ATTENUATION RELATIONSHIPS OF THE GROUND MOTION PARAMETERS CONSIDERING DIRECTIVITY EFFECTS IN THE 1999 CHI-CHI, TAIWAN EARTHQUAKE

Khosrow T. SHABESTARI [1] and Fumio YAMAZAKI[2]

ABSTRACT

In this study the characteristics of the near-fault strong ground motion records of the 1999 Chi-Chi, Taiwan earthquake (M_w=7.6), which caused severe damages to the structures and infrastructures, are investigated. The attenuation relationships of the ground motion parameters such as Peak Ground Acceleration (*PGA*), Peak Ground Velocity (*PGV*), Spectrum Intensity (*SI*), and the Japan Meteorological Agency (JMA) instrumental seismic intensity (I_{JMA}) for the hanging wall and the footwall stations of the Seismological Center of Central Weather Bureau of Taiwan (CWB) records are proposed. The results indicate that both the JMA seismic intensity and *SI* are not affected by long period contents of the velocity time histories, which are dominant in the near-field records. Since the 1999 Chi-Chi, Taiwan earthquake has provided a reliable strong ground motion data set, especially for the near-fault records, the attenuation relations of the acceleration response spectra in the maximum velocity direction and its perpendicular direction and the horizontal components considering rupture directivity effects are developed, using the Somerville et al. 1997 rupture directivity model. The proposed spectral attenuation models as well as the empirical attenuation relations of *SI* and I_{JMA} can be used in seismic hazard assessment studies and building code revision procedures.

Introduction

The powerful earthquake struck central western Taiwan nucleated under Chi-Chi town on September 21, 1999. Due to the fault plane solution and the field investigation, this event is characterized by the low-angle thrust faulting system named Chelungpu fault (Lee et al. 1999, Lee and Shin 2001). The main rupture propagated from the south to the north with a length of 100 km and width of 40 km with the maximum slip distribution (asperity) of 9 meters that concentrated in the northern part of the Chelungpu fault (Yagi and Kikuchi 1999). The strong ground motion records from the world densest network of CWB in this event provide us an unusual opportunity to investigate the characteristics of near-source ground motion. The fault

[1]Research Scientist, Earthquake Disaster Mitigation Research Center, NIED, 2465-1 Miki, Hyogo, 673-0433, Japan
[2]Professor, STAR/SAT, Asian Institute of Technology, P.O.Box.4, Klong Luang, Pathumthani 12120, Thailand

geometry (the rupture directivity and hanging wall effects) as well as the dynamic rupture process on the upper fractured-crust (Zhao et al. 1996, Chen et at. 2001) during the Chi-Chi earthquake influences the spatial ground motion distribution of near-fault region (Somerville 2000). Many researchers have developed empirical relationships, expressed in the forms of predicted equations to estimate ground motions in terms of magnitude, distance, local site conditions, and other variables using the specific tectonic setting or the worldwide data set (Abrahamson and Silva 1997, Somerville et al. 1997, Campbell 1981, Sokolov et al. 2001). In this study since we have a numerous number of the near-field records during the 1999 Chi-Chi earthquake, the attenuation characteristics of the hanging wall and the footwall regions are examined. The frequency-dependence directivity characteristics of the proper stations, which have experienced the rupture directivity effect, are investigated. Then the directivity function is calculated using the Somerville et al. 1997 model for the each selected station. The result of the proposed response spectra attenuation is compared with the empirical response spectra of Abrahamson and Silva 1997.

Near-Fault Strong Motion Characteristics

Since some of the near-fault ground motions are characterized by long-period, pulse-like time histories, an appropriate baseline correction scheme was used to preserve these important near-field motion characteristics (Boore 1999). As shown in Fig. 1 at TCU052 and TCU068 stations in the northeast hanging-wall side of Chelungpu fault, the *PGV* reached as large as 266 cm/s and 384 cm/s, respectively. On the contrary, at TCU129 station in the southern footwall side of the fault, the *PGV* observed as 79 cm/s, while its *PGA* reached more than 980 cm/s^2. In spite of these large *PGV* values, structural damages around the instruments were not so severe. This is due to the fact that the period of the pulse was much larger than the natural periods of the nearby structures. Since the *PGV* is affected by such a long period content, it is sometimes not a reliable parameter to express structure damages. In Japan, since 1996, the JMA intensity scale was revised and a large number of seismometers measuring the JMA intensity were deployed throughout Japan (JMA 1996, Yamazaki 2001, Shabestari and Yamazaki 2001). The spectrum intensity (*SI*) is one of the ground motion indices that is used to estimate the structural damage due to earthquake (Shimizu et al. 2000). In this study the *SI* values are computed for each 1-degree on the horizontal plane and the maximum of them is defined as the *SI*. The distribution between the *SI* and *PGV* is shown in Fig. 2 for the Chi-Chi earthquake. Although, in most cases the *SI* value is close to the PGV, a large difference is observed for some near-fault stations (e.g. TCU068, TCU052). This observation can be explained by the fact that the long period contents larger than 2.5s are dominant in these records. Since the *SI* is obtained as the average amplitude of the velocity response between 0.1s and 2.5s, it does not reflect such long period contents. In order to demonstrate the characteristics of near-fault strong motion from the large crustal earthquake, the resultant velocity time histories of two horizontal components on the horizontal plane between 0^0-360^0 are calculated for the near fault stations. The difference in the amplitudes of strike-normal and strike-parallel components is a very important characteristic of the near-fault ground motion records (Somerville et al. 1997, Somerville 2000). The maximum velocity direction is observed as normal to the fault for both the hanging wall stations (TCU068 and TCU072) and footwall stations (TCU0129, TCU076, TCU075, TCU065, TCU067, and TCU054), but their directions are opposite.

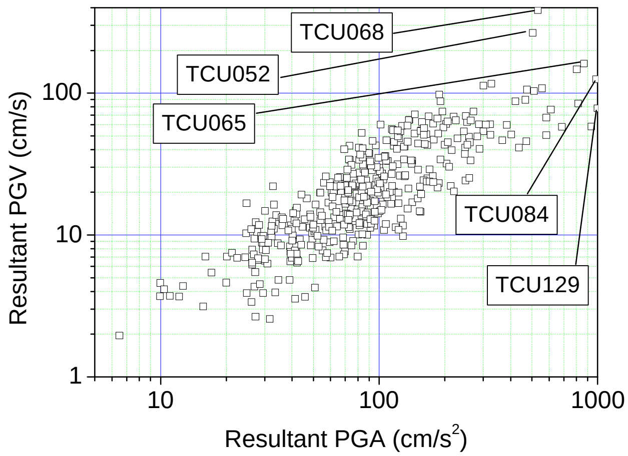

Figure 1. The relation between resultants PGV and PGA for the 1999 Chi-Chi earthquake.

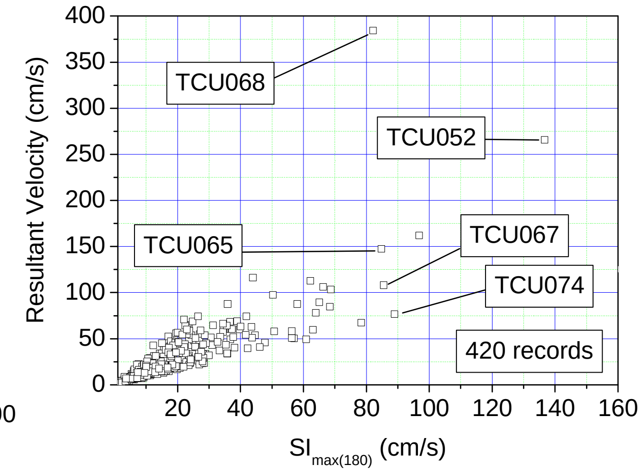

Figure 2. Resultant peak ground velocity with respect to the spectral intensity.

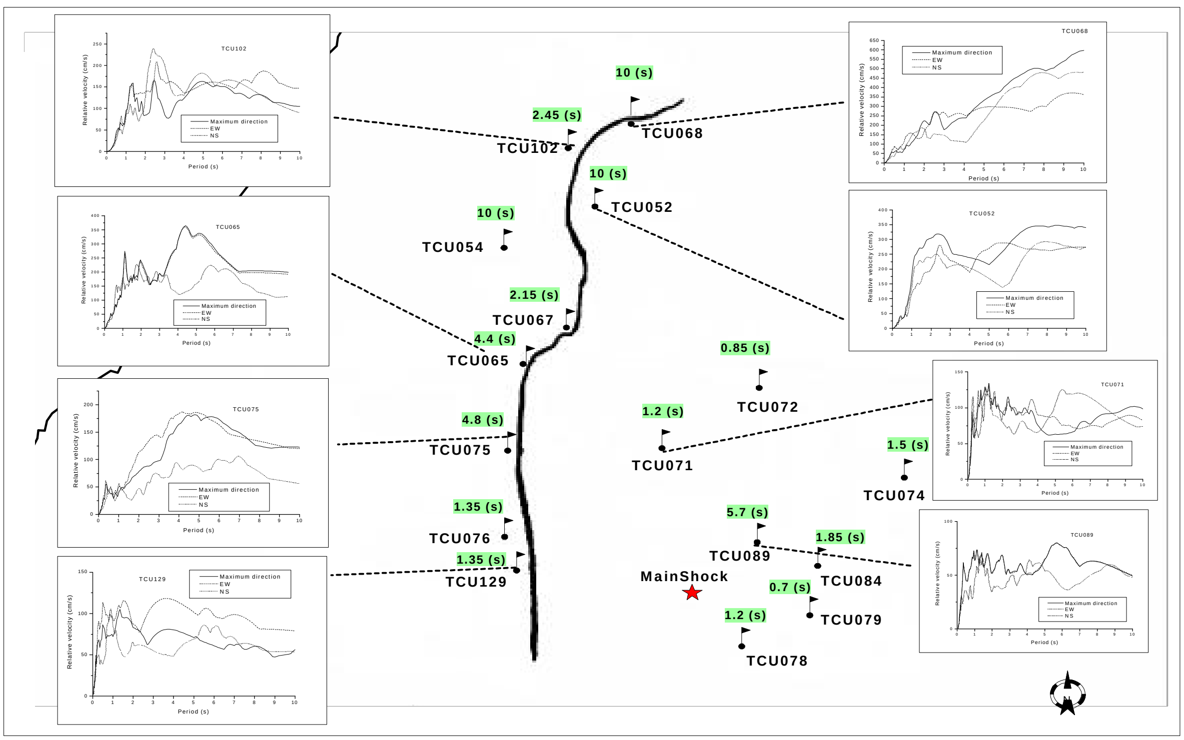

Figure 3. Distribution of the predominant period for the sixteen near-fault stations and the velocity response spectra for these stations.

To investigate the damage potential in terms of frequency contents for those important records, the velocity response spectra with 0.05 damping for the two horizontal components and the maximal velocity direction were calculated from the acceleration records. Figure 3 shows the predominant period of the velocity response spectra to the maximal velocity direction for some near-fault stations. From this figure, the effect of the pulse motion is clearly seen in the velocity response spectra. The predominant period becomes longer as the stations go to the north along the fault (mainly due to the fling effect and the rupture propagation): about 1-2s for TCU076 and TCU129, about 4-5s for TCU075 and TCU065, and about 10s for TCU052 and TCU068.

Attenuation Relationships of the Ground Motion Parameters

The catastrophic 1999 Chi-Chi, Taiwan earthquake, which caused severe damage to structures and lifeline facilities, provided reliable strong ground motion records especially at the near-fault stations. In this study the attenuation relationships for the I_{JMA}, as well as other ground motion parameters such as *SI*, *PGA*, and *PGV* are calculated for the free-field acceleration records of the CWB of Taiwan, which are located in the hanging wall and footwall sites within the sixty kilometers closest distance to the seismogenic part of the fault plane (Campbell 1987). The final data set contains ninety-five (95) pairs of the three-component acceleration records. The closest distance from each recording station to the seismogenic rupture plane is calculated using the USGS fault plane solution (Lee and Shin 2001). Then the attenuation relationships for the ground motion parameters in the 1999 Chi-Chi earthquake are developed considering a near-source saturation effect.

Attenuation Model

The attenuation model considering the near-source saturation effect for the strong ground motion indices is given by

$$y = b_0 + b_1 r + b_2 \log_{10}(r + d) + e \qquad (1)$$

in which y is $\log_{10}PGA$, $\log_{10}PGV$, $\log_{10}SI$, or the I_{JMA}, r is the closest distance to the seismogenic part of the fault plane, b_i's are the regression coefficients to be determined, d is the near-source saturation effect in kilometer, and e represents the error term. The terms $b_1 r$ and $b_2\log_{10}(r+d)$ represent anelastic attenuation and geometric spreading, respectively. The near-source saturation term (d) is applied only for the geometric spreading term. This is because in the near-source, anelastic attenuation is negligible compared with geometric spreading. Since the near-source data used in this study is from a single earthquake, the saturation effect term (d) assumed to be constant. A non-linear least square analysis for the 1999 Chi-Chi, Taiwan earthquake was performed to estimate d. This was accomplished by iterating to find d where the sum of squares of errors was minimized. The error term is defined as the difference between the predicted ground motion parameters by Eq. (1) for a trial value of d and the corresponding recorded ground motion indices.

Results of the Regression Analysis

The results of regression analysis for the ground motion parameters for this earthquake are given in Table 1. Figure 4 shows the predicted PGA_{result} (resultant of two horizontal components), PGV_{result}, *SI*, and I_{JMA} by the attenuation relationships for the hanging wall and footwall stations. Since the 1999 Chi-Chi earthquake provides a useful strong ground motion data set especially near the fault region, the near-source saturation effect (d) has been taken into account. However, since the near-field data in this study is limited to only one event it is not possible to adjust whether the records support magnitude-independence. The near-source attenuation characteristics of *PGA* have been studied by many researchers (Kamiyama et al 1987, Campbell 1981, Fukushima and Tanaka 1990). Campbell proposed the attenuation relationship considering the distance and the magnitude saturation terms using data from the United States

Table 1. The regression coefficients for the ground motion parameters obtained for the hanging wall and footwall stations in the 1999 Chi-Chi, Taiwan earthquake.

Hanging wall	b_0	b_1	b_2	***d* (km)**	e
PGA_{result}	4.227	-0.01293	-0.76	60.2	0.134
PGV_{result}	2.814	0.0	-0.95	0.0	0.197
SI	2.174	-0.01135	-0.27	0.0	0.196
I_{JMA}	8.577	-0.00997	-1.98	12.7	0.335
Footwall	b_0	b_1	b_2	***d* (km)**	e
PGA_{result}	3.380	-0.00097	-0.85	1.7	0.177
PGV_{result}	2.980	-0.00896	-0.53	74.9	0.199
SI	3.028	-0.01097	-0.71	53.3	0.165
I_{JMA}	7.865	-0.01140	-1.65	15.42	0.318

supplemented by worldwide data. Fukushima and Tanaka (1990) used 28 Japanese earthquakes and 15 worldwide events. They constrained the near-field attenuation model assuming the peak ground acceleration near the fault rupture is magnitude-independent. The main reason for the differences on the *d* term obtained in this study and other studies is referred to as the earthquake-to-earthquake component of the variability (Boore and Joyner 1982) and also the influence on the spatial distribution of the ground motion due to radiation pattern from the source to the recording site located in the hanging wall and the footwall regions. From Fig. 4 it can be seen that the mean predicted attenuation of PGA_{result}, PGV_{result}, *SI*, and I_{JMA} for the footwall stations are almost characterized by constant values at a closest distance of 3 km to the seismogenic part of the fault plane as 600 cm/s^2, 85 cm/s, 55 cm/s, and 5.8 in the JMA scale, respectively. However, in case of hanging wall stations the near-source effect cannot be observed for PGV_{result}, but at the source region (r = 3 km) PGA_{result}, *SI*, and I_{JMA} are satisfied as 700 cm/s^2, 100 cm/s, and 6.2 in the JMA scale, respectively. For the hanging wall stations significant large ground motion variations are observed comparing to those values at the footwall stations with the same closest distance. Although the mean resulting attenuation curves almost fit the data in the near fault rupture regions, still the scatterings of ground motion parameters due to local site conditions as well as hanging wall and directivity effects are observed. Thus, the fit will be improved if the recorded data are corrected for these effects.

Directivity Model Parameters

The directivity parameters for the development of the spectral attenuation relationships in the 1999 Chi-Chi, Taiwan earthquake are calculated using the Somerville et al. 1997 model. First the proper acceleration time histories, which have been experienced the directivity (forward or backward) and hanging wall effects due to the geometry of the fault and faulting type (dip-slip or strike-slip), were selected. Then the rapture directivity parameters such as width ratio (*Y*, the fraction of fault up-dip that ruptures toward site), zenith angle between fault plane and ray path propagation to each site (ϕ), the average two horizontal components spectral acceleration, and the response spectral of the maximum velocity (fault normal), and the fault parallel directions, are calculated. The schematic definition of the rupture directivity parameters *Y* and ϕ for the dip-slip

Chelungpu fault are shown in Fig. 5. The Y and ϕ mainly control the amplitude variations due to rupture directivity. In order to retain the magnitude and distance dependence, the variation on the directivity function, $Y\cos(\phi)$ with respect to the residuals between the recorded average horizontal spectral acceleration and that calculated by the empirical model of the Abrahamson and Silva (1997), which considered the hanging wall effect and site classifications using 58 earthquakes from the United States and supplemented worldwide data, are shown in the Fig. 6.

Development of Spectral Attenuation Relationships

The spectral acceleration for the average horizontal components, the fault normal (maximum velocity direction) and the fault parallel directions, based on the maximum response of the single-degree-of-freedom system with the five percent damping ratio for the 135 structural periods from 0.04s to 10s are calculated. The period dependence attenuation model consists of the directivity function term as well as the anelastic attenuation and geometric spreading terms with the near-source saturation component. The general functional form that we employ is given by

$$Sa(T) = c_1(T) + c_2(T)\, r + c_3(T)\, Y \cos(\phi) + c_4(T) \log_{10}(r + d) + e\,(T) \tag{2}$$

where $Sa(T)$ is the maximum amplitude of the acceleration response spectra under consideration, r is the closest distance between the seismogenic part of the fault and the recording station in kilometers, and $c_i(T)$'s are the coefficients to be determined for each structural period T. The term $c_3(T)Y\cos(\phi)$ represents the directivity function term. The geometric spreading coefficient c_4 is unconstrained for its physically admissible range (0 to -1.0). However, it is constrained to –1.0 for the inadmissible ranges. The e term represents the record-to-record variance. As described in the previous section the non-linear least square iterative regression analysis were performed to estimate the regression coefficients $c_i(T)$.

Results of the Regression Analysis

The results of iterative regression coefficients for the acceleration (fault normal direction) response spectra considering the directivity effect in the 1999 Chi-Chi, Taiwan earthquake are shown in Fig. 7. The regression intercept shows that the mean response and has its peak at about 0.3s-0.6s periods. The anelastic coefficient indicates an increasing trend at the intermediate periods of 0.1s–0.35s with two significant peaks at the 0.35s and 1.5s. The average variation on the directivity function coefficient has a positive trend as the structural period increases from 0.15s to 1.5s and has peaks at the 0.6s, 1.2s, and 1.5s periods.

The predicted acceleration response spectra of the fault normal, fault parallel, average of the fault normal and fault parallel, and the average of the two horizontal components for the 1999 Chi-Chi earthquake with the given closest seismogenic distance (r_{seis}) of 3 km are shown in Fig. 8. The results are compared with the empirical response spectra attenuation relationship for the average horizontal component of the Abrahamson and Silva 1997. From this figure the large amplitude variations in the fault normal direction as well as in the average horizontal spectral responses at the intermediate to the large period ranges can be observed. Although, the predicted response spectra model of Abrahamson and Silva 1997 has been included the effects of the local site, fault type, and hanging wall, it predicts much smaller values than the observed ones for the periods longer then 0.2s.

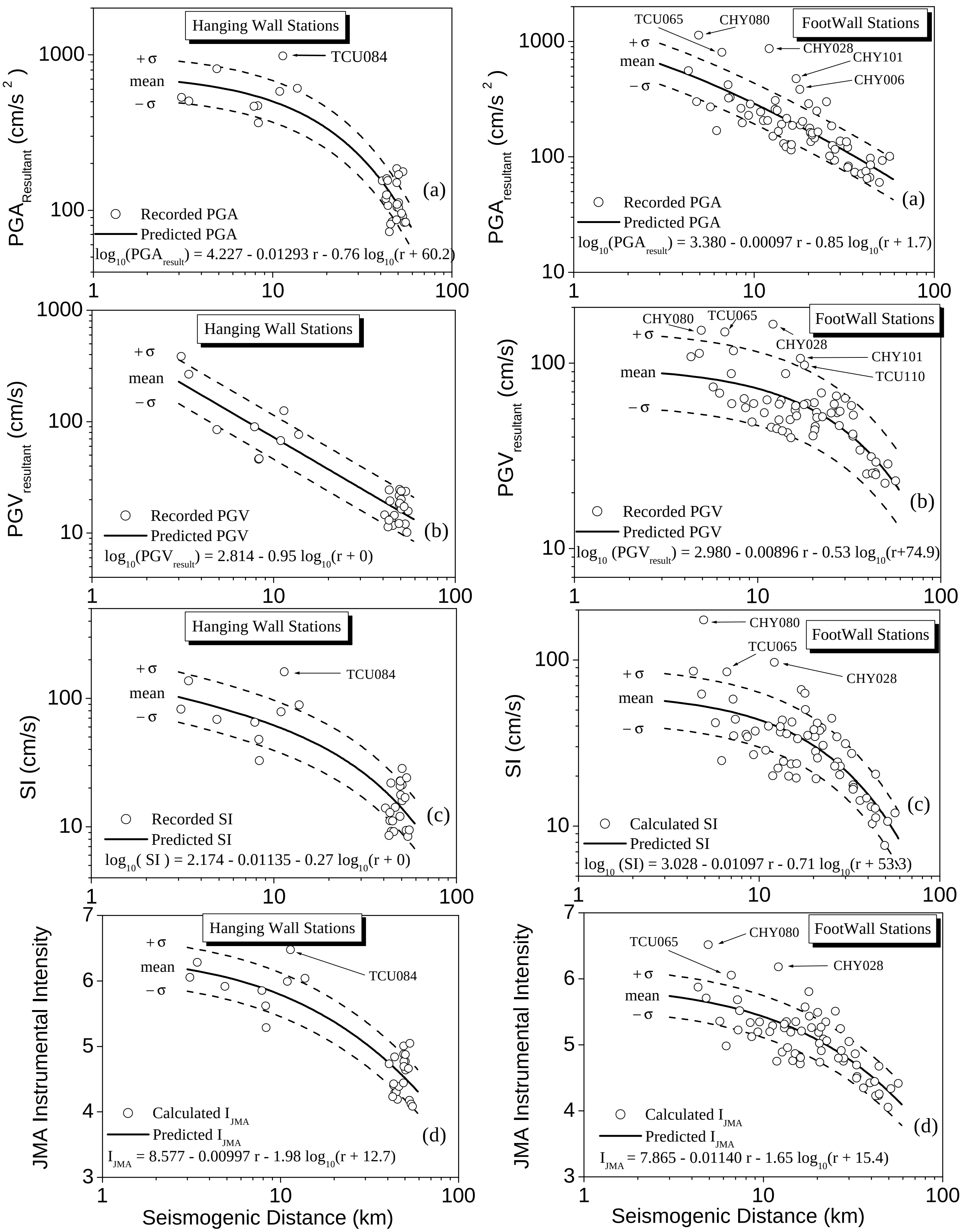

Figure 4. Predicted (a) *PGA*, (b) *PGV*, (c) *SI*, and (d) I_{JMA} by the attenuation relationship for the (left) hanging wall and (right) footwall sites in the 1999 Chi-Chi, Taiwan earthquake.

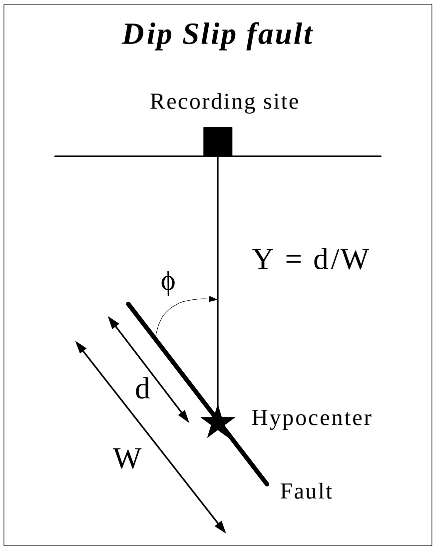

Figure 5. Definition of rupture directivity parameters (after Somerville el al. 1997).

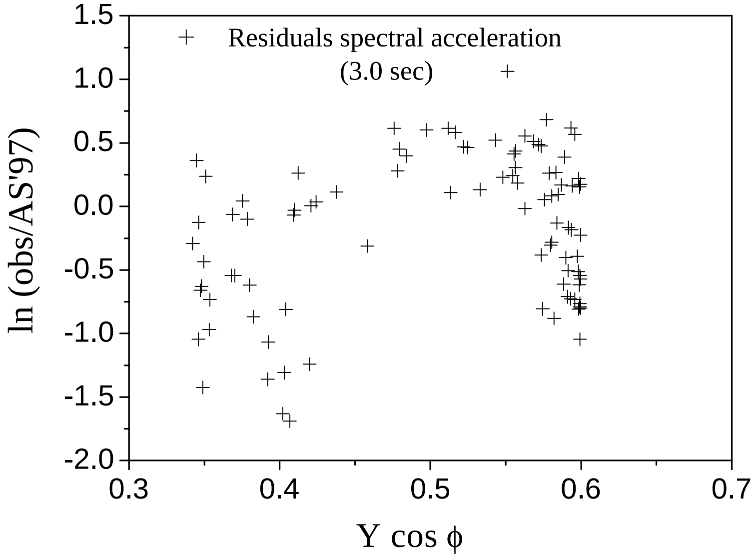

Figure 6. Residuals between recorded average horizontal spectra acceleration and the Abrahamson and Silva 1997 model as a function of the directivity parameter.

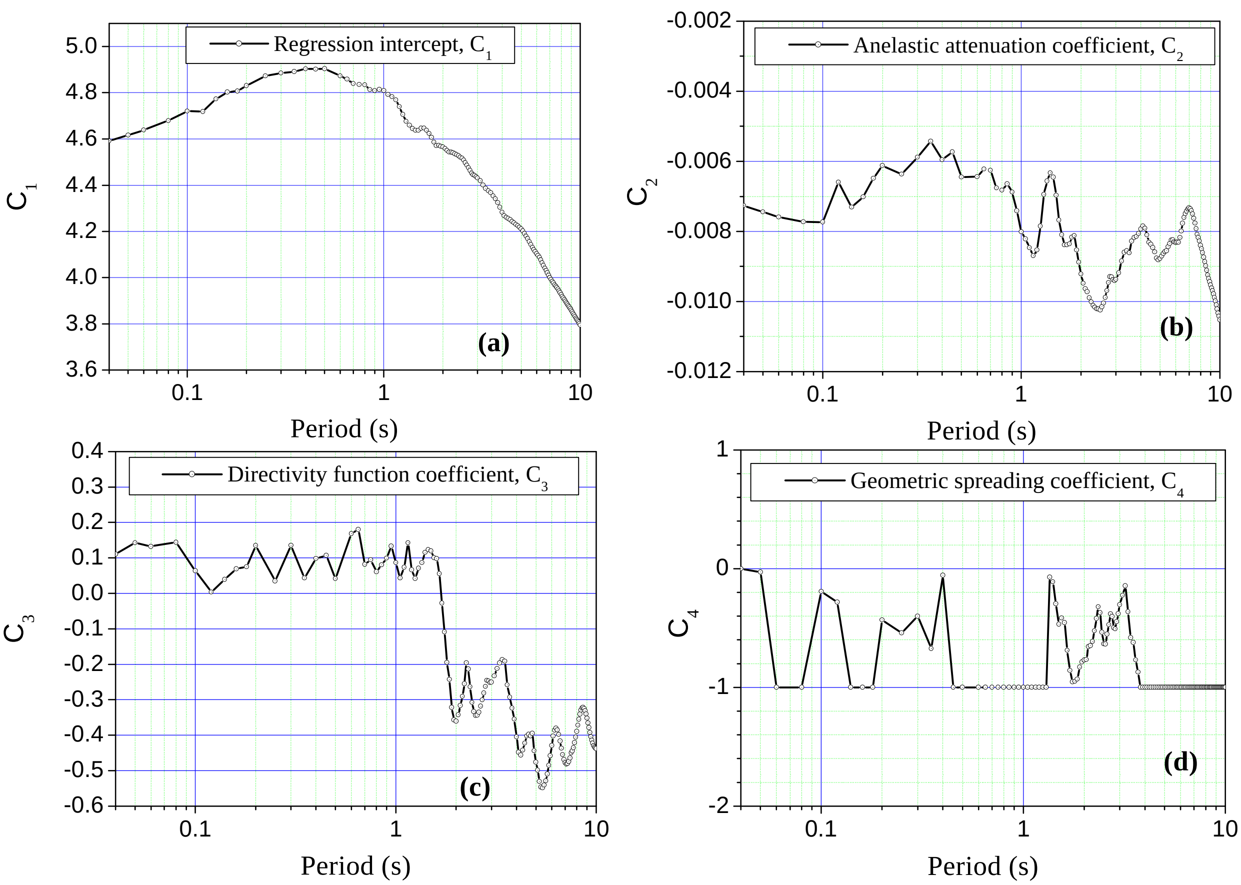

Figure 7. Regression coefficients for the acceleration response spectra (fault normal direction). The coefficients of (a) intercept, (b) anelastic, (c) directivity, and (d) geometric spreading terms for the 1999 Chi-Chi, Taiwan earthquake.

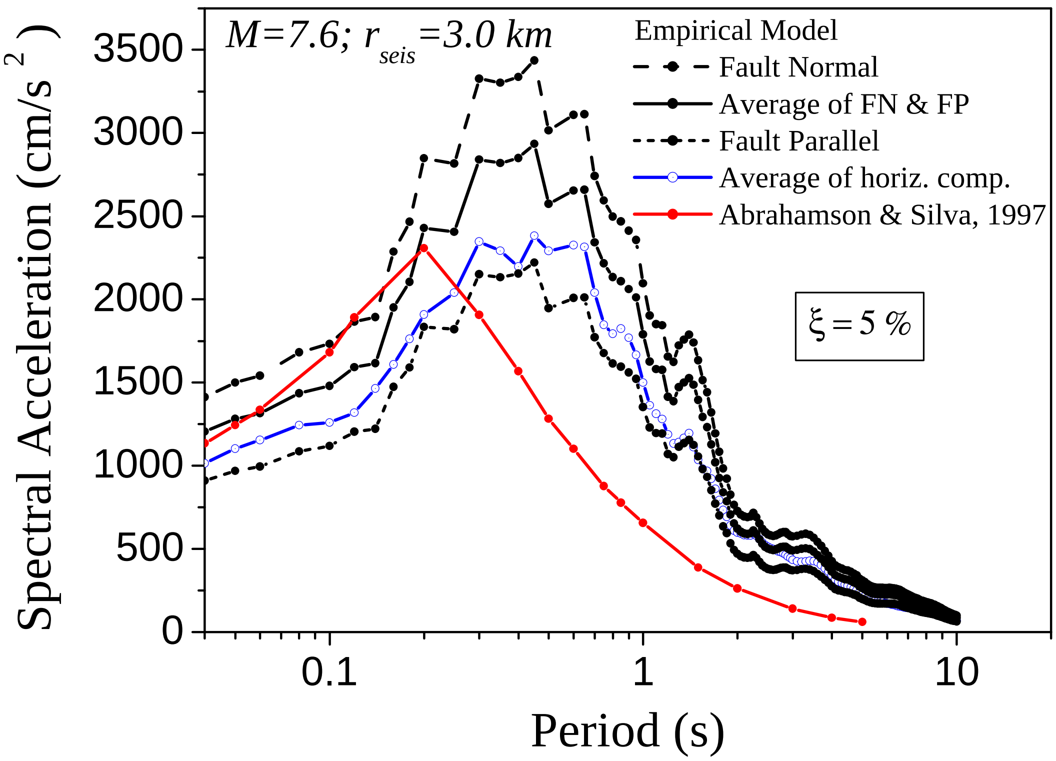

Figure 8. Predicted acceleration response spectral of fault normal, fault parallel, and average of the horizontal components for the 1999 Chi-Chi, Taiwan earthquake, and comparison with the empirical model of Abrahamson and Silva (1997).

Conclusions

In this study the near-source attenuation characteristics of the 1999 Chi-Chi, Taiwan earthquake are investigated. From the strong ground motion records of CWB, the hanging wall, directivity, and the local site effects have been observed from the maximum velocity direction (fault normal direction) and from the frequency contents of the near-fault records. Since there are significant numbers of the near-field data registered during this earthquake, attenuation relationships for the ground motion parameters were developed considering the near-source saturation effect for the hanging wall and footwall stations. The distance adjustment term (*d*), applied only for the geometric spreading term, was assumed to be a constant. At a shortest distance of 3 km to the seismogenic part of the rupture plane the mean resulting attenuation curves for the *PGA*, *SI*, and I_{JMA} were found to be the constant values in the source region. At the source region the predicted mean attenuation values for the hanging wall site are larger than those values for the footwall sites. Using the fault geometry model of the Chelungpu fault and following the Somerville et al. 1997 model, the directivity parameters for the selected stations in the 1999 Chi-Chi earthquake were calculated. Then the empirical acceleration response spectral relations for the maximum velocity and its perpendicular directions and for the average horizontal motion considering directivity effect are developed. Thus, the obtained resulting response spectra attenuation from this large crustal magnitude earthquake has important implications for the current buildings codes revision studies considering fault geometry and dynamic rupture models as well as source, path, and local site effects.

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