.16 and Figure 4.17. In Figure 4.16, the site amplification function of NEHRP class C sites at Taiwan and California is almost identical at high frequency ($>3\text{Hz}$) but slightly different at lower frequency ($<3\text{Hz}$). The H/V ratio estimate of site amplification is close to these two amplification functions at low frequency ($<3\text{Hz}$), but shows a significant decrease at the higher frequency ($>3\text{Hz}$) due to the effect of the high-frequency diminution operator (κ_0). Figure 4.17 is the comparison of the site amplification for NEHRP class D sites which shows the similar characteristic as Figure 4.16; the disagreement between H/V and the theoretical estimate is significant at all frequencies. There is a noticeable difference in the high frequency between the quarter wavelength estimates for Taiwan VS. California, probably because the approach adopted to calculate the site amplification for NEHRP class D sites in California is different from that used in this study. The site amplification function for NEHRP class D sites in California is based on the empirical analysis (ratio of response spectra between sites with $\bar{V}_{30} = 620 \text{ m/sec}$ and desired sites) and it was corrected from the site amplification function for sites with $\bar{V}_{30} = 620 \text{ m/sec}$. Meanwhile, there was an assumption to calculate the site amplification function for California NEHRP class D sites that the ratio of Fourier and response spectra are the same which is not strictly true especially for the high frequency (Boore and Joyner, 1997).

Table 4.6. Sample shear wave velocity structure to calculate the site amplification function by quarter wavelength approximation approach

Sample input file to site_amp at station: CHY002

Depth	SVel	Dens
0	232.55	2.00
10.5	285.71	2.00
11.0	294.11	2.00
16.0	303.03	2.00
16.5	312.50	2.00
28.0	322.58	2.00
83.0	1286.2	2.09
136.5	1574.8	2.12
190.0	1801.7	2.14
1460.0	2700.9	2.23
2730.0	3059.1	2.26
4000.0	3300.7	2.28
5333.0	3380.1	2.29
6666.0	3445.6	2.29
7999.0	3500.1	2.30

SVel = Shear wave velocity

Dens = Density

The site effects at a specific site are the product of the site amplification function and the high frequency diminution operator (κ_0). Thus in Figure 4.16 and Figure 4.17, the quarter wavelength amplification need to be multiplied by the κ_0 to obtain the net amplification. However, for the H/V ratio approach, the kappa effect may have been removed by spectral division if the kappa value remains the same for the horizontal component and the vertical component.

In fact, the kappa operator value for the horizontal component is not equal to that of the vertical component (at least for Chi-Chi case). If κ_{0H} is equal to κ_{0V} , $\frac{FA_H}{FA_V}$ should be used in the simulations as net site amplification. Thus, Equation 4.5 can be re-written as:

$$\frac{FA_H}{FA_V} = \text{Amp} \frac{\exp(-\pi f \kappa_{0H})}{\exp(-\pi f \kappa_{0V})} \quad (4.9)$$

where Amp is the site amplification, κ_{0H} is kappa for horizontal component and κ_{0V} is kappa for vertical component. As mentioned in Chap 2, the site term in the stochastic simulations is referred as the product of the site amplification and the horizontal high frequency diminution operator.

Thus, $A(f)_{H/V} \cdot \exp(-\pi \kappa_{0V})$ which is the site term should be used in simulations when the κ_0 for vertical component is not considered as zero. Figure 4.18 and Figure 4.19 are the site term as the product of the site amplification and the high frequency diminution operator of the horizontal component (quarter wavelength approximation approach) and the product of the H/V ratio and the vertical component high frequency diminution operator. According to Figure 4.18 and Figure 4.19, the site terms calculated from H/V ratio method and the quarter wavelength approximation method are very similar within the frequency range of interest. Our results indicate that the H/V ratio can be a good choice for the site amplification function if no shear wave velocity information is available. In Figure 4.18 and Figure 4.19,

the site term at high frequency for Taiwan and California is different because of the different kappa value used for these two regions ($\kappa_{0H}=0.07$ in Taiwan and $\kappa_{0H}=0.035$ in California).

4.7 Duration of Motions

In this study, the duration time of the seismogram is defined as follows. The start time of the signal is the arrival time of the shear wave which is picked visually from the seismogram; the end time of the signal is first picked visually but then compared with the calculated time to accumulate 90% of the energy of the whole seismogram. If the calculated time is earlier than the observed end time, then the calculated time is used as the end time of the signal. Duration is often expressed as a function of distance(R) as: (Atkinson and Boore, 1995)

$$T(R) = T_0 + dR \quad (4.10)$$

T_0 is the source duration time which can be calculated using Equation 4.11

$$T_0 = \frac{1}{2f_0} \quad (4.11)$$

Equation 4.12 is used to obtain the corner frequency f_0 which was based on source parameters of earthquake records in ENA (Eastern North America) (Atkinson and Boore, 1995).

$$\log(f_0) = 2.41 - 0.533M \quad (4.12)$$

where M is the moment magnitude of the target earthquake.

Figure 4.20 plots duration versus rupture-station distance. T_0 can be roughly

determined as 26 sec from the Y-axis intercept value of Figure 4.20. The slope of the duration curve d is 0.1 in this case. The T_0 value calculated from Equation 4.11 is about 22 sec, which is very close to the result inferred from observation. The agreement between the calculated T_0 and the observed one suggest that the definition of the shear wave window is reasonable in the study. With help of Equation 4.10, the duration time at any site can be determined.

Figure 4.1. The fault plane adopted (Wang *et al.*, 2001) in this study

Figure 4.2. The pre-determined slip distribution model used in this study (Wang *et al.*, 2001), the star is the epicenter; the downdip direction is along the bottom line (0-40km) of the figure and the strike is along the left boundary (0-70km) of the figure.

Figure 4.3. Sample Fourier acceleration amplitude to calculate κ at station ALS: (a) Linear View (b) Log View

Figure 4.4. κ versus station-rupture distance to calculate κ_0 of rock stations (U-D)

Figure 4.5. κ versus station-rupture distance to calculate κ_0 of rock stations (N-S)

Figure 4.6. κ versus station-rupture distance to calculate κ_0 of rock stations (E-W)

Figure 4.7. κ versus station-rupture distance to calculate κ_0 of soil stations (U-D)

Figure 4.8. κ versus station-rupture distance to calculate κ_0 of soil stations (N-S)

Figure 4.9. κ versus station-rupture distance to calculate κ_0 of soil stations (E-W)

Figure 4.10. (a) Attenuation curve of PGA for rock stations (vertical) (b) Residual distribution of PGA attenuation regression analysis for rock stations (vertical)

Figure 4.11. (a) Attenuation curve for Fourier acceleration amplitude at 1 Hz (vertical). (b) Residual distribution of attenuation analysis of Fourier acceleration amplitude at 1 Hz (vertical)

Figure 4.12. (a) Attenuation curve for Fourier acceleration amplitude at 5 Hz (vertical). (b) Residual distribution of attenuation analysis of Fourier acceleration amplitude at 5 Hz (vertical)

Figure 4.13. Q model; the vertical error bars are 95% confidence interval

Figure 4.14. The shear wave velocity (V_s) structure used in this study at rock station CHY006

Figure 4.15. The shear wave velocity (V_s) structure used in this study at soil station CHY001

Figure 4.16. Comparison of site amplifications based on H/V and quarter wavelength approaches (QWL) for Taiwan and based on quarter wavelength approach (QWL) for California (NEHRP class C)

Figure 4.17. Comparison of site amplifications based on H/V and quarter wavelength approaches (QWL) for Taiwan and based on quarter wavelength approach (QWL) for California (NEHRP class D)

Figure 4.18. Comparison of site term ($A(f) \cdot \exp^{-\pi \kappa_0 f}$) of NEHRP class C sites between Taiwan (based on H/V combined with $\kappa_{0V}=0.051$ and quarter wavelength approximation (QWL) combined with $\kappa_{0H}=0.064$) and California (based on quarter wavelength approximation (QWL) combined with $\kappa_{0H}=0.035$)

Figure 4.19. Comparison of site term ($A(f) \cdot \exp^{-\pi \kappa_0 f}$) of NEHRP class D sites between Taiwan (based on H/V combined with $\kappa_{0V}=0.057$ and quarter wavelength approximation (QWL) combined with $\kappa_{0H}=0.066$) and California (base on quarter wavelength approach (QWL) combined with $\kappa_{0H}=0.035$)

Figure 4.20. Duration of motions in the Chi-Chi mainshock

Chapter 5

SIMULATION OF THE CHI-CHI EARTHQUAKE GROUND MOTION

5.1 Introduction

After obtaining all of the needed input parameters for the stochastic simulation, the following steps are used to finalize the simulation. First, I use the rock stations (NEHRP class C) as reference stations to calibrate the input model: that is, to determine two “free parameters” stress drop and pulsing percentage, which can not be directly derived from the seismic records. These parameters are determined based on the minimization of root mean square of residuals ($\text{rms} = \sqrt{\frac{\sum_{i=1}^N (r_i \cdot r_i)}{N}}$, where r is the model residual for each frequency bin and $N=24$ is the number of frequency bin). Then, the estimated stress drop and pulsing percentage are applied to the soil stations to analyze the possible non-linear soil response.

Finally, the soil stations located in the Taipei metropolitan area are selected to analyze the effect of the Taipei basin on ground motions.

5.2 Input Model

All of the input parameters for the simulations are listed in Table 5.1. Fault geometrical parameters and other physical parameters are as discussed in Chapter 4. Only two “free” parameters, stress drop and pulsing percentage, are unknown and should be calibrated. I vary the stress drop from 20 to 100 bars in 10 bar steps, while the pulsing percentage is fixed at 50% to search for the result that produces

minimum rms of residuals where residual is defined as $\text{Log}(\text{PSA}_{\text{obs}})_i - \text{Log}(\text{PSA}_{\text{sim}})_i$. PSA_{obs} is the arithmetic average of the E-W and N-S components PSA at the i^{th} station. The pulsing percentage does not affect the stress drop dramatically; thus, the pulsing percentage can be fixed in the determination of stress drop. (The stress drop determines the high frequency level of ground motion while pulsing percentage affects low frequencies only.)

Table 5.1: Input model parameters for the extended finite fault stochastic simulation

Fault dimension (km)	70 x 40
Subfault dimension (km)	6.4 x 5
Depth of fault (km)	0
Fault orientation	strike:5°,dip:34°
Mainshock moment magnitude (M_W)	7.6
Hypocenter location (subfault)	4 4
V_s (km/s)	3.2
Density (g/cm^3)	2.7
Stress parameters (bars)	increase from 20 to 100 with step 10
Pulsing percentage	fix as 50% to determine stress drop then increase from 10% to 90% in 10% steps
Windowing function	Saragoni-Hart
Geometric spreading	-0.9
$Q(f)$	$Q = 294 \cdot f^{0.61}$
Duration	$T = T_0 + d \cdot R$ (Atkinson and Boore, 1995) $d=0.1$
Kappa operator (κ)	0.065
Amplification	NEHRP class C (quarter wavelength approximation)
Site classification	NEHRP class C
Slip model	random slip distribution

5.3 Results and Analysis

In the following sections, simulation based on the parameters shown in Table 5.1 is conducted for rock stations to calibrate the model and then applied to soil stations investigating the non-linear soil and the basin responses.

5.3.1 Simulation for Rock Stations

The averaged residual for models with different stress drop (from 20 bars to 100 bars with 10 bars increment) but fixed pulsing percentage (50%) are plotted together in Figure 5.1 to find the average stress drop in the 1999 Chi-Chi mainshock. According to Figure 5.1, the stress drop of the mainshock is between 30 and 50 bars. After determining the stress drop range, the combined effect of the stress drop and the pulsing percentage are evaluated by varying the stress drop from 30 bars to 50 bars (with 5 bars increment) and pulsing percentage from 10% to 90% (with step 10 %). Table 5.2 shows the comparison of the model bias with different stress drop and pulsing percentages. According to the model bias shown in Table 5.2 the stress drop is about 40 bars and the pulsing percentage is above 80% (The average model bias and the root mean square of the model bias are the smallest).

Table 5.2 Comparison of Model bias for different stress drop and pulsing percentage combination

	Freq	0.10	0.13	0.16	0.20	0.25	0.32	0.40	0.50	0.63	0.79	1.00	1.26	1.58	2.00	2.51	3.16	3.98	5.01	6.31	7.94	10.00	12.59	15.85	20.00	AVG	RMS
Sress(P)																											
30 (10)		0.06	0.09	0.07	0.04	-0.01	-0.01	-0.02	0.03	0.04	0.08	0.11	0.11	0.1	0.08	0.03	0	-0.04	-0.09	-0.12	-0.11	-0.09	-0.05	-0.02	0.01	0.012	0.341
30 (20)		0.06	0.09	0.07	0.04	-0.01	-0.01	-0.02	0.03	0.04	0.08	0.11	0.11	0.1	0.08	0.03	0	-0.04	-0.09	-0.12	-0.11	-0.09	-0.05	-0.02	0.01	0.012	0.341
30 (30)		0.06	0.09	0.07	0.04	-0.01	-0.01	-0.02	0.03	0.04	0.08	0.11	0.11	0.1	0.08	0.03	0	-0.04	-0.09	-0.12	-0.11	-0.09	-0.05	-0.02	0.01	0.012	0.341
30 (40)		0.07	0.11	0.09	0.07	0.02	0.03	0.02	0.07	0.09	0.13	0.15	0.15	0.14	0.12	0.08	0.05	0.01	-0.04	-0.07	-0.07	-0.05	-0.01	0.02	0.05	0.051	0.408
30 (50)		0.07	0.11	0.09	0.07	0.02	0.03	0.02	0.07	0.09	0.13	0.15	0.15	0.14	0.12	0.08	0.05	0.01	-0.04	-0.07	-0.07	-0.05	-0.01	0.02	0.05	0.051	0.408
30 (60)		0.08	0.12	0.1	0.09	0.04	0.04	0.04	0.09	0.1	0.14	0.17	0.17	0.16	0.14	0.1	0.07	0.03	-0.02	-0.05	-0.05	-0.03	0.01	0.04	0.07	0.069	0.462
30 (70)		0.08	0.12	0.1	0.09	0.04	0.04	0.04	0.09	0.1	0.14	0.17	0.17	0.16	0.14	0.1	0.07	0.03	-0.02	-0.05	-0.05	-0.03	0.01	0.04	0.07	0.069	0.462
30 (80)		0.08	0.13	0.11	0.1	0.05	0.05	0.05	0.1	0.11	0.15	0.18	0.18	0.17	0.15	0.11	0.08	0.04	-0.01	-0.04	-0.04	-0.02	0.02	0.05	0.08	0.078	0.497
30 (90)		0.08	0.13	0.11	0.1	0.05	0.05	0.05	0.1	0.11	0.15	0.18	0.18	0.17	0.15	0.11	0.08	0.04	-0.01	-0.04	-0.04	-0.02	0.02	0.05	0.08	0.078	0.497
35 (10)		0.03	0.06	0.03	0	-0.05	-0.05	-0.06	-0.02	0	0.04	0.06	0.06	0.05	0.04	-0.01	-0.04	-0.08	-0.13	-0.16	-0.16	-0.14	-0.1	-0.07	-0.04	0.031	0.374
35 (20)		0.03	0.06	0.03	0	-0.05	-0.05	-0.06	-0.02	0	0.04	0.06	0.06	0.05	0.04	-0.01	-0.04	-0.08	-0.13	-0.16	-0.16	-0.14	-0.1	-0.07	-0.04	0.031	0.374
35 (30)		0.03	0.06	0.03	0	-0.05	-0.05	-0.06	-0.02	0	0.04	0.06	0.06	0.05	0.04	-0.01	-0.04	-0.08	-0.13	-0.16	-0.16	-0.14	-0.1	-0.07	-0.04	0.031	0.374
35 (40)		0.04	0.07	0.05	0.03	-0.02	-0.02	-0.02	0.02	0.04	0.08	0.11	0.11	0.1	0.08	0.03	0	-0.04	-0.09	-0.12	-0.11	-0.09	-0.05	-0.02	0	0.008	0.329
35 (50)		0.04	0.07	0.05	0.03	-0.02	-0.02	-0.02	0.02	0.04	0.08	0.11	0.11	0.1	0.08	0.03	0	-0.04	-0.09	-0.12	-0.11	-0.09	-0.05	-0.02	0	0.008	0.329
35 (60)		0.04	0.08	0.06	0.05	0	0	-0.01	0.04	0.06	0.1	0.13	0.12	0.12	0.1	0.05	0.02	-0.02	-0.07	-0.1	-0.09	-0.07	-0.03	0	0.02	0.025	0.343
35 (70)		0.04	0.08	0.06	0.05	0	0	-0.01	0.04	0.06	0.1	0.13	0.12	0.12	0.1	0.05	0.02	-0.02	-0.07	-0.1	-0.09	-0.07	-0.03	0	0.02	0.025	0.343
35 (80)		0.05	0.09	0.07	0.05	0.01	0.01	0	0.05	0.07	0.11	0.14	0.13	0.13	0.11	0.06	0.04	-0.01	-0.06	-0.08	-0.08	-0.06	-0.02	0.01	0.04	0.036	0.361
35 (90)		0.05	0.09	0.07	0.05	0.01	0.01	0	0.05	0.07	0.11	0.14	0.13	0.13	0.11	0.06	0.04	-0.01	-0.06	-0.08	-0.08	-0.06	-0.02	0.01	0.04	0.036	0.361
40 (10)		0	0.03	0	-0.03	-0.09	-0.09	-0.1	-0.05	-0.04	0	0.03	0.02	0.02	0	-0.05	-0.08	-0.12	-0.17	-0.2	-0.2	-0.18	-0.14	-0.11	-0.08	0.068	0.486
40 (20)		0	0.03	0	-0.03	-0.09	-0.09	-0.1	-0.05	-0.04	0	0.03	0.02	0.02	0	-0.05	-0.08	-0.12	-0.17	-0.2	-0.2	-0.18	-0.14	-0.11	-0.08	0.068	0.486
40 (30)		0	0.03	0	-0.03	-0.09	-0.09	-0.1	-0.05	-0.04	0	0.03	0.02	0.02	0	-0.05	-0.08	-0.12	-0.17	-0.2	-0.2	-0.18	-0.14	-0.11	-0.08	0.068	0.486
40 (40)		0.01	0.04	0.02	0	-0.05	-0.05	-0.06	-0.01	0	0.04	0.07	0.07	0.06	0.04	0	-0.03	-0.08	-0.13	-0.15	-0.15	-0.13	-0.09	-0.06	-0.03	0.028	0.355
40 (50)		0.01	0.04	0.02	0	-0.05	-0.05	-0.06	-0.01	0	0.04	0.07	0.07	0.06	0.04	0	-0.03	-0.08	-0.13	-0.15	-0.15	-0.13	-0.09	-0.06	-0.03	0.028	0.355
40 (60)		0.01	0.05	0.03	0.01	-0.04	-0.04	-0.04	0	0.02	0.06	0.09	0.09	0.08	0.06	0.02	-0.01	-0.06	-0.11	-0.13	-0.13	-0.11	-0.07	-0.04	-0.01	0.011	0.328
40 (70)		-0.05	0	-0.03	-0.04	-0.06	-0.05	-0.04	0.02	0.05	0.09	0.14	0.15	0.15	0.12	0.09	0.07	0.04	-0.01	-0.05	-0.05	-0.04	0	0.03	0.06	0.025	0.358
40 (80)		0.01	0.05	0.04	0.02	-0.03	-0.03	-0.03	0.01	0.03	0.07	0.1	0.1	0.09	0.07	0.03	0	-0.05	-0.09	-0.12	-0.12	-0.1	-0.06	-0.03	0	0.002	0.318
40 (90)		0.01	0.05	0.04	0.02	-0.03	-0.03	-0.03	0.01	0.03	0.07	0.1	0.1	0.09	0.07	0.03	0	-0.05	-0.09	-0.12	-0.12	-0.1	-0.06	-0.03	0	0.002	0.318
45 (10)		-0.02	0	-0.03	-0.06	-0.12	-0.12	-0.13	-0.09	-0.07	-0.04	-0.01	-0.01	-0.02	-0.04	-0.08	-0.11	-0.16	-0.21	-0.23	-0.23	-0.21	-0.17	-0.14	-0.11	0.100	0.605
45 (20)		-0.02	0	-0.03	-0.06	-0.12	-0.12	-0.13	-0.09	-0.07	-0.04	-0.01	-0.01	-0.02	-0.04	-0.08	-0.11	-0.16	-0.21	-0.23	-0.23	-0.21	-0.17	-0.14	-0.11	0.100	0.605
45 (30)		-0.02	0	-0.03	-0.06	-0.12	-0.12	-0.13	-0.09	-0.07	-0.04	-0.01	-0.01	-0.02	-0.04	-0.08	-0.11	-0.16	-0.21	-0.23	-0.23	-0.21	-0.17	-0.14	-0.11	0.100	0.605
45 (40)		-0.02	0.01	-0.01	-0.03	-0.09	-0.09	-0.09	-0.05	-0.03	0.01	0.03	0.03	0.02	0.01	-0.04	-0.07	-0.11	-0.16	-0.19	-0.19	-0.17	-0.13	-0.1	-0.07	0.064	0.457
45 (50)		-0.02	0.01	-0.01	-0.03	-0.09	-0.09	-0.09	-0.05	-0.03	0.01	0.03	0.03	0.02	0.01	-0.04	-0.07	-0.11	-0.16	-0.19	-0.19	-0.17	-0.13	-0.1	-0.07	0.064	0.457
45 (60)		-0.02	0.02	0	-0.02	-0.07	-0.07	-0.08	-0.03	-0.01	0.03	0.05	0.05	0.04	0.03	-0.02	-0.05	-0.09	-0.14	-0.17	-0.17	-0.15	-0.11	-0.08	-0.05	0.046	0.398
45 (70)		-0.02	0.02	0	-0.02	-0.07	-0.07	-0.08	-0.03	-0.01	0.03	0.05	0.05	0.04	0.03	-0.02	-0.05	-0.09	-0.14	-0.17	-0.17	-0.15	-0.11	-0.08	-0.05	0.046	0.398
45 (80)		-0.01	0.03	0.01	-0.01	-0.06	-0.06	-0.07	-0.02	0	0.04	0.06	0.06	0.05	0.04	-0.01	-0.04	-0.08	-0.13	-0.16	-0.15	-0.13	-0.1	-0.07	-0.04	0.035	0.365
45 (90)		-0.01	0.03	0.01	-0.01	-0.06	-0.06	-0.07	-0.02	0	0.04	0.06	0.06	0.05	0.04	-0.01	-0.04	-0.08	-0.13	-0.16	-0.15	-0.13	-0.1	-0.07	-0.04	0.035	0.365
50 (10)		-0.04	-0.02	-0.06	-0.09	-0.15	-0.15	-0.16	-0.12	-0.1	-0.07	-0.04	-0.04	-0.05	-0.07	-0.11	-0.14	-0.19	-0.24	-0.27	-0.26	-0.24	-0.2	-0.17	-0.14	0.130	0.732
50 (20)		-0.04	-0.02	-0.06	-0.09	-0.15	-0.15	-0.16	-0.12	-0.1	-0.07	-0.04	-0.04	-0.05	-0.07	-0.11	-0.14	-0.19	-0.24	-0.27	-0.26	-0.24	-0.2	-0.17	-0.14	0.130	0.732
50 (30)		-0.04	-0.02	-0.06	-0.09	-0.15	-0.15	-0.16	-0.12	-0.1	-0.07	-0.04	-0.04	-0.05	-0.07	-0.11	-0.14	-0.19	-0.24	-0.27	-0.26	-0.24	-0.2	-0.17	-0.14	0.130	0.732
50 (40)		-0.04	-0.01	-0.04	-0.06	-0.11	-0.11	-0.12	-0.08	-0.06	-0.02	0	0	-0.01	-0.02	-0.07	-0.1	-0.14	-0.19	-0.22	-0.22	-0.2	-0.16	-0.13	-0.1	0.092	0.562
50 (50)		-0.04	-0.01	-0.04	-0.06	-0.11	-0.11	-0.12	-0.08	-0.06	-0.02	0	0	-0.01	-0.02	-0.07	-0.1	-0.14	-0.19	-0.22	-0.22	-0.2	-0.16	-0.13	-0.1	0.092	0.562
50 (60)		-0.04	-0.01	-0.03	-0.05	-0.1	-0.1	-0.11	-0.06	-0.04	0	0.02	0.02	0.01	0	-0.05	-0.08	-0.12	-0.17	-0.2	-0.2	-0.18	-0.14	-0.11	-0.08	0.076	0.496
50 (70)		-0.04	-0.01	-0.03	-0.05	-0.1	-0.1	-0.11	-0.06	-0.04	0	0.02	0.02	0.01	0	-0.05	-0.08	-0.12	-0.17	-0.2	-0.2	-0.18	-0.14	-0.11	-0.08	0.076	0.496
50 (80)		-0.04	0	-0.02	-0.04	-0.09	-0.09	-0.1	-0.05	-0.03	0.01	0.03	0.03	0.02	0.01	-0.04	-0.07	-0.11	-0.16	-0.19	-0.18	-0.17	-0.13	-0.1	-0.07	0.066	0.457
50 (90)		-0.04	0	-0.02	-0.04	-0.09	-0.09	-0.1	-0.05	-0.03	0.01	0.03	0.03	0.02	0.01	-0.04	-0.07	-0.11	-0.16	-0.19	-0.18	-0.17	-0.13	-0.1	-0.07	0.066	0.457

[Note: AVG is the arithmetic average model bias for all interested frequency span.

RMS is the root mean square defined as $\sqrt{(\sum (r^2))/N}$ where r is the model residual for each frequency and N is the number of frequency bin

Figure 5.2 shows the average model bias $\text{Log}(\text{PSA}_{\text{obs}}) - \text{Log}(\text{PSA}_{\text{sim}})$ versus frequency for the calibrated model (stress drop=40 bars and pulsing percentage=80%). For the frequency below 0.8Hz, the model fits the recorded data very well, showing the near zero mean residual. However, the overall residual between 0.8Hz and 2Hz is positive, showing a minor underestimate of the simulated ground motion due to the possible underestimation of the site amplification function (the dominant contributing factor for the underestimation is probably the basin effect around 1 Hz in Taipei basin area, which is discussed in detail later). The residual between 4Hz and 10Hz is negative, demonstrating overestimation from the input model. From another point of view, Figure 5.3 shows the residual distribution over distance for 0.5Hz and Figure 5.4 shows the residual distribution for 1Hz. Figure 5.5 and Figure 5.6 are the residual distribution for 5Hz and 10Hz, respectively. Figure 5.3 has zero mean residual and no trend over distance. Figure 5.4 has positive average residual (about 0.1) but no obvious trend over distance. The positive upward shift of the residual for 1Hz is reasonable. Figure 5.5 and Figure 5.6 both show a downward shift of the model bias but no obvious trend over distance. There is no noticeable trend in the model residual distribution over distance indicating that the attenuation model chosen in this study is reasonable.

Apart from the random slip distribution model (generated randomly by the computer program) used in the above model calibration, the pre-determined slip distribution model by Wang *et al.* (2001) is also used in the simulation to investigate the effect of the rupture process on the simulation. Figure 5.7 is the model bias over frequency, showing a slight downward shift compared with the residual distribution of the random slip distribution model. However, only minor differences appear between Figure 5.2 and Figure 5.7, demonstrating that there is little effect of the rupture pro-

cess on the overall model bias using the finite fault stochastic simulation technique; this was also pointed out by Beresnev and Atkinson (1998b). Meanwhile, the residual distribution versus distance at 0.5Hz (Figure 5.8), 1Hz (Figure 5.9), 5Hz (Figure 5.10) and 10Hz (Figure 5.11) are plotted to investigate the effect of the pre-determined slip model on the model bias, especially on the near source records, which may be significantly controlled by the directivity effect. The above residual distribution versus distance figures of the pre-determined slip model show such effect, especially in the high frequency. Figure 5.12 and Figure 5.13 compare the map view of the model bias for the random slip and prescribed slip models at 1 Hz and 10 Hz, respectively. Generally, these two figures only show some minor difference (the overall bias difference between random slip and pre-determined slip model is small, as discussed above). However, for the near-fault region, the difference is noticeable indicating the possible effect of the slip distribution model on the near-fault stations, especially at high frequency.

The H/V ratio is also used in the simulation to compare the accuracy of the H/V ratio method and the quarter wavelength approximation approach. Parameters used in the simulations remain the same as that in Table 5.1 except κ_0 is set as κ_{0V} and the site amplification is the H/V ratio. Thus, the overall site term is $A(f)_{H/V} \cdot \exp^{-\pi\kappa_{0V}f}$. Figure 5.14 compares the model bias versus frequency using the H/V ratio as the amplification function and the quarter-wavelength estimates as site amplification; this indicates that there is little difference between the two approaches. For low frequencies, there is a downward shift for the H/V ratio model compared with the quarter wavelength approximation model because the site amplification effects derived from the H/V ratio method is larger than that from the quarter wavelength approximation approach (See Figure 4.18). Figure 5.15 and Figure 5.16 are the bias versus distance

at 1 Hz and 5 Hz showing the similar distribution pattern as that in the calibrated model. All in all, the quarter wavelength approximation method is preferred to calculate the site amplification function but it needs the detailed shear wave velocity information for the research region (in most cases, such information is not available). The H/V ratio shows similar applicability as the quarter wavelength approximation approach, according to this study, but it is much more economical than the quarter wavelength approximation method. It could be a suitable candidate for the site amplification calculation when the shear wave velocity information is not available for the research area.

5.3.2 Simulation for linear behavior of soil stations

In this step, the simulation is applied to soil stations (NEHRP class D sites) with the obtained stress drop (40 bars), the pulsing percentage (80%) and other listed parameters in Table 5.1. Different site amplification schemes are used; one based on the quarter wavelength approximation approach and another based on the H/V ratio.

Simulation for soil stations using quarter wavelength approximation as site amplification First, site amplification for NEHRP class D stations calculated by the quarter wavelength approximation method is used in simulations. Figure 5.17 shows the residual distribution over frequency, indicating an underestimation at low frequency but overestimating of ground motions at high frequency. Figure 5.18 and Figure 5.19 plot the residual distribution versus distance at frequency 0.5 Hz and 2 Hz, and show a noticeable upward trend over distance. This might be a manifestation of nonlinear site response, as it indicates relative overestimation of near-source amplitudes at high frequencies.

Simulation for soil stations using H/V ratio as site amplification H/V ratio combined with the vertical kappa operator ($\kappa_{0V} = 0.057$) for NEHRP class D stations, may also be used as the site amplification function in simulations. The residual versus frequency graph (Figure 5.20) shows an improvement compared with Figure 5.17. However, Figure 5.21 and Figure 5.22 still shows evidence of the nonlinear soil response in the Chi-Chi mainshock with the H/V ratio as site amplification, but the effect is smaller than that of quarter wavelength approximation, shown in Figure 5.17. This suggests that the nonlinearity may be similar on both vertical and horizontal components. Thus, degree of most evidence of nonlinearity is cancelled out in the H/V method.

5.3.3 Simulation for non-linear behavior of soil stations

Background theory The above discussion witnesses the possible nonlinear behavior of the soil stations. Thus, in the following session, the nonlinear soil response correction method based on empirical analysis of other earthquakes (Choi and Stewart, 2005) is used and the general methodology of the non-linear correction approach is discussed in detail. Basically, the nonlinear correction approach is based on Equation 5.1:

$$\text{PSA}_{\text{corrected}} = \text{PSA}_{\text{simulated}} \cdot \exp(b_{\text{cor}}) \quad (5.1)$$

where $\text{PSA}_{\text{corrected}}$ is PSA after correction for nonlinearity, $\text{PSA}_{\text{simulated}}$ is the simulated PSA without correction (eg. ground motion simulated at the reference site condition, NEHRP class C, using the calibrated model parameters and then corrected to the desired soil station condition using the correction factor described below). b_{cor} is the correction factor (Equation 5.2 and Equation 5.3) which comprises the linear amplification correction factor and an empirical nonlinear amplification correction

factor derived from a large strong-motion database (Boore and Atkinson, 2005).

$$b_{cor} = b_{lin} \ln(v_{30}/v_{ref}) + b_{nl} \ln(0.06/0.1) \quad \text{for } pga4nl \leq 0.06g \quad (5.2)$$

and

$$b_{cor} = b_{lin} \ln(v_{30}/v_{ref}) + b_{nl} \ln(pga4nl/0.1) \quad \text{for } pga4nl > 0.06g \quad (5.3)$$

where b_{lin} is the linear correction coefficient, v_{30} is the average shear wave velocity of the upper 30 meter layer at stations, v_{ref} is the reference rock station (In this study, $v_{ref}=500$ m/s because $\bar{v}_{30}$ of NEHRP class C sites is equal to 500 m/s in Taiwan). b_{lin} used in this study is published by Choi and Stewart (2005) based on the empirical analysis of many earthquakes (similar linear coefficients were also published by Boore *et al.* (1997) and their comparison is shown in Figure 5.23). b_{nl} is the nonlinear correction coefficient and the $pga4nl$ is the threshold of the peak ground acceleration above which the nonlinear response occurs. The $pga4nl$ value can be obtained by Equation 5.8 (Boore and Atkinson, 2005). b_{nl} could be calculated by Equation 5.4 to 5.7 (Boore and Atkinson, 2005).

$$b_{nl} = b_1 \quad \text{for } v_{30} \leq v_1 \quad (5.4)$$

$$b_{nl} = (b_1 - b_2) \ln(v_{30}/v_2) / \ln(v_1/v_2) + b_2 \quad \text{for } v_1 < v_{30} \leq v_2 \quad (5.5)$$

$$b_{nl} = b_2 \ln(v_{30}/v_{ref}) / \ln(v_2/v_{ref}) \quad \text{for } v_2 < v_{30} \leq v_{ref} \quad (5.6)$$

$$b_{nl} = 0 \quad \text{for } v_{30} > v_{ref} \quad (5.7)$$

where b_1 , b_2 are regression coefficients empirically determined by Choi and Stewart (2005) (See Table 5.3 for details), v_1 , v_2 are the boundary of the piecewise function, v_{30} is the average shear wave velocity of the upper 30 meter at stations, V_{ref} is the

shear wave velocity of the reference rock station (Boore and Atkinson, 2005).

$$\log(\text{pga4nl}) = 2.573 - 0.55 \log(r/5) - 0.005(r - 5) + 0.241\text{eps} \quad \text{for } M_W > 7.0 \quad (5.8)$$

where $r = \sqrt{r_{jb}^2 + 3.0^2}$, r_{jb} is the Joyner-Boore distance and eps is the number of sigmas (=0 for median PGA) and PGA is in cm/s/s (Boore and Atkinson, 2005).

In the following section, firstly, the empirical correction just for the linear case by Boore and Atkinson (2005) from NEHRP class C to NEHRP class D stations will be discussed and then compared with the above two simulations (Quarter wavelength approximation and H/V on NEHRP class D). Secondly, the nonlinear correction scheme based on Boore and Atkinson (2005) are applied to the simulations.

When the simulated PGA value at the station is below the nonlinear threshold (0.06g in this study), only linear correction is considered. Otherwise, the nonlinear correction is applied. Figure 5.24 and Figure 5.25 demonstrate the variation of the linear correction term ($b_{cor(lin)}$), the nonlinear correction term ($b_{cor(nl)}$) and the combined effect of the linear and the nonlinear corrections for two different PGA values (0.05g and 0.15g), respectively. Figure 5.24 shows the linear correction effect because there is no nonlinearity effect for PGA below 0.06g. In Figure 5.25, the linear, nonlinear correction terms and their combination are plotted (PGA=0.15g). Furthermore, the exponential form of the correction term ($\exp^{b_{cor}}$) is shown in Figure 5.26 for PGA=0.15g.

In this section, the above correction terms are applied in the site amplification term for the simulations. First, ground motions at soil stations are generated using the NEHRP class C site amplification (at reference class C site) calculated by quarter wavelength method. Then, only the linear correction term is applied to correct the ground motions which are simulated on reference stations to the desired site conditions

(In this case, it is to eliminate the difference between NEHRP class C stations and NEHRP class D stations based on the empirical analysis using Equation 5.2). For stations whose PGA is smaller than the nonlinearity threshold (0.06g), nonlinear correction has no effect on the ground motions ($\exp^{b_{cor}}$ is equal to 1); while for other stations, nonlinear correction is used to remove the effects of soil nonlinearity.

Empirical linear correction between NEHRP class C and NEHRP class D stations Figure 5.27 shows the model residual distribution versus frequency for the simulated motions with only the linear correction. It shows the near zero residual from low to intermediate frequencies but an overestimation of ground motions at high frequency. Figure 5.28, Figure 5.29, Figure 5.30 and Figure 5.31 are residual distribution over distance at frequency 0.5 Hz, 2 Hz, 5 Hz and 10 Hz. These graphs also suggest soil nonlinearity at near source stations. Then, in the next step, nonlinear correction is added to the site term and its effects on the near-source stations are illustrated in Figure 5.33 to Figure 5.36.

Result of nonlinear correction based on Boore and Atkinson (2005) The nonlinear correction approach uses equation 5.4 to 5.7 to calculate the nonlinear correction coefficient b_{nl} (Boore and Atkinson, 2005). Figure 5.32 shows the model residual distribution over frequency for the nonlinear correction scheme proposed by Boore and Atkinson (2005). Figure 5.33, Figure 5.34, Figure 5.35 and Figure 5.36 show the model bias distribution versus distance and its least square regressed trend at 0.5 Hz, 2 Hz, 5 Hz and 10 Hz, respectively. Comparison between model residual distribution before nonlinear correction (only linear correction is applied) in Figure 5.28- 5.31 and after nonlinear correction (linear correction and nonlinear correction are both applied) in Figure 5.33- 5.36 clearly shows the nonlinear behaviour of

soil sites in the near-fault region.

In conclusion, comparing Figure 5.32 with Figure 5.17 and according to the simulation results of the soil stations based on the above four models, we may conclude that:

1. There is nonlinear soil behavior at near-fault stations during the Chi-Chi mainshock based on site amplification modeling for NEHRP class D sites (quarter wavelength approximation and H/V).
2. The empirical linear correction term performs well for low and intermediate frequencies but shows overestimation of ground motions at high frequency. It also shows the soil nonlinearity effect during the Chi-Chi mainshock.
3. The nonlinear correction scheme based on Boore and Atkinson (2005) shows a noticeable correction effect in the near source stations, but for the far field, there is an over-correction trend.

Basin Effects As noticed by Fletcher and Wen (2005), the PGA and PGV value of the seismic records in the Taipei basin were significantly amplified during the 1999 Chi-Chi mainshock. In this study, the extended fault simulation method is applied to the soil stations (NEHRP class D) located in the Taipei basin to see whether the basin effect is significant for PSA as well and at which frequencies the basin effect significantly amplifies the motions. Figure 5.37 shows a topographic map of the Taipei metropolitan area. In this study, about 24 soil stations (NEHRP class D) located in Taipei basin are used (up-triangle in Figure 5.37). According to the geological province map of Taiwan (see Figure 2.13), Taipei basin is located in Holocene Alluvium which is one of the softest layers in Taiwan. The procedure of the simulation for the soil stations in Taipei basin is the same as that for nonlinearity

correction, that is, the ground motion at these soil stations was simulated using the reference site amplification function (NEHRP class C) and then the linear, nonlinear corrections are applied just to stations located in the Taipei basin. Figure 5.38 is the model bias of the simulation indicating a strong basin amplification between 0.4 Hz and 2 Hz, especially around 1 Hz, for high frequencies the effect is not significant. Figure 5.40, Figure 5.41 and Figure 5.42 are the model bias versus distance for 0.5 Hz, 1 Hz and 10 Hz respectively. These three figures clearly demonstrate the basin effect of the soil stations in the Taipei basin, for low to intermediate frequencies.

If I subtract the bias given by Figure 5.32 from bias given by Figure 5.38, the basin effect is separated out from the nonlinear effect, on average. Thus, the basin effect, by itself, is given in Figure 5.39.

Table 5.3: Linear and nonlinear correction coefficients used in this study. After Choi and Stewart (2005).

Period (sec)	c	b_1	b_2
0.01	-0.36 ± 0.06	-0.64	-0.14 ± 0.04
0.02	-0.34 ± 0.06	-0.63	-0.12 ± 0.04
0.03	-0.33 ± 0.06	-0.62	-0.11 ± 0.04
0.04	-0.31 ± 0.06	-0.61	-0.11 ± 0.04
0.05	-0.29 ± 0.06	-0.64	-0.11 ± 0.04
0.06	-0.25 ± 0.06	-0.64	-0.11 ± 0.04
0.075	-0.23 ± 0.06	-0.64	-0.11 ± 0.04
0.09	-0.23 ± 0.07	-0.64	-0.12 ± 0.04
0.1	-0.25 ± 0.07	-0.6	-0.13 ± 0.04
0.12	-0.26 ± 0.07	-0.56	-0.14 ± 0.04
0.15	-0.28 ± 0.07	-0.53	-0.18 ± 0.04
0.17	-0.29 ± 0.07	-0.53	-0.19 ± 0.04
0.2	-0.31 ± 0.07	-0.52	-0.19 ± 0.04
0.24	-0.38 ± 0.07	-0.52	-0.16 ± 0.04
0.3	-0.44 ± 0.07	-0.52	-0.14 ± 0.05
0.36	-0.48 ± 0.07	-0.51	-0.11 ± 0.05
0.4	-0.5 ± 0.07	-0.51	-0.1 ± 0.05
0.46	-0.55 ± 0.07	-0.5	-0.08 ± 0.05
0.5	-0.6 ± 0.07	-0.5	-0.06 ± 0.05
0.6	-0.66 ± 0.07	-0.49	-0.03 ± 0.05
0.75	-0.69 ± 0.07	-0.47	0 ± 0.05
0.85	-0.69 ± 0.07	-0.46	0 ± 0.05
1	-0.7 ± 0.07	-0.44	0 ± 0.05
1.5	-0.72 ± 0.08	-0.4	0 ± 0.06
2	-0.73 ± 0.08	-0.38	0 ± 0.06
3	-0.74 ± 0.09	-0.34	0 ± 0.07
4	-0.75 ± 0.09	-0.31	0 ± 0.07
5	-0.75 ± 0.14	-0.3	0 ± 0.11

Figure 5.1. Model bias comparison for models with different stress drop (the stress drop increases from 20 bars to 100 bars with step 10 bars) but fixed pulsing percentage (50%)

Figure 5.2. Model bias for the preferred model on rock stations (NEHRP class C) with stress drop = 40 bars and pulsing percentage = 80%; RMS is the root mean square of the model bias

Figure 5.3. Model bias versus distance for the preferred model (NEHRP class C) at 0.5 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.4. Model bias versus distance for the preferred model (NEHRP class C) at 1 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.5. Model bias versus distance for the preferred model (NEHRP class C) at 5 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.6. Model bias versus distance for the preferred model (NEHRP class C) at 10 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.7. Model bias for the preferred model on rock stations (NEHRP class C) using the pre-determined slip model (stress drop = 40 bars, pulsing percentage = 80%); RMS is the root mean square of the model bias

Figure 5.8. Model bias versus distance for the pre-determined slip model (NEHRP class C) at 0.5 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.9. Model bias versus distance for pre-determined slip model (NEHRP class C) at 1 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.10. Model bias versus distance for pre-determined slip model (NEHRP class C) at 5 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.11. Model bias versus distance for pre-determined slip model (NEHRP class C) at 10 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.12. (a) Map view of the model bias for the preferred model (NEHRP class C) using the random slip distribution model (1 Hz) (b) Map view of the model bias for the preferred model (NEHRP class C) using the pre-determined slip distribution model (1 Hz); the rectangle is the fault plane (Wang *et al.*, 2001)

Figure 5.13. (a) Map view of the model bias for the preferred model (NEHRP class C) using the random slip distribution model (10 Hz) (b) Map view of the model bias for the preferred model (NEHRP class C) using the pre-determined slip distribution model (10 Hz); the rectangle is the fault plane (Wang *et al.*, 2001)

Figure 5.14. Comparison of the model bias for the models with H/V ratio as site amplification and with quarter wavelength approximation as site amplification (stress drop = 40 bars, pulsing percentage = 80%); RMS is the root mean square of the model bias

Figure 5.15. Model bias versus distance for the preferred model (NEHRP class C) using H/V as site amplification at 1 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.16. Model bias versus distance for the preferred model (NEHRP class C) using H/V as site amplification at 5 Hz (stress drop = 40 bars, pulsing percentage = 80%)

Figure 5.17. Model bias versus frequency for soil stations (NEHRP class D sites) using linear site amplification factor calculated by quarter wavelength approximation; RMS is the root mean square of the model bias

Figure 5.18. Model bias versus distance for soil stations (NEHRP class D sites) using linear site amplification factor calculated by quarter wavelength approximation (0.5 Hz)

Figure 5.19. Model bias versus distance for soil stations (NEHRP class D sites) using linear site amplification factor calculated by quarter wavelength approximation (2 Hz)

Figure 5.20. Model bias versus frequency for soil stations (NEHRP class D sites) using H/V ratio as site amplification factor; RMS is the root mean square of the model bias

Figure 5.21. Model bias versus distance for soil stations (NEHRP class D sites) using H/V ratio as site amplification factor (0.5 Hz)

Figure 5.22. Model bias versus distance for soil stations (NEHRP class D sites) using H/V ratio as site amplification factor (2 Hz)

Figure 5.23. Comparison of the linear correction coefficient function between Boore *et al.* (1997) and Choi and Stewart (2005).

Figure 5.24. Comparison of linear and nonlinear correction term for PGA=0.05g based on Boore and Atkinson (2005) (5Hz)

Figure 5.25. Comparison of linear and nonlinear correction term for PGA=0.15g based on Boore and Atkinson (2005) (5Hz)

Figure 5.26. Comparison of the exponential form of the linear and nonlinear correction term for PGA=0.15g based on Boore and Atkinson (2005) (5Hz)

Figure 5.27. Model bias versus frequency for soil stations (NEHRP class D sites) using only linear correction by Boore and Atkinson (2005); RMS is the root mean square of the model bias

Figure 5.28. Model bias versus distance for soil stations (NEHRP class D sites) after linear correction (0.5 Hz) using Boore and Atkinson (2005) method

Figure 5.29. Model bias versus distance for soil stations (NEHRP class D sites) after linear correction (2 Hz) using Boore and Atkinson (2005) method

Figure 5.30. Model bias versus distance for soil stations (NEHRP class D sites) after linear correction (5 Hz) using Boore and Atkinson (2005) method

Figure 5.31. Model bias versus distance for soil stations (NEHRP class D sites) after linear correction (10 Hz) using Boore and Atkinson (2005) method

Figure 5.32. Model bias versus frequency for soil stations (NEHRP class D sites) using nonlinear correction by Boore and Atkinson (2005); RMS is the root mean square of the model bias

Figure 5.33. Model bias versus distance for soil stations (NEHRP class D sites) after linear and nonlinear correction (0.5 Hz) using Boore and Atkinson (2005) method

Figure 5.34. Model bias versus distance for soil stations (NEHRP class D sites) after linear and nonlinear correction (2 Hz) using Boore and Atkinson (2005) method

Figure 5.35. Model bias versus distance for soil stations (NEHRP class D sites) after linear and nonlinear correction (5 Hz) using Boore and Atkinson (2005) method

Figure 5.36. Model bias versus distance for soil stations (NEHRP class D sites) after linear and nonlinear correction (10 Hz) using Boore and Atkinson (2005) method

Figure 5.37. Topographic map of Taipei region, the up-triangles are NEHRP class D sites while the circles are NEHRP class C sites

Figure 5.38. Model bias versus frequency for soil stations (NEHRP class D sites) in the Taipei basin using nonlinear correction method by Boore and Atkinson (2005)

Figure 5.39. Model bias versus frequency for soil stations (NEHRP class D sites) in the Taipei basin using nonlinear correction method by Boore and Atkinson (2005) (This map is the residual in Figure 5.38 minus that of Figure 5.32, demonstrating the net basin effect.)

Figure 5.40. Model bias versus distance for soil stations (NEHRP class D sites) in the Taipei basin (0.5Hz) using nonlinear correction method by Boore and Atkinson (2005)

Figure 5.41. Model bias versus distance for soil stations (NEHRP class D sites) in the Taipei basin (1Hz) using nonlinear correction method by Boore and Atkinson (2005)

Figure 5.42. Model bias versus distance for soil stations (NEHRP class D sites) in the Taipei basin (10Hz) using nonlinear correction method by Boore and Atkinson (2005)

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The finite-fault stochastic simulation technique is a robust method which can simulate the dominant characteristics of earthquake ground motions in the frequency and time domains. It has been validated in Puerto Rico (Motazedian, 2002), California (Motazedian and Atkinson, 2005) and then in this study. The seismological model to specify the spectrum of subfaults is the key factor in the stochastic modeling. In this study, most of the model parameters (Seismic wave propagation property, quality factor, high frequency diminution operator, ground motion duration and site amplification function) were first derived empirically using the recorded ground motion data. The model was then applied to the rock stations (NEHRP class C sites) and soil stations (NEHRP class D sites). Comparison of simulated motions to observations leads to the following conclusions:

1. The stress parameter of the 1999 Chi-Chi mainshock, characterizing high-frequency radiation, is about 40 bars. The pulsing percentage of the rupture is above 80%.
A stress drop of 40 bars is relatively low compared to typical values of 50 to 70 bars for California earthquakes (eg. (Atkinson and Silva, 1997)).
2. The horizontal κ_0 value is 0.065 for rock and soil stations, which is significantly larger than that for California ($\kappa_0=0.035$ (Boore and Joyner, 1997)).

3. The site amplification function based on the quarter wavelength approximation method for NEHRP class C sites of Taiwan is very close to that of California.
4. The H/V ratio may also be used as a site amplification function in the simulations. The model bias indicates that the H/V ratio approach and the quarter wavelength approximation method are equivalent in terms of overall performance. Thus the H/V ratio approach could be an economical alternative to the quarter wavelength approximation method for areas where shear-wave velocity profiles are not available.
5. The slip distribution model has little overall effect on the accuracy of the simulated ground motions but may significantly affect the predicted motions at near-source stations due to the directivity effect.
6. Simulation results suggest significant soil nonlinearity for near-fault sites for the Chi-Chi mainshock for soil stations.
7. Basin effects are observed for soil stations in Taipei basin area, for ground motions of intermediate frequencies (around 1 Hz). This could result in significant damage to structures in the Taipei metropolitan region during future great earthquakes and needs to be carefully considered in the building code.

6.2 Future Work

The following are possible future research directions for the extended fault simulation technique in Taiwan Island.

- The extended stochastic simulation method can be further validated by the aftershock events of the 1999 Chi-Chi earthquake. By analyzing the aftershock

records, the attenuation characteristics and quality factor (Q) of Taiwan can be better understood.

- The results of the extended stochastic simulation technique could be improved by including the impulsive behavior of the ground motion especially for near-source records, since the impulsive behavior was observed in the 1999 Chi-Chi earthquake (eg. station TCU052). Methods to include these effects are described by Mavroeidis and Papageorgiou (2003) and incorporated into the EXSIM code of Motazedian and Atkinson (2005).
- The directivity effects of the ground motion could be analyzed by comparison of the durations of simulated seismograms and the recorded ones.

REFERENCES

- Aki, K.** (1966). Generation and propagation of G waves from the Niigata earthquake of June 16, 1964. Part 2. Estimation of earthquake moment, released energy, and stress-strain drop from the G wave spectrum. *Bull. Earthq. Res. Inst.* **44**, 73–88.
- Aki, K.** (1967). Scaling law of seismic spectrum. *J. Geophys. Res.* **72**, 1217–1231.
- Anderson, J. and Hough, S.** (1984). A model for the shape of the Fourier amplitude spectrum of acceleration at high frequency. *Bull. Seism. Soc. Am.* **74**, 1969–1339.
- Atkinson, G.** (2004). Empirical attenuation of ground-motion spectral amplitudes in southeastern Canada and the northeastern United States. *Bull. Seism. Soc. Am.* **94**, 1079 – 1095.
- Atkinson, G. and Boore, D.** (1995). New ground motion relations for Eastern North America. *Bull. Seism. Soc. Am.* **85**, 17–30.
- Atkinson, G. and Boore, D.** (1997). Stochastic point-source modeling of ground motions in the Cascadia region. *Seism. Res. Lett.* **68**, 74–85.
- Atkinson, G. and Silva, W.** (1997). Empirical source spectra for California earthquakes. *Bull. Seism. Soc. Am.* **87**, 97–113.
- Atkinson, G. and Silva, W.** (2000). Stochastic modeling of California ground motions. *Bull. Seism. Soc. Am.* **90**, 255–274.
- Beresnev, I. and Atkinson, G.** (1997). Modeling finite fault radiation from the w^n spectrum. *Bull. Seism. Soc. Am.* **87**, 67–84.
- Beresnev, I. and Atkinson, G.** (1998a). FINSIM—a FORTRAN program for simulating stochastic acceleration time histories from finite faults. *Seism. Res. Lett.* **67**, 27–32.
- Beresnev, I. and Atkinson, G.** (1998b). Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California, earthquake. I. Validation on rock sites. *Bull. Seism. Soc. Am.* **88**, 1392–1401.
- Beresnev, I. and Atkinson, G.** (1999). Generic finite-fault model for ground-motion prediction in Eastern North America. *Bull. Seism. Soc. Am.* **89**, 608–625.

- Boatwright, J. and Choy, G.** (1992). Acceleration source spectra for large earthquakes in northeastern North America. *Bull. Seism. Soc. Am.* **82**, 660–682.
- Boore, D.** (1983). Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. *Bull. Seism. Soc. Am.* **73**, 1865–1894.
- Boore, D.** (1996). SMSIM - FORTRAN programs for simulating groundmotions from earthquakes: version 1.0. Open - File Rept. 96-80-A (text) and 96-80-B (diskette) 73P., U.S. Geol. Surv.
- Boore, D. and Atkinson, G.** (1987). Stochastic prediction of ground motion and spectral response parameters at hard-rock sites in Eastern North America. *Bull. Seism. Soc. Am.* **77**, 440–467.
- Boore, D. and Atkinson, G.** (2005). Provisional ground-motion prediction equations. Technical report, PEER.
- Boore, D. and Joyner, W.** (1997). Site amplification for generic rock sites. *Bull. Seism. Soc. Am.* **87**, 327–341.
- Boore, D., Joyner, W. and Fumal, T.** (1997). Equations for estimating horizontal response spectral and peak acceleration from western North American earthquakes: A summary of recent work. *Seism. Res. Lett.* **68**, 128–153.
- Boore, D. M.** (2003). Simulation of ground motion using the stochastic method. *Pure and Applied Geophysics* **160**, 635–675.
- Borcherdt, R.** (1995). Estimates of site-dependent response spectra for design. *Earthquake Spectra* **10**, 617–654.
- Bracewell, R. N.** (2000). *The Fourier transform and its applications*. Boston: McGraw Hill.
- Brune, J. N.** (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes. *J. Geophys. Res.* **75**, 4997–5009.
- Castro, R., Rovelli, A., Cocco, M., Di Bona, M. and Pacor, F.** (2001). Stochastic simulation of strong-motion records from the 26 September 1997 (m_w 6), Umbria-Marche (Central Italy) earthquake. *Bull. Seism. Soc. Am.* **91**, 27–39.
- CENTRAL GEOLOGICAL SURVEY (MOEA)** (2006). General geology and geologic provinces of taiwan. URL: (http://www.moeacgs.gov.tw/english/twgeol/twgeol_generalgeol.jsp). Webpage.

- Central Weather Bureau (Taiwan)** (2006). Destructive earthquakes in the 20th century (1900-1999). URL: (http://scman.cwb.gov.tw/eqv5/damage_list/1900after.htm). Webpage.
- Choi, Y. and Stewart, J.** (2005). Nonlinear site amplification as function of 30 m shear wave velocity. *Earthquake Spectra* **21**, 1–30.
- Fletcher, J. and Wen, K.-L.** (2005). Strong ground motion in the Taipei basin from the 1999 Chi-Chi, Taiwan, earthquake. *Bull. Seism. Soc. Am.* **95**, 1428–1446.
- Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., S., H. and Hopper, M.** (1996). National seismic hazard maps: Documentation. Open-File Rept 69, U.S. Geol. Surv.
- Haddon, R.** (1996). Earthquake source spectra in Eastern North America. *Bull. Seism. Soc. Am.* **86**, 1300–1313.
- Hanks, T.** (1982). f_{max} . *Bull. Seism. Soc. Am.* **72**, 1867–1879.
- Institute of Earth Sciences, Academia Sinica (Taipei)** (2006). Tectonic framework and seismotectonics of taiwan. URL: (http://www.earth.sinica.edu.tw/921/921chichi.tectonics_eng.htm). Webpage.
- Irikura, K., Kamae, K. and Dalguer, L.** (2000). Source model for simulating ground motion during the 1999 Chi-Chi earthquake. *Earthquake Engineering and Engineering Seismology*. **2**, 1–14.
- Kikuchi, M., Yagi, Y. and Yamanaka, Y.** (2000). Source process of Chi-Chi, Taiwan earthquake of September 21, 1999 inferred from teleseismic body waves. *Bull. Earthq. Res. Inst. Univ. Tokyo* **75**, 1–13.
- Lachet, C. and Bard, P.** (1994). Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique. *J. Phy. Earth.* **42**, 377–397.
- Lee, C.-T., Cheng, C.-T., Liao, C.-W. and Tsai, Y.-B.** (2001a). Site classification of Taiwan free-field strong-motion stations. *Bull. Seism. Soc. Am.* **91**, 1283–1297.
- Lee, W., Shin, T., Kuo, K. and Chen, K.** (1999). CWB free-field strong-motion data from the 921 Chi-Chi earthquake. Technical report, Seismology Center, Central Weather Bureau, Seismology Center, Central Weather Bureau, Taipei, Taiwan.
- Lee, W., Shin, T., Kuo, K., Chen, K. and Fu, C.** (2001b). CWB free-field strong-motion data from the 21 September Chi-Chi, Taiwan, earthquake. *Bull. Seism. Soc. Am.* **2**, 134–142.

- Lermo, J. and Chavez-Garcia, F. J.** (1994). Are micro-tremors useful in site response evaluation? *Bull. Seism. Soc. Am.* **84**, 1350–1364.
- Liu, K.-S. and Tsai, Y.-B.** (2005). Attenuation relationship of peak ground acceleration and velocity for crustal earthquakes in Taiwan. *Bull. Seism. Soc. Am.* **95**, 1045–1058.
- Mavroeidis, G. P. and Papageorgiou, A. S.** (2003). A mathematical representation of near-fault ground motions. *Bull. Seism. Soc. Am.* **93**, 1099–1131.
- Motazedian, D.** (2002). *Development of Earthquake Ground Motion Relations for Puerto Rico*. Ph.D. thesis, Carleton University.
- Motazedian, D. and Atkinson, G.** (2005). Stochastic finite-fault modeling based on a dynamic corner frequency. *Bull. Seism. Soc. Am.* **95**, 995–1010.
- Nakamura, Y.** (1989). A method for dynamic characteristics estimation of subsurface using micro-tremor on ground surface. *QR RTRI*. **30**, 25–33.
- Pacor, F., Cultrera, G., A., M. and Cocco, M.** (2005). Finite fault modeling of strong ground motion using a hybrid deterministic-stochastic approach. *Bull. Seism. Soc. Am.* **95**, 225–240.
- Papageorgiou, A. and Aki, K.** (1983). A specific barrier for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion. II. Application of the model. *Bull. Seism. Soc. Am.* **73**, 953–978.
- PEER** (2005). Source parameters of 1999 Chi-Chi earthquake. Technical report, PEER.
- Phung, V., Atkinson, G. and Lau, D.** (2004). Methodology for site classification using strong ground motion data from the 1999 Chi-Chi, Taiwan earthquake. Vancouver, B.C., Canada: 13th World Conference on Earthquake Engineering.
- Roumelioti, Z. and Beresnev, I.** (2003). Stochastic finite-fault modeling of ground motions from the 1999 Chi-Chi, Taiwan, earthquake: Application to rock and soil sites with implications for nonlinear site response. *Bull. Seism. Soc. Am.* **93**, 1691 – 1702.
- Roumelioti, Z. and Kiratzi, A.** (2002). Stochastic simulation of strong-motion records from the 15 April 1979 (M 7.1) montenegro earthquake. *Bull. Seism. Soc. Am.* **92**, 1095–1101.

Schneider, J., Silva, W. and Stark, C. (1993). Ground motion model for the 1989 M 6.9 Loma Prieta earthquake including effects of source, path, and site. *Earthquake Spectra* **9**, 251–287.

Shin, T.-C. and Teng, T.-l. (2001). An overview of the 1999 Chi-Chi, Taiwan, earthquake. *Bull. Seism. Soc. Am.* **91**, 895–913.

Sokolov, V. Y., Loh, C.-H. and Wen, K.-L. (2002). Comparison of the Taiwan Chi-Chi earthquake strong-motion data and ground-motion assessment based on spectral model from smaller earthquakes in Taiwan. *Bull. Seism. Soc. Am.* **92**, 1855–1877.

Wang, W.-H., Chang, S.-H. and Chen, C.-H. (2001). Fault slip inverted from surface displacements during the 1999 Chi-Chi, Taiwan, earthquake. *Bull. Seism. Soc. Am.* **91**, 1167–1181.

APPENDIX A

SAMPLE SIMULATED ACCELEROGRAMS

The following section demonstrates the comparison of two sample simulated accelerograms and recorded accelerograms (two horizontal components) at station ALS and station HWA056.

- Figure A.1: Station ALS – Near fault station with epicentral distance 38.8km and fault-station distance 10.8km
- Figure A.2: Station HWA056 – Intermediate distance station with epicentral distance 80.3km and fault-station distance 41.1km:

Figure A.1. Comparison of simulated accelerogram and recorded accelerogram at station ALS

Figure A.2. Comparison of simulated accelerogram and recorded accelerogram at station HWA056