# Hanging Wall and Footwall Effects on Ground Motions: An Empirical Approach

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## 1. Introduction

Recent empirical and numerical models indicated that the peak ground accelerations (PGA) on hanging wall and footwall sites from thrust earthquakes likely to show a systematic difference[1]. Based on the geometry of dipping faults, the ground motion at hanging wall sites have larger motion than that on footwall sites at the same seismogenic-distance. In this study a systematic difference in strong ground motion at the hanging wall and footwall stations during the 1999 Chi-Chi, Taiwan earthquake ($M_w$=7.6) is investigated using the residuals of the ground motion from the Chi-Chi earthquake-specific attenuation relations. The empirical attenuation relations for the PGA at the hanging wall and footwall sites are derived using the recently released comprehensive free-field records of Seismological Center of Central Weather Bureau (CWB) of Taiwan[2].

## 2. The 1999 Chi-Chi Earthquake-specific Attenuation Relations

Since the 1999 Chi-Chi earthquake was well recorded, the event-specific attenuation relations of PGA are derived for all the selected records within the shortest distance of the sixty kilometers to the seismogenic part of the fault plane[3] (including recording stations off the ends of the Chelungpu fault, with the 110 acceleration records). The numbers of records from the hanging wall and footwall stations (excluding sites off the end of the fault rupture) are 37 and 66, respectively. The attenuation model considering anelastic attenuation, geometric spreading, and near-source saturation terms for PGA is given by

$$\log_{10} PGA = b_0 + b_1 r_{seis} + b_2 \log_{10} (r_{seis} + d) + e \qquad (1)$$

in which $r_{seis}$ is the closest distance to the seismogenic part of the fault plane[3], $b_i$'s are the regression coefficients to be determined, $d$ is the near-source saturation effect in kilometer, and $e$ represents the error term[4]. The results of regression analysis for the peak acceleration are given in Table 1. Figure 1 shows the mean predicted $PGA_{result}$ (resultant of two horizontal components) by the Chi-Chi earthquake-specific attenuation relationships for all the selected near field, hanging wall, and footwall stations, respectively.

## 3. Hanging Wall and Footwall Effects

The hanging wall and footwall effects are demonstrated by examining the residuals from the mean Chi-Chi earthquake-specific attenuation relation. The $PGA_{result}$ residuals for recording stations on the hanging wall and footwall are shown (hatch sign) in Fig. 2. The footwall stations are plotted at negative distances to distinguish them from the hanging wall sites. The PGA residuals on the hanging wall show a positive bias trend for the seismogenic distance range of 3 to 30 km with the mean bias of 0.43 and the standard deviation of 0.058. However, for the footwall sites there is no significant bias over the same distance range with the mean residual of $0.03 \pm 0.006$ (Fig. 2). For the 1999 Chi-Chi, Taiwan earthquake the maximum difference in the residual on the hanging wall and footwall over this distance range is about 0.50.

## 4. Empirical Model of Hanging Wall and Footwall Effects

In order to model the residuals trends on both hanging wall and footwall sites, we propose an empirical approach. The difference between the mean predicted Chi-Chi earthquake-specific attenuation relationship and the mean attenuation relations for the hanging wall and footwall sites could represent the general trends of the hanging wall and footwall, respectively. As it can be seen from Fig. 2 the continuous empirical-residual curve (black line) for the hanging wall reaches to its maximum value as 0.47 over the seismogenic distances of 5 to 30 km. However, the empirical residual function for the footwall sites does not represent a significant trend, it shows an average residual trend of 0.04 versus the same seismogenic distances to the fault plane (see the continuous black line for the footwall sites). For the distance dependence of PGA residuals in the 1999 Chi-Chi earthquake on the hanging wall (hatch dot and continuous black line), we used the piecewise continuous functional form[1] (Eq. 2). The proposed empirical model derived from the Chi-Chi earthquake-specific attenuation model is used for the most affected seismogenic distance range of 5 to 25 km. A cosine function proposed by Abrahamson and Somerville (1996), which gives a smooth decay with increasing source-to-site distance are used for the seismogenic distances of 0 to 5 km and 25 to 50 km, respectively. Based on the trends in the residuals, the distance-dependent hanging wall effect can be written as

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$$HW_{effect}(r_{seis}) = c_1/2\,[\cos(\pi\,(r_{seis} - x_1)/(x_2 - x_1) + \pi) + 1] \quad x_1 < r_{seis} < x_2 \qquad (2)$$

$$\mathrm{Prd}(r_{seis})_{Hanging\_wall} - \mathrm{Prd}(r_{seis})_{All} \quad x_2 \le r_{seis} \le x_3 \quad (x_1 = 0\ \mathrm{km};\ x_2 = 5\ \mathrm{km})$$

$$c_2/2\,[\cos(\pi\,(r_{seis} - x_3)/(x_4 - x_3)) + 1] \quad x_3 < r_{seis} < x_4 \quad (x_3 = 25\ \mathrm{km};\ x_4 = 50\ \mathrm{km})$$

in which $HW_{effect}(r_{seis})$ is the hanging wall effect function and $\mathrm{Prd}(r_{seis})$ is the mean predicted Chi-Chi earthquake-specific attenuation curve. The boundary distances, $x_1$, $x_2$, $x_3$, and $x_4$, are fixed using the residual-trend distributions and the initial values for the cosine function, $c_1$ and $c_2$, are assigned from the proposed empirical curve (see Fig. 2 and Eq. 2). The obtained result (see red line in Fig. 2) shows a good agreement with the Abrahamson and Somerville's result, which was derived from the thirteen records on hanging wall sites during the 1994 Northridge and supplemented by the United States and worldwide data with the reverse/oblique earthquakes (see pink line in Fig. 2).

**Table 1.** The obtained regression coefficients for the PGA.

| $PGA_{resultant}$ | $b_0$ | $b_1$ | $b_2$ | $d$ (km) | e |
|---|---|---|---|---|---|
| **All data set** | 3.685 | 0.0 | -0.99 | 5.1 | 0.039 |
| **Hanging wall** | 4.757 | -0.01288 | -0.89 | 69.2 | 0.018 |
| **Footwall** | 3.674 | -0.00096 | -0.98 | 6.0 | 0.032 |

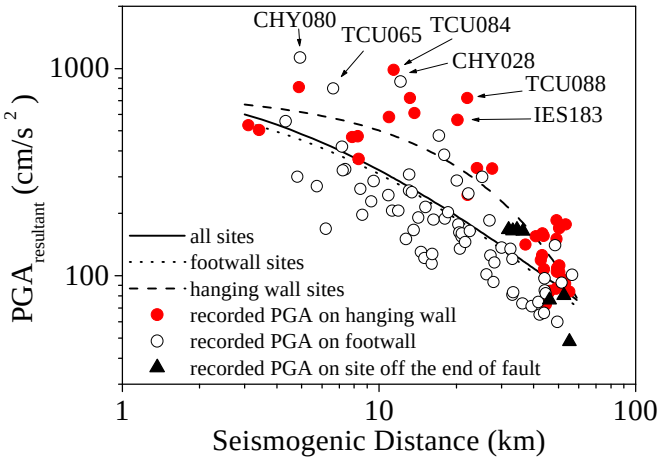


**Fig.1** The Chi-Chi earthquake specific attenuation relations.

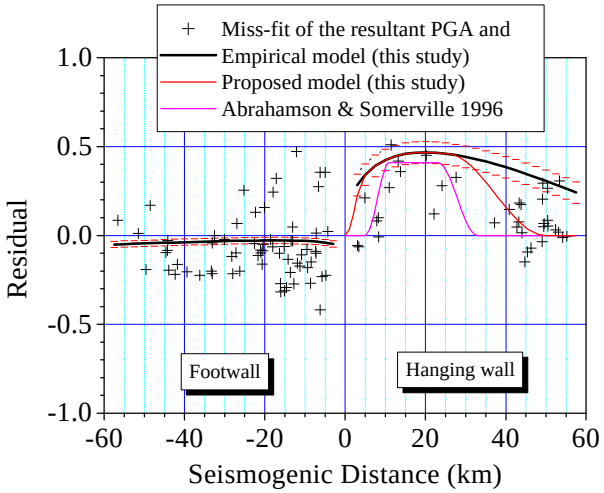


**Fig. 2** Empirical model of the PGA residuals on the hanging wall and footwall (for more details refer to the text).

## 5. Conclusions

In this study the systematic differences in the ground motions on hanging wall and footwall sites were investigated for the 1999 Chi-Chi, Taiwan earthquake. Since this earthquake was well recorded by the CWB, the event-specific attenuation relations for the near-field, hanging wall, and footwall sites were developed. The proposed empirical model for PGA on the hanging wall showed about 46% to 50% higher values than the mean attenuation for all the sites over the limited range of seismogenic distance from 5 to 25 km. In contrast, the proposed model for PGA on the footwall does not show significant difference from the mean attenuation relation in the 1999 Chi-Chi, Taiwan earthquake. A similar amplitude trend for the hanging wall effect has been observed from previous studies. The systematic difference of PGA on hanging wall sites are likely to be recurrently observed in future reverse earthquakes. Thus, the proposed hanging wall function should be considered in seismic hazard analyses in regions with a thrust faulting system.

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