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A Proposal of Spectral Directivity Amplification Factor Using Strong-Motion Records of the 1999 Chi-Chi, Taiwan Earthquake

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ABSTARCT

Near-fault earthquake ground motion can be strongly enhanced relative to more distant sites, due to the proximity to the source and the presence of directivity effects caused by coherent, long-period velocity pulses. Realistic capturing and modeling of near-source strong motion records is complicated by many factors such as geometry and style –of faulting, local soil conditions, 3D basin effects, large attenuation, topographic relief, and strong underground heterogeneity. Rapid development of strong-motion instrumentations results in more accurate and efficient modeling of these important features. The 1999 Chi-Chi, Taiwan earthquake with a moment magnitude of 7.6 provides the largest acceleration data set recorded by the Seismological Center of the Central Weather Bureau of Taiwan (CWB). In this study the attenuation characteristics of the hanging wall and the footwall regions are examined. Then a period dependent, empirical, spectral amplitude factor model representing the directivity effects for the dip-slip faulting system is developed. The proposed model shows a larger spectral amplification ratio than the previous study result by Somerville et al. 1997. During the Chi-Chi earthquake, the maximum spectral directivity factors have been registered in the up-dip region around the surface exposure of the Chelungpu fault. Since the proposed spectral directivity factor is a magnitude- and distance-independent, it can be easily implemented into attenuation relations, seismic hazard assessment, and building code revision studies for the regions with a dip-slip faulting.

1. INTRODUCTION

Rupture directivity effects result in spatial amplitude variations of near-field ground motion records. Capturing this phenomenon from major earthquakes recorded by recently developed strong-motion networks leads to improve existing ground motion attenuation relations. The 1999 Chi-Chi, Taiwan earthquake provides the largest acceleration data set recorded by the CWB since the strong-motion seismology studies began[1)]. The strong ground motion records from this event provide us an unusual opportunity to investigate the characteristics of near-source ground motion. The fault geometry as well as the dynamic rupture process on the upper fractured-crust[2)] during the Chi-Chi earthquake influences the spatial ground motion distribution of near-fault region[3)]. 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[4)]. In this study the attenuation characteristics of the near-fault strong ground motion of the 1999 Chi-Chi, Taiwan earthquake (M_w=7.6) are investigated. Then the directivity effects, which resulting from dip-slip faulting system and rupture propagation toward recording sites are proposed in terms of an empirical spectral factor. The result of the proposed empirical response spectral amplitude ratio is compared with the previous result of Somerville et al.[5]. The proposed spectral directivity factor derived from the single event without any influence of inter-event variability and in the meanwhile since, the model is magnitude and distance-independence, the result might be augmented to other attenuation relations as well as for the current building codes revision studies.

2. ATTENUATION CHARACTERISTICS OF NEAR-FAULT MOTIONS

Since the 1999 Chi-Chi, Taiwan earthquake was well recorded, the event-specific attenuation relations of the JMA instrumental seismic intensity I_{JMA} as well as other ground motion parameters such as Spectrum Intensity *SI*, Peak Ground Motion *PGA*, and Peak Ground Velocity *PGV* are derived for all the selected records within the shortest distance of the sixty kilometers to the seismogenic part of the fault plane[6]. The final data sets for the hanging wall and footwall stations (excluding sites off the end of the fault rupture) contain thirty-seven (37) and sixty-six (66) pairs of the three-component acceleration records, respectively. The closest distance from each recording station to the seismogenic rupture plane is calculated using the USGS fault plane solution[7]. Then the 1999 Chi-Chi earthquake specific attenuation relationships for the ground motion parameters are developed considering a near-source saturation effect.

2.1. Regression Model

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

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

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 ε represents the error term. The terms b_1r 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) was 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.

2.2. Results of the Regression Analysis

The results of regression analysis for the ground motion parameters for this earthquake are given in Table 1. Figure 1 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 for the near 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 [7]. 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[8] and also the influence on the spatial distribution of the ground motion due to the radiation pattern from the source to the recording sites, located in the hanging wall and the footwall regions. From Fig. 1 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 550 cm/s^2, 90 cm/s, 56 cm/s, and 5.7 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 670 cm/s^2, 100 cm/s, and 6.2 in the JMA scale, respectively. For the hanging wall stations, significant large ground motion variation is 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[9].

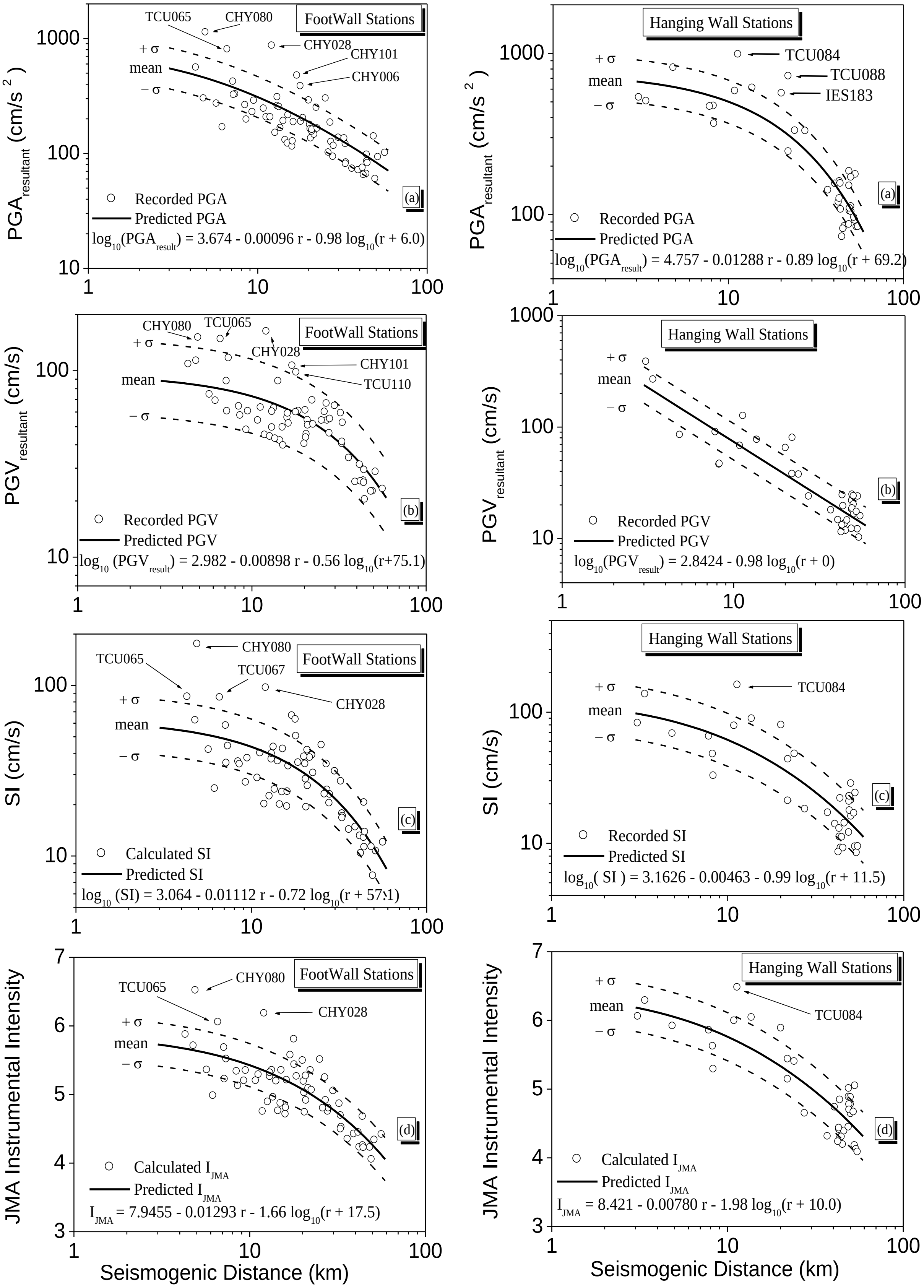

Figure 1. Predicted (a) *PGA*, (b) *PGV*, (c) *SI*, and (d) I_{JMA} by the attenuation relationship for the (left) footwall and (right) hanging wall sites in the 1999 Chi-Chi, Taiwan earthquake.

Table 1. Regression coefficients for the ground motion indices

Hanging wall	$\mathbf{b_0}$	$\mathbf{b_1}$	$\mathbf{b_2}$	**d (km)**	**ε**
PGA_{result}	4.757	-0.01288	-0.89	69.2	0.135
PGV_{result}	2.842	0.0	-0.98	0.0	0.163
SI	3.162	-0.00463	-0.99	11.5	0.202
I_{JMA}	8.421	-0.00780	-1.98	10.0	0.350
Footwall	$\mathbf{b_0}$	$\mathbf{b_1}$	$\mathbf{b_2}$	**d (km)**	**ε**
PGA_{result}	3.674	-0.00096	-0.98	6.0	0.178
PGV_{result}	2.982	-0.00898	-0.86	75.1	0.199
SI	3.064	-0.01112	-0.72	57.1	0.162
I_{JMA}	7.945	-0.01293	-1.66	17.5	0.315

3. EMPIRICAL DIRECTIVITY MODEL

The directivity and ground motion parameters for the development of the spectral amplification factor in the 1999 Chi-Chi, Taiwan earthquake are calculated using the Somerville et al. 1997 model[5)].

3.1. Directivity Model Parameters

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), and the average two horizontal components spectral acceleration are calculated. The schematic definition of the rupture directivity parameters Y and ϕ for the dip-slip Chelungpu fault are shown in Fig. 2. The Y and ϕ mainly control the amplitude variations due to rupture directivity. In order to retain the magnitude and distance dependence, the variation of 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[4)], which considered the hanging wall effect and site classifications using 58 earthquakes from the United States and supplemented worldwide data, is demonstrated in Fig. 3 for the selected structural periods.

3.2. Spatial Variation in Residual Response Spectra

The residual between recorded and model spectral acceleration is only a function of the distance width ratio, Y, and zenith angle, ϕ. The dependence of the directivity model on these two parameters was examined by the regression analysis of the current data set. The residuals were fit using the directivity function form as

$$r = C_1 + C_2\, Y \cos\phi + \sigma \qquad (2)$$

where r is the residual of the natural logarithm of the spectral acceleration at a given period, C_1 and C_2 are period dependent coefficients to be determined by linear regression, and σ represents the intra-event standard deviation. The obtained coefficients are plotted as a function of period in Fig. 4. Although there are small variations on obtained coefficients, the general trends of regression coefficients, which smoothed by a polynomial fitting, are in good agreement with the Somerville et al. 1997 results[5)] (Fig. 4). The constant term, C_1 has an inverse dependence on the amplitude residual, which indicates a reduction in the base ground motion level while increments are added at recording stations having directivity effects. The directivity function coefficient, C_2, shows a significant amplification for periods greater than 0.5s. The directivity effects start from 0.6 second period and increase with period (Table 2). For the dip-slip (thrust) faulting, the maximum directivity conditions ($Y \cos\phi = 1$) cause amplitude about 1.8 times larger than the average at 2 seconds period, which is two times larger than the corresponding amplification factor obtained by the Somerville et al.[5] study. For various structural periods the spatial variation in the directivity factor during the 1999 Chi-Chi earthquake was evaluated for the near-fault stations as shown in Fig. 5. From this figure, it can be seen that the rupture directivity effects are larger and almost concentrated on the top edge of the surface-faulting region. Although relatively small directivity factors registered for the period ranges of 0.6 s to 1.0 s due to the low-angle Chelungpu faulting system and the shallow focal-depth of this event[10,11], significant rupture-directivity attributions have been observed for the longer periods. The spectral directivity factor results in 30% amplification at the period of 5.0 s (Figure 5).

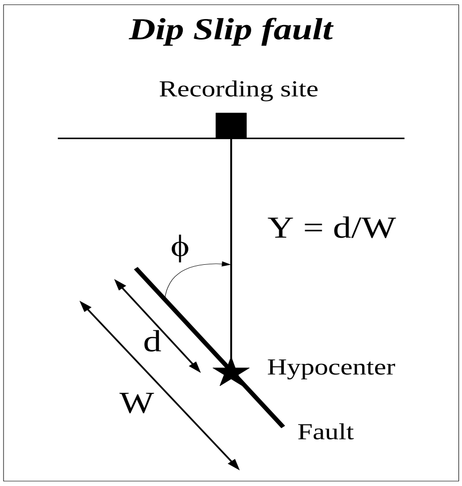

Figure 2. Definition of rupture directivity Parameters.

Table 2. Proposed spectral amplification factor due to directivity effects

Period (s)	C_1	C_2	C_1^*	C_2^*	σ	τ	$σ^*$	$τ^*$
0.6	0.000	0.000	0.000	0.000	0.395	0.000	0.514	0.000
0.75	-0.129	0.255	-0.045	0.008	0.393	0.000	0.549	0.000
1.0	-0.278	0.552	-0.104	0.178	0.356	0.000	0.540	0.001
1.5	-0.448	0.890	-0.186	0.318	0.325	0.000	0.568	0.169
2.0	-0.640	1.269	-0.245	0.418	0.331	0.000	0.602	0.260
3.0	-0.852	1.690	-0.327	0.559	0.298	0.000	0.690	0.211
4.0	-1.085	2.152	-0.386	0.659	0.420	0.000	0.616	0.360
5.0	-1.339	2.655	-0.431	0.737	0.638	0.000	0.634	0.522

C_1 and C_2 : Period dependence intercept and directivity coefficients
σ: Intra-event standard deviation
τ: Inter-event standard deviation
*: Directivity model results of Somerville *et al*., 1997

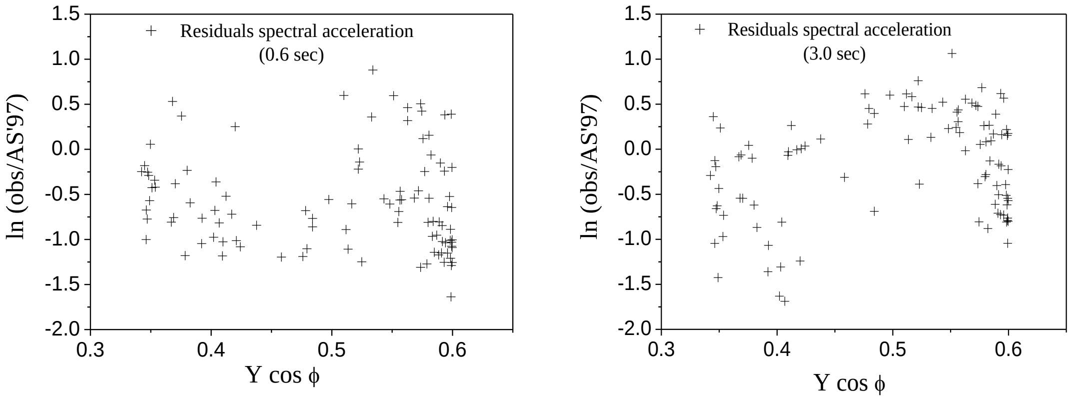

Figure 3. Residuals between recorded average horizontal spectral acceleration and the Abrahamson and Silva 1997 model as a function of the directivity parameter for some structural periods.

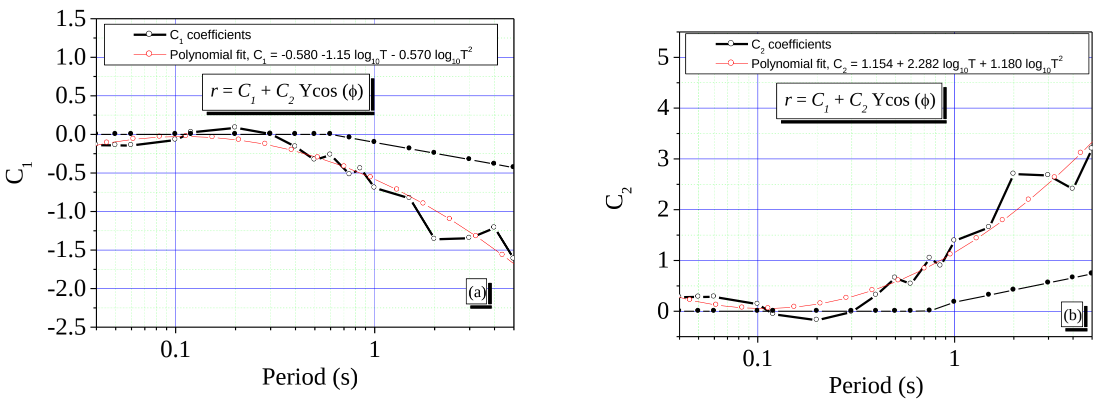

Figure 4. Results of the linear regression analysis for directivity model for (a) intercept and (b) directivity function coefficients.

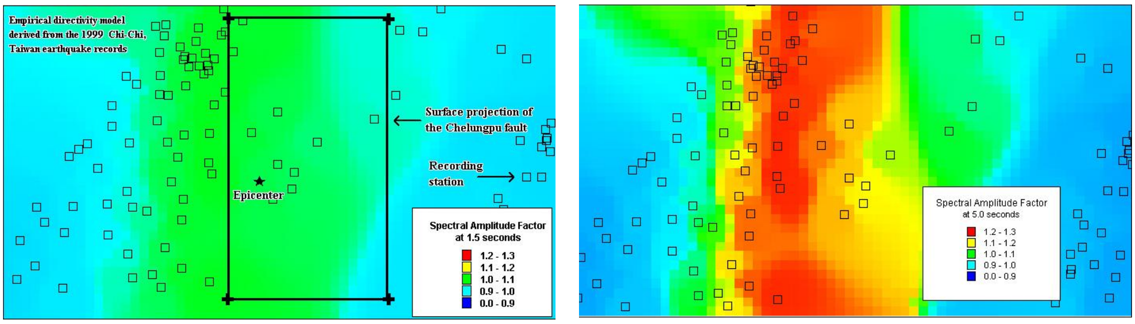

Figure 5. Illustration of spatial variation due to long-period directivity factor, using the proposed spectral directivity model for some periods during the 1999 Chi-Chi, Taiwan earthquake.

4. CONCLUSIONS

In this study the near-fault characteristics of strong-motion records during the 1999 Chi-Chi, Taiwan earthquake are investigated. From the near-field strong ground motion records of CWB, the hanging wall, directivity, and the local site effects have been observed. Since there are significant numbers of the near-field data registered during this earthquake, the 1999 Chi-Chi earthquake-specific attenuation relationships for the ground motion parameters were developed considering the near-source saturation effect for the hanging wall and footwall stations. 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 recording stations in the 1999 Chi-Chi earthquake were calculated. Directivity model parameters are assigned magnitude and distance-independent using the residuals between recorded average horizontal response spectra and those calculated from Abrahamson and Silva 1997. An empirical directivity model of the response spectral amplitude ratio is proposed using the comprehensive CWB records during the 1999 Chi-Chi, Taiwan earthquake. The obtained result for the dip-slip fault shows significant rapture directivity amplification feature in ground motion for periods longer than one second, comparing those with the previous studies results. The proposed empirical model can be easily implemented into attenuation relations, seismic hazard studies, and specific structures, which are sensitive to long-period ground motions, in the regions with a dip-slip (thrust) faulting.

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