Root-mean-square distance and effects of hanging wall/footwall

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ABSTRACT: The hanging wall/footwall effects (HW/FW effects) are obvious in the near-fault ground motions of Chi-Chi earthquake, Taiwan, on September 21, 1999. The main cause of HW/FW effects is believed that the hanging wall sites are on general closer to the dipping fault than the sites at the same rupture distances (Drup) located on the footwall, that is to say, the rupture distance is unable to capture the general proximity of a site to a dipping fault plane. In order to overcome the shortcoming of the rupture distance, the root-mean-square distance (Drms) is introduced in this paper. Using the root-mean-square distance, the attenuation relationships of PGA are developed. By examining the residuals from the Chi-Chi earthquake-specific attenuation relations, the systematic differences between PGA of the hanging wall sites and the median attenuation for Chi-Chi earthquake are not found. This result confirms that the HW/FW effect is a geometric effect caused by the asymmetry of dipping fault. Therefore, the HW/FW effects on the near-fault ground motions can be ignored in the future attenuation analysis if we use the root-mean-square distance as the source-to-site distance measure.
Keywords: hanging wall/footwall effects, root-mean-square distance, rupture distance, Chi-Chi earthquake

1. Introduction

The hanging wall/footwall effect (the HW/FW effect) is one of most important characteristics of near-fault ground motions during the large earthquakes such as the 1994 Northridge and the 1999 Chi-Chi earthquake. Making good use of the large numbers of near-fault ground motions recorded during the two earthquakes, the HW/FW effects of peak ground acceleration (PGA) and response spectral acceleration (RSA) are quantified by evaluating the residuals got from the regression analysis. In the near-fault zone (Within the rupture distance D_{rup} of 25Km), the PGA and RSA on the hanging wall are much greater than those on the footwall at the same D_{rup}. (Gao *et al*,2001;Abrahamson *et al*,1996;1997; Chang *et al*,2004;Wang *et al*,2002). As matter of fact, the HW/FW effect is not restricted to the PGA and RSA, the peak ground velocity (PGV) and the peak ground displacement (PGD) on the hanging wall are also greater than those on the footwall at the same D_{rup} according to the 2D and 3D dynamics simulation of dipping-fault, as well as some observational evidences (Brune *et al*, 1996; Shi *et al*, 1998; 2003; Oglsbey *et al*, 2000).

In this paper, the source-to-receiver distance measures used in the traditional attenuation analysis are compared and summarized firstly. Then using different distance measures, the HW/FW effects of PGA, PGV and PGD during the 1999 Chi-Chi earthquake are examined by evaluating the residuals of ground motion from the regression relations. Followed the method put forward by Abrahamson *et al* in 1996, the ground motions' comparison between the hanging wall site and footwall site at the same rupture distance D_{rup}, as well as the same root-mean-square distance D_{rms}, are performed in this paper. If there are great difference when the D_{rup} measure is used, while there is no significant difference when the D_{rms} measure is used. Then the HW/FW effects of near-fault ground motions are believed to be a geometrical effect caused by the distance asymmetry of dipping fault

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2. Distance measure and attenuation relations

2.1 Distance measure

The distance measure (see figure 1)widely used before in the attenuation analysis, such as the rupture distance (D_{rup}, the shortest distance from the station to the rupture surface), Joyner–Boore distance (D_{jb}, the shortest horizontal distance to the vertical projection of the rupture) and the seismogenic distance (D_{seis}, the shortest distance to the seismogenic portion of a fault) and so on, share a common characteristic that they cannot represent the nearness degree between the station and the whole rupture plane on general. All the distance measures mentioned above make use of the distance between the site and a single point of the fault to approximate the distance between the site and the whole rupture plane. These distance measures are suitable and accurate for the teleseism which can be expressed as point source model approximately. However for the large earthquake, the rupture is up to one hundred kilometers, the rupture fault cannot be simplified as a point source. Therefore these distance measures are not applicable

To accurately represent the general proximity between the station and the fault plane, the root-mean-square distance (D_{rms}) is a good choice. The D_{rms} is defined as: $D_{rms}=(\int_{\Sigma} D^{-2}(\zeta,x)d\Sigma/A)^{-1/2}$,in which $D(\zeta, x)$ (see figure 1)is the distance from the recording site x to a point ζ on the fault plane Σ, and A is total area of fault surface. This distance measure is a weighted average distance between the site and all points on the fault.

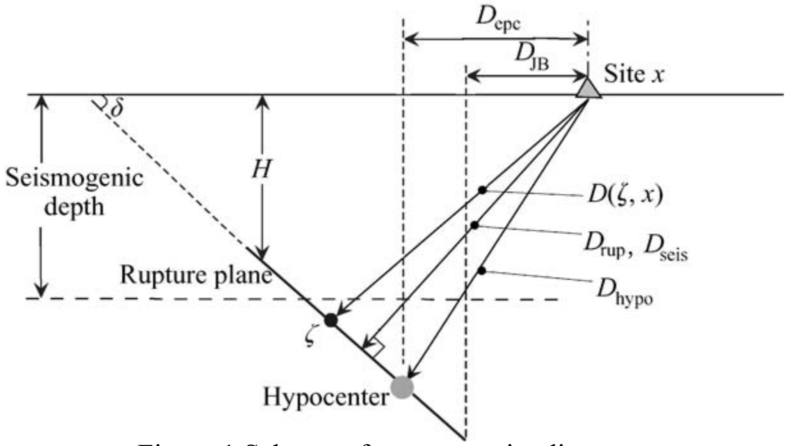

Figure 1.Scheme of source-to-site distances

2.2 Attenuation relations

During the 1999 Chi-Chi earthquake, a total of 441 strong ground motions were recorded. According to the quality of the records, all of the records are classified into A, B, C and D class, in which the D class is not suitable for scientific research. So a total of 298 PGA belonging to A, B and C class are used. Additionally, 255 pieces of PGV and PGD processed by PEER and COSMOS are collected by the author, and also used in this research. There are only 11 sites locate on the hanging wall, and 69 on the footwall, the others are called neutral sites outside of hanging wall and footwall.

According to the method of quantifying the HW/FW effects, the Chi-Chi earthquake specific attenuation relations should be developed first. Since the goal of this research is not to develop the attenuation relationships for engineering application, the following simple regression model is adopted：

$$\ln(A_P)=a+b\times\ln(D+c) \qquad (1)$$

In which, A_P is PGA(cm/s^2),PGV(cm/s)or PGD(cm), D is distance measure D_{rup} (Km) or D_{rms} (Km),the coefficients a, b and c for PGA, PGV and PGD estimated using the ordinary least squares are listed in table 1, and the attenuation curves are plotted in figure 2. Most of the sites belong to site class C or D based on the 1997 Uniform Building Code (UBC) classification scheme (Lee *et al,* 2001), so the effect of site condition is not taken into consideration. For all the ground motion parameters used in this study, the geometric mean of the two horizontal components is used.

Table 1. Coefficients for Chi-Chi Earthquake Specific Attenuation Relations

Ground motion	D_{rup} a	D_{rup} b	D_{rup} c	D_{rup} σ	D_{rms} a	D_{rms} b	D_{rms} c	D_{rms} σ
PGA:	10.80	-1.38	24.39	0.5160	10.58	-1.28	7.81	0.5516
PGV:	7.22	-0.96	9.30	0.5690	5.83	-0.60	-13.05	0.7114
PGD:	8.59	-1.40	8.00	0.2646	7.56	-1.12	-12.21	0.7755

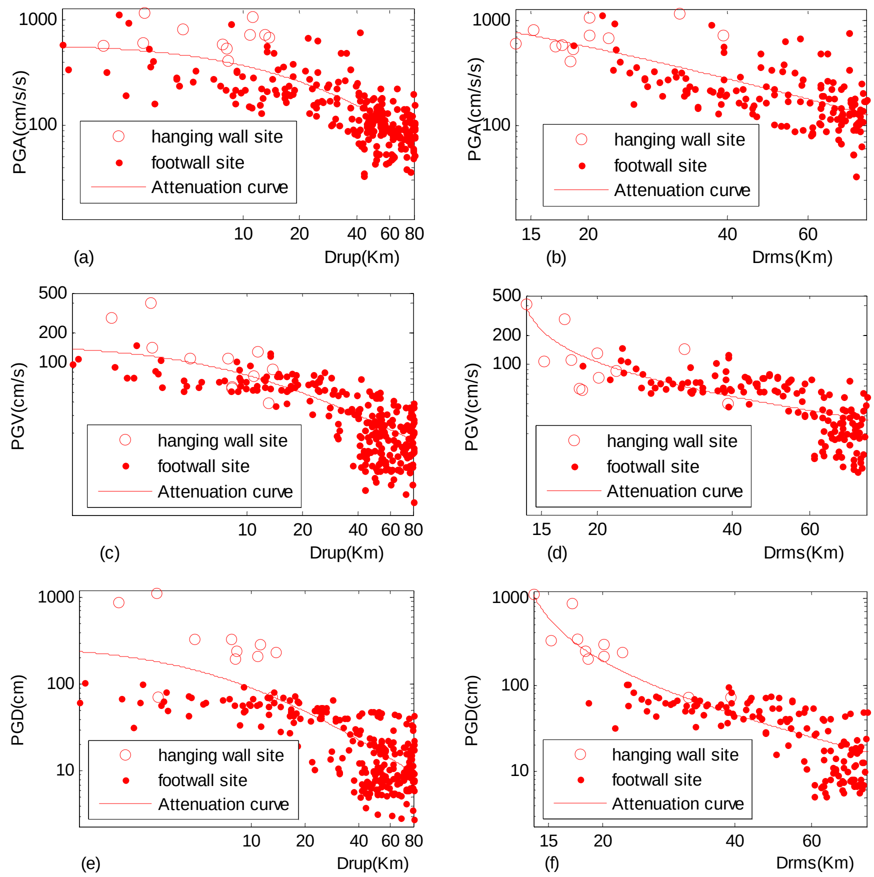

Figure 2. The attenuation curves of the Chi-Chi earthquake.(a),(b)PGA; (c),(d)PGV; (e),(f)PGD
The left column is based on the D_{rup} and the right one on D_{rms}

3. The hanging wall/footwall effects analysis

The earthquake records are marked as the observed values (PGA_{Obs}, PGV_{Obs} and PGD_{Obs}) and those got from the attenuation relations are marked as the predicted value (PGA_{Pred}, PGV_{Pred} and PGD_{Pred}). The logarithm residual ($\ln(PGA_{Obs}/PGA_{Pred})$, $\ln(PGV_{Obs}/PGV_{Pred})$ and $\ln(PGD_{Obs}/PGD_{Pred})$) is used to examine the HW/FW effects. The larger the residual is, the larger the differences between the ground motions on the hanging wall and those on the footwall are. On the contrary, when the logarithm residual approaches to zero, the difference disappears, that is to say, the HW/FW effects become insignificant.

3.1 Using the D_{rup} as source-to-site distance measure

Using the attenuation relations developed above, the logarithm residuals are computed, and then plotted in figure 3.In this figure, both of the footwall sites and the neutral sites(outside of the hanging wall and footwall side) are plotted at negative distances to separate them from the 11 hanging wall sites. Additionally, the hanging wall sites are marked as circle and the other sites as point.

The left column of the figure 3 is based on the D_{rup} measure. From these figures (a),(c),(e), we can see most of the residuals of the 11 hanging wall sites are biased to the positive, only few values are less than zero. Especially, the residuals of PGA on the hanging wall are all positive within the D_{rup} of 25Km, whereas some of the residuals of PGV and PGD are also negative. This shows the ground motions on the hanging wall is much greater than the average level. In contrast, the residuals of the other sites (the footwall sites and the neural sites outside of hanging wall and footwall) locate symmetrically around the zero line, that is to say, the horizontal PGA, PGV and PGD approximate the average level without amplification. This shows there are great differences between the ground motions of hanging wall and footwall when the D_{rup} is used as distance measure.

This phenomena can also be seen from the attenuation curves in figure 2(a), (c),(e). Most of the hanging wall sites (open circle) located above the predicted curves when the D_{rup} is used as the distance measure, however, the other sites located around the curves without obvious bias.

3.2 Using the D_{rms} as source-to-site distance measure

Similarly, the logarithm residuals are computed and shown in figure 3(b), (d),(f) using the D_{rms} as the distance measure.

These figures show that the logarithm residuals distribute homogenously around the zero line, no matter where the site locates. Even though the sites locate on the hanging wall, there is no obvious bias relative to the zero line. That is to say, the ground motions are equal to the average level approximately all through the distance range. These can also be seen from the attenuation curves plotted in figure 2(b), (d), (f). All the points surround the predicted curves tightly and symmetrically without obvious bias. The HW/FW effects of PGV and PGD become insignificant when the D_{rms} is used as distance measure.

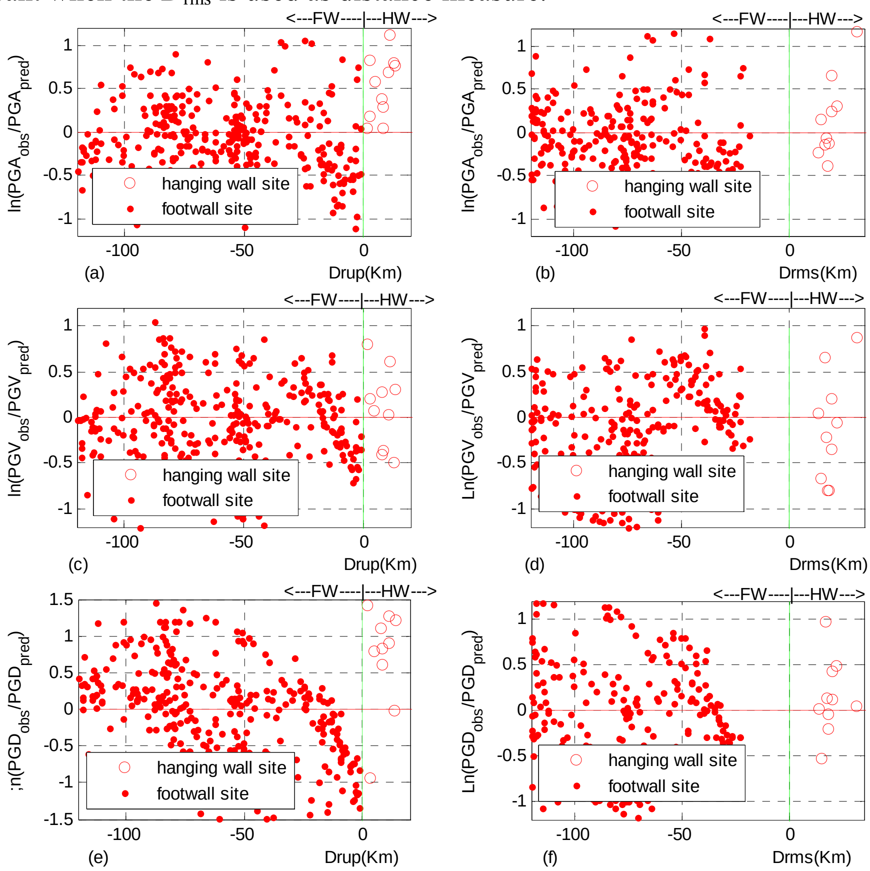

Figure 3.The residuals of the ground motions during the Chi-Chi earthquake.(a),(b)PGA; (c),(d)PGV; (e),(f)PGD
The left column is based on the D_{rup} and the right one on D_{rms}

In order to compare the result got from the regression analysis above, the mean values of residuals of all hanging wall sites are listed in table 2.

From the table we can see:

(1) All the mean residuals are positive when the D_{rup} is used. This means that the HW/FW effects of PGA, PGV and PGD are all significant, whereas they have different degree of amplification. The PGA and PGD have larger mean value than the PGV, and the mean values of PGA are greater than those of PGD.

(2) All the mean residuals of PGV and PGD are close to zero when the D_{rms} is used, even the negative values

appear. These demonstrate that the HW/FW effects of PGA, PGV and PGD disappear. That is to say, the ground motions on hanging wall correspond to the average level without amplification comparing with those on the footwall.

Table 2.The mean residuals of all HW sites using different distance measures

Ground motions	D_{rms}	D_{rup}
PGA	0.05	0.68
PGV	-0.11	0.28
PGD	0.14	0.90

4. Conclusion and discussion

In fact, the site locates on the hanging wall is much closer to the rupture plane than the site on the footwall at the same rupture distance D_{rup}, that is to say, the root-mean-square distance D_{rms} of the hanging wall site is less than that of the footwall site. As we well known, the ground motions attenuate with the increase of distance. The -2 exponent in the definition of D_{rms} is in view of the geometrical attenuation of seismic wave from a point source in the homogeneous space. Therefore, comparing with the other distance measure, the D_{rms} is more suitable for the attenuation analysis of the ground motions.

Based on the regression analysis above, we can see that the ground motions on hanging wall site have not be amplified relative to those of the footwall site at the same D_{rms}, however, significant differences exist between the ground motions on the hanging wall and footwall when D_{rup} is used. In other words, the HW/FW effects of the near-fault ground motions do not exist so long as the hanging wall receiver and the footwall receiver have the same root-mean-square distance. Therefore, the HW/FW effect is mainly a geometric effect caused by the asymmetry of dipping fault.

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