PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

# NGA-West2 Model for Estimating Average Horizontal Values of Pseudo-Absolute Spectral Accelerations Generated by Crustal Earthquakes

**I. M. Idriss**
Department of Civil and Environmental Engineering
University of California, Davis

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ABSTRACT

A model for estimating average horizontal values of pseudo-absolute spectral accelerations generated by crustal earthquakes is developed as part of this study. The NGA-West2 Project significantly expanded the data base of motions recorded during earthquakes and offered the opportunity to re-examine and update the NGA relationships published by the NGA developers in 2008. The new data set comprised 21,539 recordings obtained during earthquakes with magnitudes ranging from 3 to 7.9, recorded at distance ranging from 0.2 km to well over 300 km, and for recording stations with $V_{s30}$ ranging from 100 to 2000 m/sec. These data spanned the large magnitude range (M = 4.5 to 7.9) and the small magnitude range.

This study concentrated on the use of the large magnitude free field data set recorded at distances less than 175 km; this data set consists of 7120 recordings recorded at sites with $V_{s30}$ ranging from 100 to 2000 m/sec. These were further segregated into three $V_{s30}$ bins. One bin was for data recorded at sites with $V_{s30}$ = 100 to 211 m/sec, which constitute "soft soil sites." The second bin comprised the data recorded at sites with 211 m/sec < $V_{s30}$ < 450 m/sec, which exhibit moderate to strong nonlinear characteristics, especially for sites with $V_{s30}$ less than about 300 m/sec (~1000 fps).

The third bin was for data recorded at sites with $V_{s30}$ = 450 to 2000 m/sec. These sites may be reasonably designated as "quasi-linear sites" because they appear to show very weak nonlinearity, especially for sites with $V_{s30}$ exceeding about 600 m/sec (~2000 fps). The model presented in this report covers only sites with this range of $V_{s30}$.

The use of this model should be limited to M ≥ 5, to distances less than about 150 km, and to $V_{s30} \geq$ 450 m/sec. For sites with $V_{s30}$ > 1200 m/sec, the PSA values calculated using $V_{s30}$ = 1200 m/sec are used.

# ACKNOWLEDGMENTS

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The author is grateful to the many young post-doctoral fellows at PEER without whose input, efforts and enthusiasm, the NGA-West2 Project would have been far more difficult to complete. While each of these post-doc contributed significantly to this effort, three particularly stand out, namely, Dr. Timothy Ancheta, Dr. Albert Kottke, and Dr. Tadahiro Kishida. Dr. Yousef Bozorgnia, Executive Director of PEER, was instrumental in managing the Project and Ms. Clair Johnson edited the report. The help and cooperation of these five colleagues are gratefully acknowledged.

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# 1 Data Selection

## 1.1 INTRODUCTION

The development of a model for estimating average horizontal values of pseudo-absolute spectral accelerations generated by crustal earthquakes using the most recently compiled earthquake ground motions data is presented in this report. The data compilation and other supporting activities are part of the NGA-West2 research project being completed under the auspices of PEER.

## 1.2 GENERAL

As part of the NGA-West2 Project, a flatfile was created containing the information pertaining to 21,539 recordings obtained during earthquakes with magnitudes ranging from 3 to 7.9. The spectral ordinates provided in this flatfile comprised the RotD50 spectral values (five-percent damping) obtained by rotating the two recorded horizontal components as described in Boore (2010). Of these recordings, 10,943 were gathered from earthquakes with magnitudes ranging from 4.5 to 7.9, which are considered the "large magnitude" data set. Removing entries that had no listed magnitude (M), mechanism, closest distance to the source ($R_{rup}$), Joyner-Boore distance ($R_{jb}$), depth to top of rupture, $V_{s30}$, peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and spectral values for $T = 0.01$ to 20 sec, resulted in reducing the number of entries to 10,819. Of these, 6642 recordings are at free-field sites (Geomatrix designation: A, A-B, B, F, I, I-F, K, L, and M), and 4097 recordings are at sites where no Geomatrix designation was included. The latter recordings were considered to have been at free-field sites. That is, the total number of "free-field" recordings contained the "large magnitude" data set is 10,739.

Examination of the recordings for a number of earthquakes show a significant change in the slope of PGA (and spectral values) versus $R_{rup}$ for $R_{rup}$ exceeding 150 to 175 km. Accordingly, only recordings obtained at $R_{rup} \leq 175$ km were selected for this study. In addition, all earthquakes having less than three recordings were not included. The recordings from a number of earthquakes, such as the Taiwan's Smart Array, also were not included.

Consequently, the remaining recordings totaled 7,120 and covered the following ranges:

- M = 4.5 to 7.9
- $R_{rup}$ = 0.2 to 175 km
- $V_{s30}$ = 100 to 2000 m/sec

These 7120 recordings were generated by 160 earthquakes, which can be summarized as follows: eighty-three earthquakes in California; six earthquakes in Taiwan – the Chi-Chi main shock and five aftershocks; and seventy-one earthquakes in: other parts of the U.S. (Alaska, Idaho, and Nevada), in Canada, China, Greece, Iran, Italy, Japan, Mexico, New Zealand and Turkey.

## 1.3 EXAMINATION OF DATA

Examination of the recorded data led to binning the data into three $V_{s30}$ ranges. One bin was for data recorded at sites with $V_{s30} \leq 211$ m/sec ($V_{s30}$ = 100 to 211 m/sec), which constitute "soft soil sites." The choice of $V_{s30}$ = 211 m/sec was made to include sites (e.g., El Centro array #7) that are known to have "soft soil sites" characteristics. Another bin was for data recorded at sites with $V_{s30} \geq 450$ m/sec ($V_{s30}$ = 450 to 2000 m/sec). The choice of $V_{s30}$ = 450 is based on the considerations discussed later in this section; these sites may be reasonably designated as "quasi-linear sites" because they appear to show very weak nonlinearity, especially for sites with $V_{s30}$ exceeding about 600 m/sec (~2000 fps). The remaining data were recorded at sites with 211 m/sec < $V_{s30}$ < 450 m/sec, which exhibit moderate to strong nonlinear characteristics, especially for sites with $V_{s30}$ less than about 300 m/sec (~1000 fps).

The number of recordings at "soft soil sites," $V_{s30} \leq 211$ m/sec, is 432, of which 51 were recorded during the Chi-Chi, Taiwan, mainshock, and 176 were recorded during the five Chi-Chi aftershocks. The number of recordings at "nonlinear soil sites," 211 m/sec < $V_{s30}$ < 450 m/sec, is 4158, of which 153 were recorded during the Chi-Chi, Taiwan, mainshock, and 558 were recorded during the five Chi-Chi aftershocks. The number of recordings at "quasi-linear sites," $V_{s30} \geq 450$ m/sec, is 2545, of which 192 were recorded during the Chi-Chi, Taiwan, mainshock, and 674 were recorded during the five Chi-Chi aftershocks.

The magnitude-distance, magnitude-$V_{s30}$, magnitude-PGA, magnitude-PGV, and magnitude-peak PGD distributions of the 7120 recordings are presented in Figures 1.1, 1.2, 1.3, 1.4, and 1.5, respectively. Note that the spectral values for $T$ = 0.01 sec are used in this study to represent PGA in lieu of the peak value of the rotated accelerogram.

The information gleamed from Figures 1.1 through 1.5 may be summarized as follows:

- Figure 1.1 (magnitude-distance distribution) shows that the number of recordings, at distances less than about 10 km, has significantly increased since the first NGA project. However, the recordings within each of the $V_{s30}$ bins, is still not sufficiently robust. It is, therefore, difficult to "mathematically" constrain the values at small distances, particularly for large magnitude earthquakes. Reliance must also be placed on some physical attributes, analytical results, and on judgment.
- Figure 1.2 (magnitude-$V_{s30}$ distribution) shows that only a few recordings (65) were at sites with $V_{s30} \geq 1000$ m/sec. That is, over 95% of the recordings within the "quasi-linear sites" bin are on stiff or firm soils, and soft or weathered rock.
- Figures 1.3, 1.4, and 1.5 (magnitude-PGA, magnitude-PGV, magnitude-PGD distributions, respectively) show that except for a handful of recordings, the values of PGA are less than about 0.8 *g*, the values of PGV

are less than about 100 cm/sec, and the values of PGD are less than about 80 cm.

- Figures 1.3, 1.4, and 1.5 also show that PGA is far less dependent on magnitude than PGV, and that PGD is somewhat more dependent on magnitude than PGV.

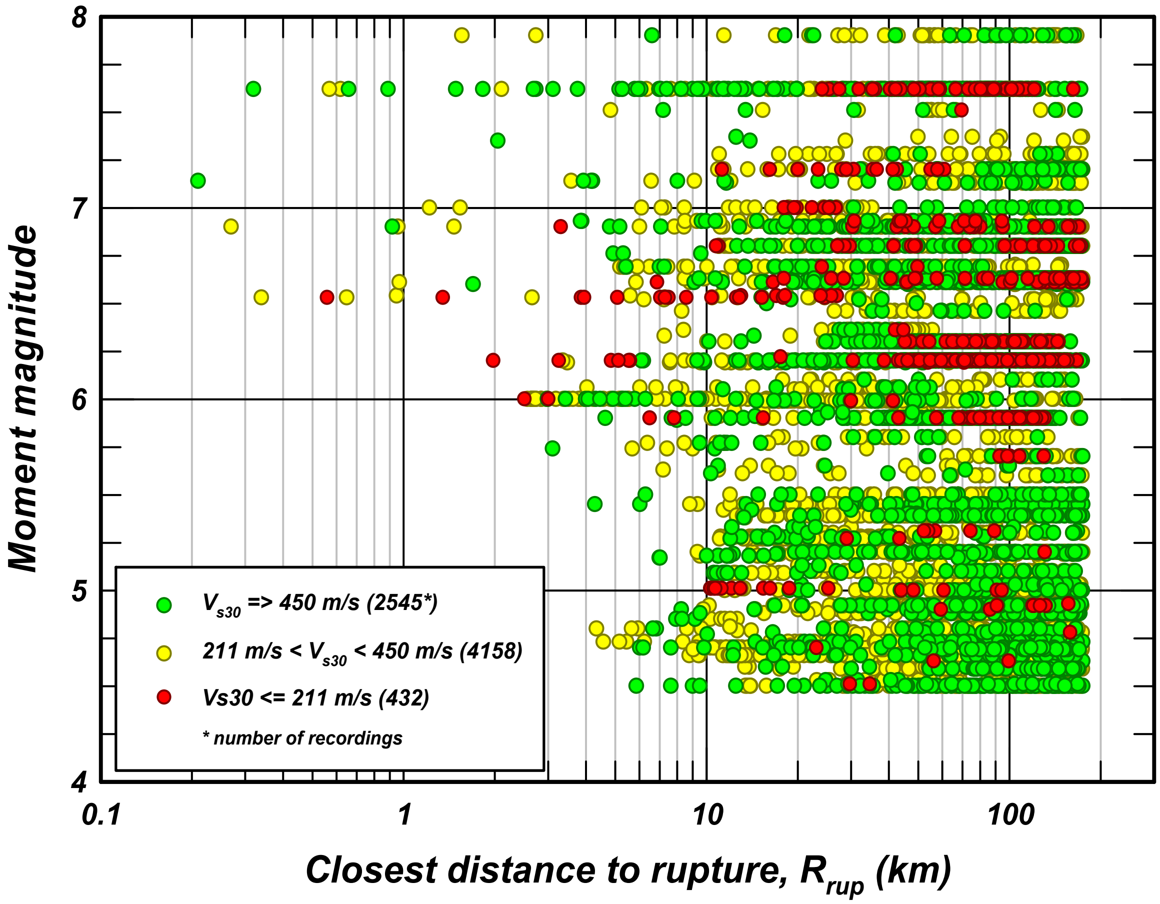


**Figure 1.1 Magnitude-distance distribution of NGA-West2 free-field records for distances ≤ 175 km and M ≥ 4.5 grouped in three $V_{s30}$ bins ($V_{s30}$ ≥ 450 m/sec; 211 m/sec < $V_{s30}$ < 450 m/sec; and $V_{s30}$ ≤ 211 m/sec).**

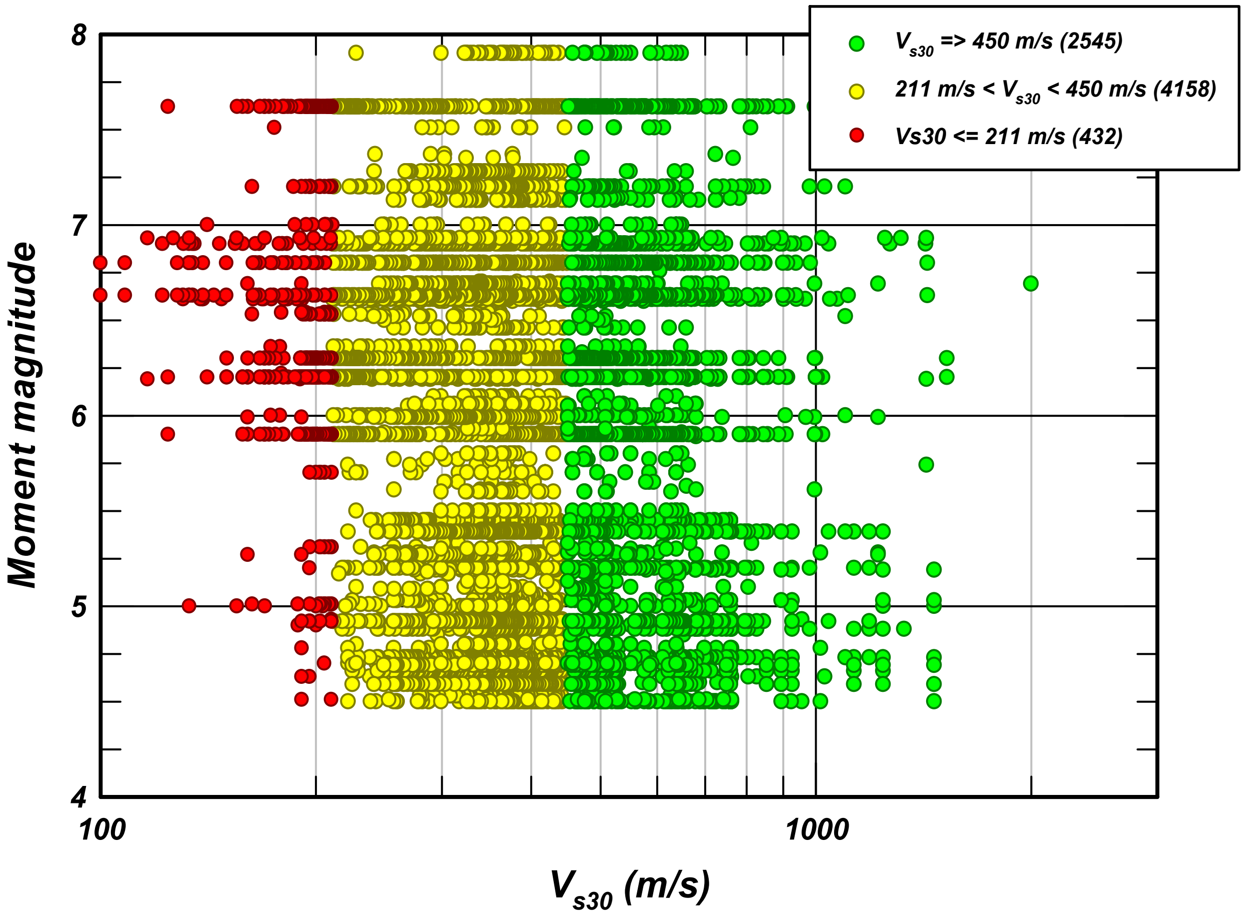


**Figure 1.2 Magnitude-$V_{s30}$ distribution of NGA-West2 free field records for distances ≤ 175 km and M ≥ 4.5 grouped in three $V_{s30}$ bins ($V_{s30}$ ≥ 450 m/sec; 211 m/sec < $V_{s30}$ < 450 m/sec; and $V_{s30}$ ≤ 211 m/sec).**

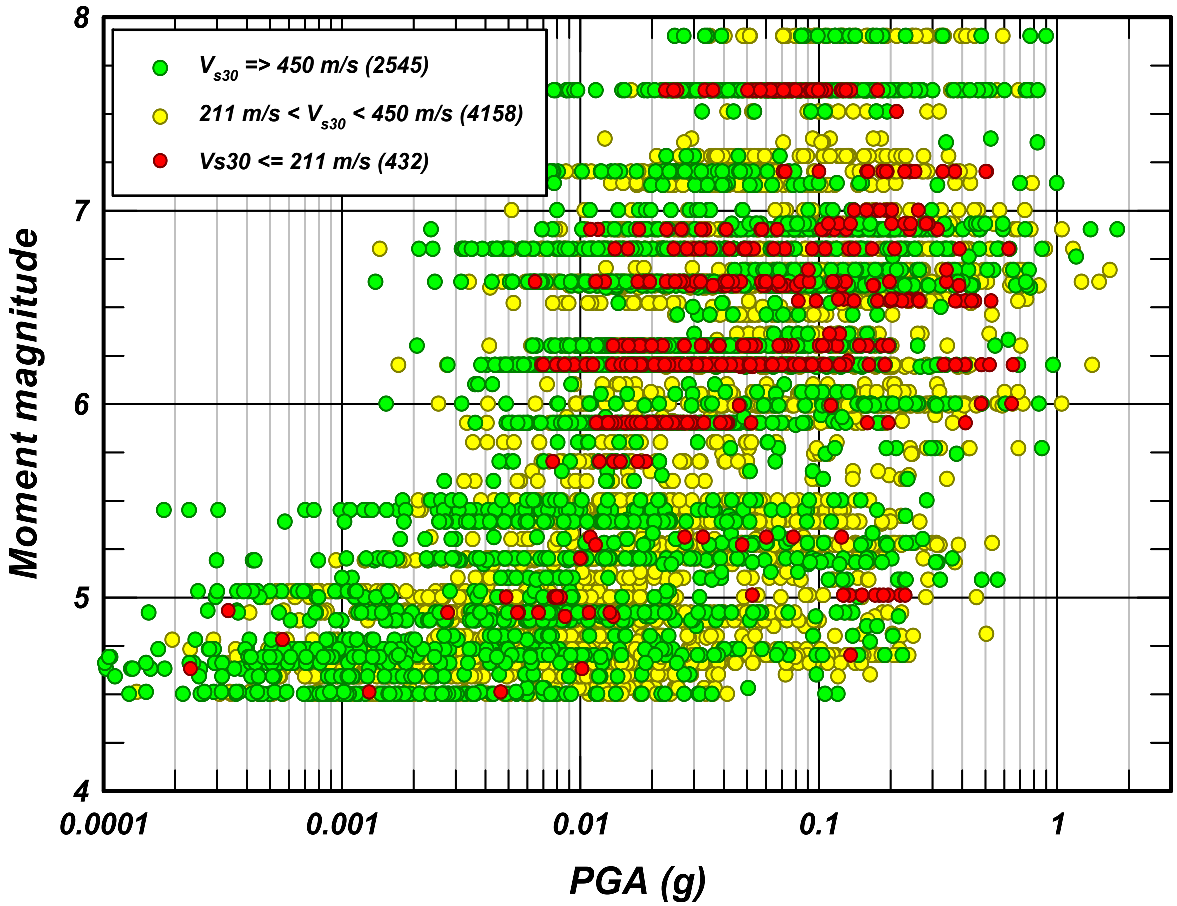


**Figure 1.3** **Magnitude-PGA distribution of NGA-West2 free field records for distances ≤ 175 km and M ≥ 4.5 grouped in three $V_{s30}$ bins ($V_{s30}$ ≥ 450 m/sec; 211 m/sec < $V_{s30}$ < 450 m/sec; and $V_{s30}$ ≤ 211 m/sec).**

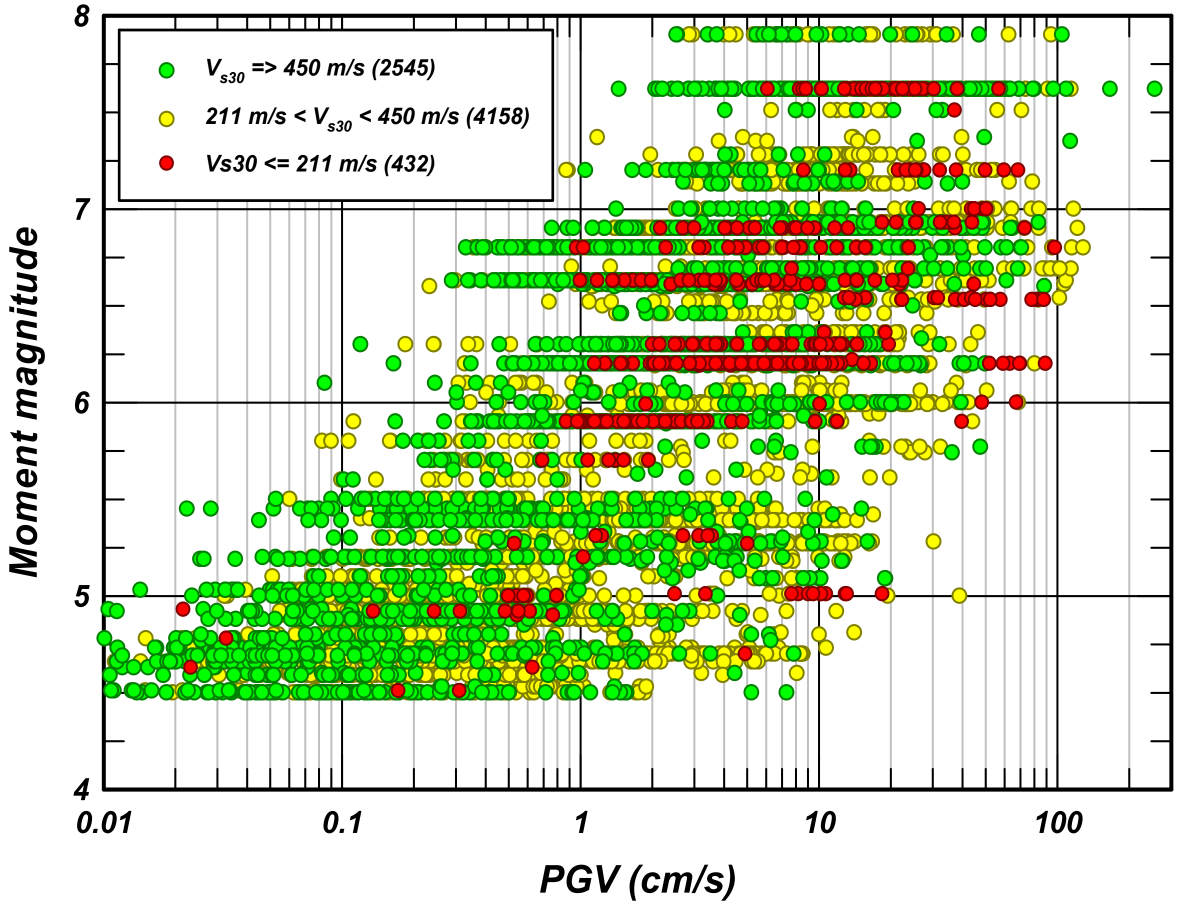


**Figure 1.4** **Magnitude-PGV distribution of NGA-West2 free field records for distances ≤ 175 km and M ≥ 4.5 grouped in three $V_{s30}$ bins ($V_{s30}$ ≥ 450 m/sec; 211 m/sec < $V_{s30}$ < 450 m/sec; and $V_{s30}$ ≤ 211 m/sec).**

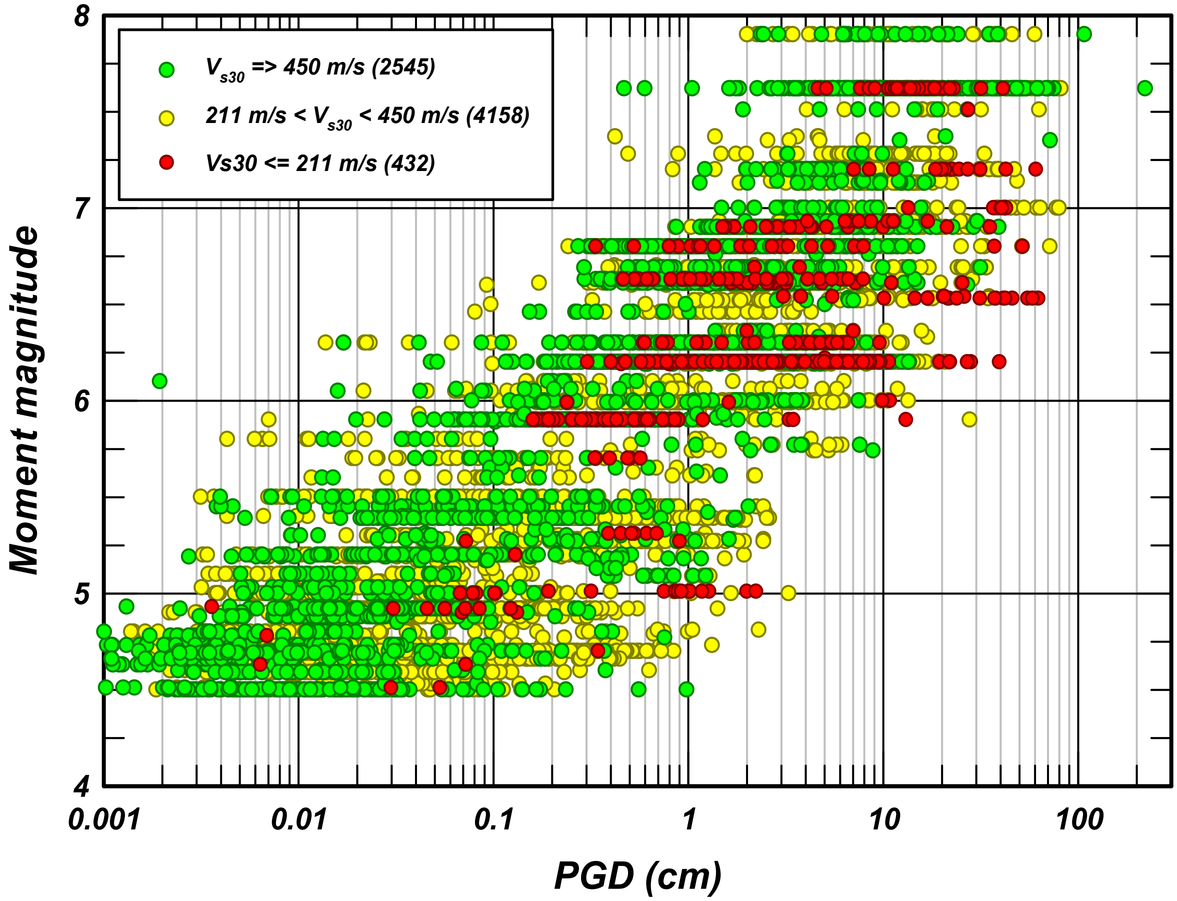


**Figure 1.5** **Magnitude-PGD distribution of NGA-West2 free field records for distances ≤ 175 km and M ≥ 4.5 grouped in three $V_{s30}$ bins ($V_{s30}$ ≥ 450 m/sec; 211 m/sec < $V_{s30}$ < 450 m/sec; and $V_{s30}$ ≤ 211 m/sec).**

## 1.4 EXAMINATION OF NONLINEARITY

The sites at which the recordings examined in the previous section comprise a wide range of subsurface conditions. To assess the extent of nonlinearity exhibited at the recording sites, a proxy for "shear strain" induced by the shaking will be used. Seismologist have long suggested that the ratio of the particle velocity at the ground surface (PGV) divided by the average shear wave velocity of the underlying subsurface profile is a reasonable indication of the maximum shear strain, $\gamma_{max}$, induced during shaking. That is:

$$\gamma_{max} = \left( PGV / V_{s30} \right) \tag{1.1}$$

The use of $V_{s30}$ in this study is dictated by the fact that only that information is available for all the sites.

To estimate a "shear stress-shear strain" relationship, PGA can be used as a proxy for shear stress. Accordingly, the values of PGA versus $\gamma_{max}$ for each of the site bins described above can be readily calculated using the information provided in the flatfile for each site. These values are presented in Figure 1.6, which shows that progressively smaller strains are induced as the "stiffness" of the sites increases and also shows that progressively larger strains are induced as the level of shaking is increased.

The information available for the sites within "quasi-linear sites" bin ($V_{s30}$ = 450 to 2000 m/sec) are examined in more detail in Figure 1.7. The cumulative distribution of $\gamma_{max}$ for the recordings obtained during the Chi-Chi, Taiwan, mainshock, those obtained during the Chi-Chi, Taiwan, five aftershocks included in the flatfile, and those for all the other events within this bin are presented in Figure 1.7. The information in Figure 1.7 indicates that the behavior of the sites in Taiwan during the main shock is significantly different from that during the five aftershocks and from that of all the other recordings for sites with $V_{s30}$ = 450 to 2000 m/sec. Because of this, it was felt that the recordings from the Chi-Chi, Taiwan, mainshock should not be included in the $V_{s30}$ = 450 to 2000 m/sec bin. However, including the five Chi-Chi aftershocks is appropriate.

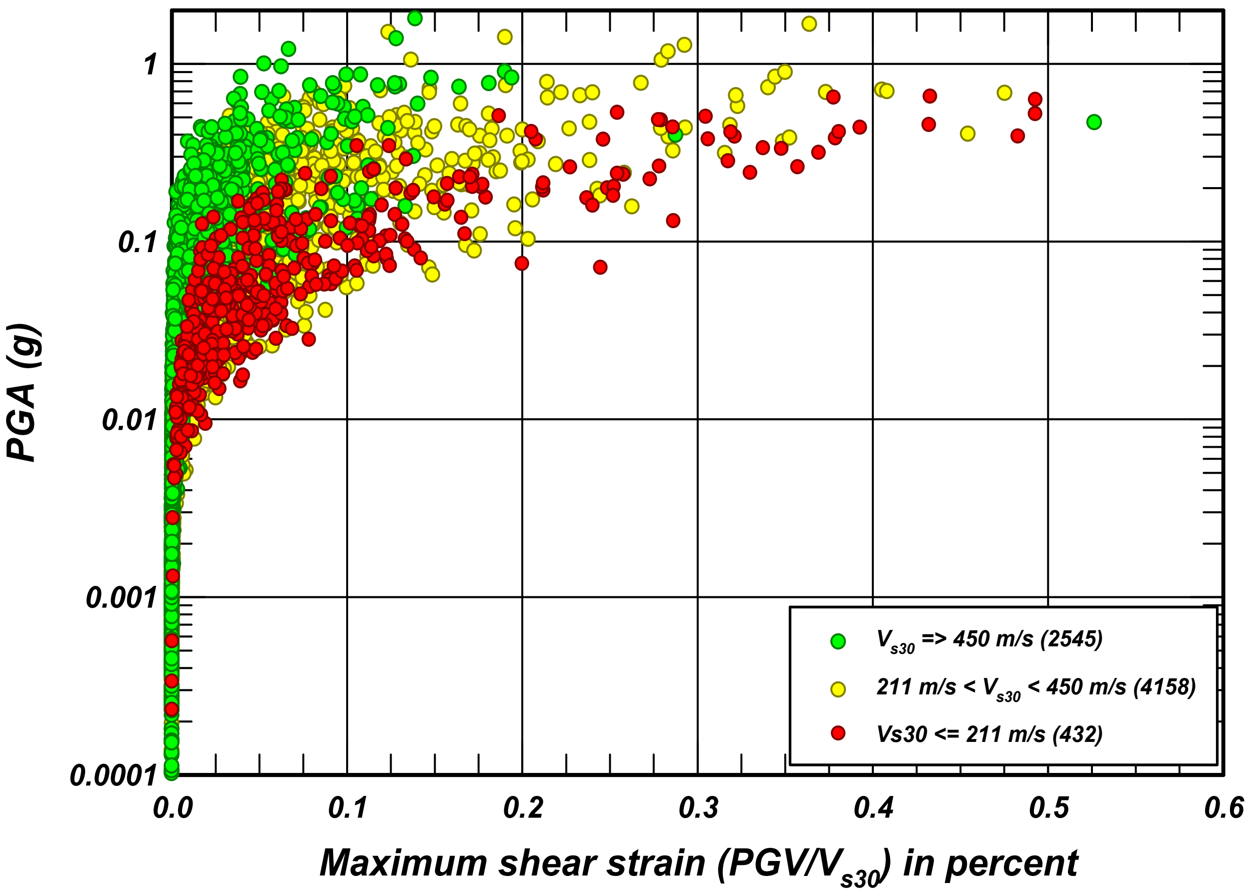


**Figure 1.6** **Distribution of maximum strain (PGV/$V_{s30}$) of NGA-West2 free-field recording stations at distances ≤ 175 km and M ≥ 4.5 grouped in three $V_{s30}$ bins ($V_{s30}$ ≥ 450 m/sec; 211 m/sec < $V_{s30}$ < 450 m/sec; and $V_{s30}$ ≤ 211 m/sec).**

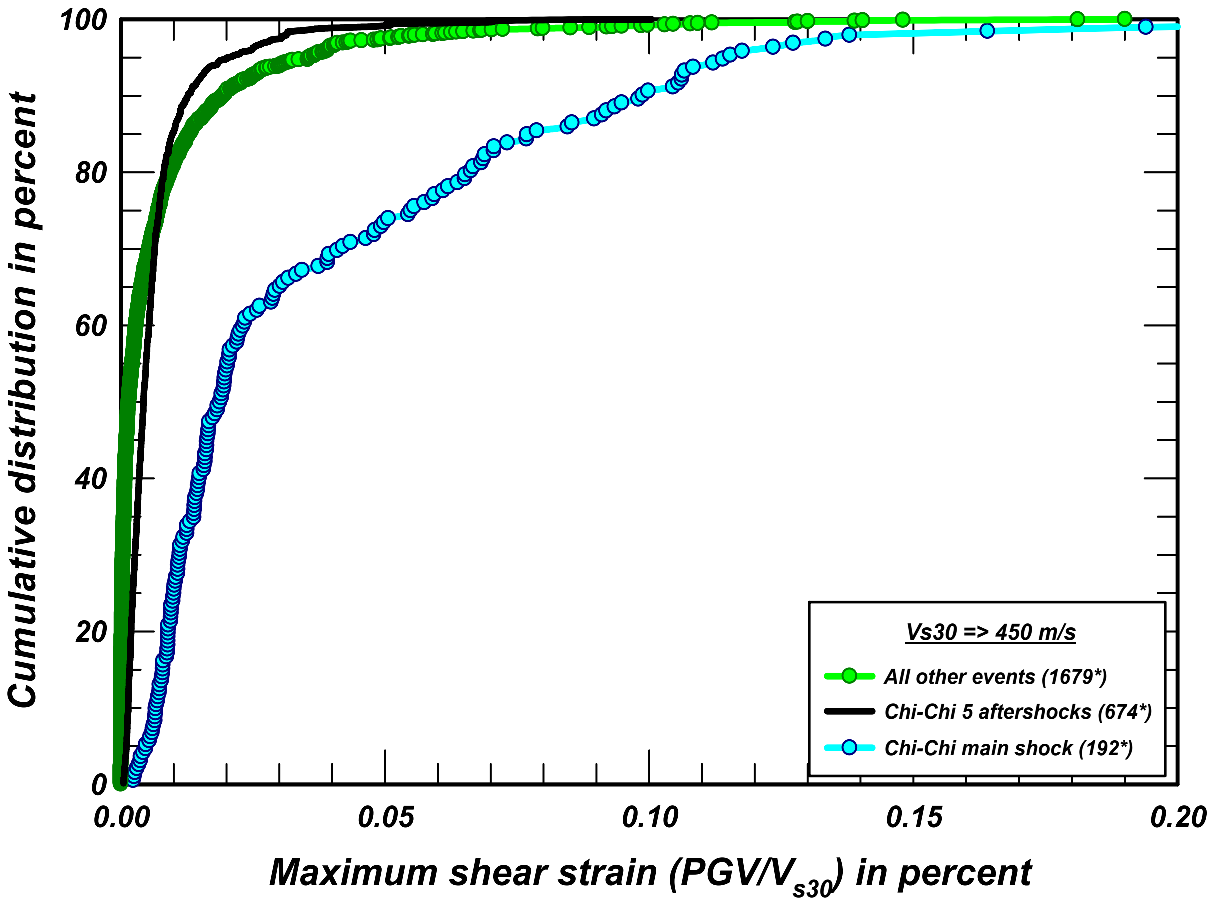


**Figure 1.7** **Distribution of maximum strain (PGV/$V_{s30}$) of NGA-West2 free field recording stations at distances ≤ 175 km with $V_{s30}$ ≥ 450 m/sec during the Chi-Chi main shock, Chi-Chi aftershocks, and all other earthquakes, M ≥ 4.5.**

Totally different trends were observed for the recordings included in the other two bins in that including or not including the recordings from the Chi-Chi mainshock had little effect on the cumulative distribution of $\gamma_{max}$. Therefore, the recordings from the Chi-Chi mainshock will be included in the "NL soil sites" and the "soft soil sites" bins, when the data in those bins are studied in more detail.

The cumulative distribution of $\gamma_{max}$ for the recordings within the "quasi-linear sites" bin, (excluding the recordings obtained during the Chi-Chi main shock), those obtained within the "NL soil sites" bin, and those within the "soft soil sites" bin are presented in Figure 1.8. The information in this figure and the modulus reduction curves shown in Figure 1.9 lead to the following observations:

- The modulus reduction curves shown in Figure 1.9 cover a wide range of geotechnical materials, from moderately dense sands at relatively shallow depths to competent rock. It is believed that for the "quasi-linear sites" ($V_{s30}$ = 450 to 2000), probably the most applicable curves are:

- a curve very close to that identified as the peninsular range in Figure 1.9 for sites with $V_{s30}$ ranging from about 450 m/sec to 600 m/sec
- the weathered rock curve for sites with $V_{s30}$ ranging from about 600 m/sec to 1000 m/sec; and
- a curve about halfway between the weathered rock and the competent rock, up to a maximum shear strain of about 0.1% for sites with $V_{s30}$ = 1000 to 2000 m/sec. The remaining "soil" modulus reduction curves in Figure 1.9 are applicable to the sites with $Vs30$ < 450 m/sec, including the soft soil sites.
- The modulus reduction curves in Figure 1.9 show that for soils (the lower 5 curves in Figure 1.9), the maximum modulus can decrease by about 8 to 16% (average of about 12%) if the strain levels induced by shaking are as high as about 0.01%. In this regard, it should be noted that the shear strains used in Figure 1.9 represent laboratory-applied shear strains of uniform amplitude over a number of cycles. The shear strains induced by the earthquake ground motions are not uniform in amplitude. The use of an "equivalent uniform strain" to represent the strain level induced during shaking was introduced as part of the equivalent linear site response methodology (Idriss and Seed, 1967; Seed and Idriss, 1969). The equivalent uniform strain is typically 0.4 to about 0.75 of the maximum shear strain, depending on the duration of shaking, which is a function of magnitude, among others. The following equation has been used for this purpose (Idriss and Sun, 1992):

$$\frac{\gamma_{unif}}{\gamma_{max}} = \frac{(M-1)}{10} \tag{1.2}$$

- On that basis then, and using a ratio of $\gamma_{unif}$ to $\gamma_{max}$ of say two-thirds, the 0.01% uniform strain would correspond to 0.015%. At this level of strain, the soil is behaving mostly in the linear range with very thin hysteretic loops as shaking goes on. Accordingly, a modulus reduction of less than about 12% would constitute essentially a linear or quasi-linear behavior.
- A modulus reduction of 12% corresponds to about a uniform shear strain of about 0.01%, for soil sites with $V_{s30}$ < 450 m/sec as noted above, corresponds to about 0.016% for sites with $V_{s30}$ = 450 to 600 m/sec, and corresponds to about 0.05 to 0.1% for sites with $V_{s30}$ greater than 600 m/sec.
- Using these uniform shear strain values as the demarcation between essentially linear and non-linear site response and taking into account the conversion from uniform to maximum strain, the cumulative plots in Figure 1.8 indicate that:
- no more than about 4% of the sites in the "quasi-linear site" bin extended into the mildly nonlinear range;

- at least 30% of the sites in the "NL soil sites" bin extended into the moderately to high nonlinear range
- close to 70% of the sites in the "soft soil sites" bin extended well into the nonlinear range.

The recordings at the sites in the "quasi-linear sites" bin are further examined by binning the recording in eight $V_{s30}$ bins ($V_{s30}$ = 450 to 800 m/sec in 50 m/sec increments and one bin for $V_{s30}$ = 800 to 2000 m/sec) and by using Equation (1.2) to obtain the proxy equivalent uniform shear strain for each recording. The corresponding values of PGA versus equivalent uniform shear strain for the eight bins are presented in Figure 1.10. Using the values above for demarcation of linear-nonlinear behavior and the information in Figure 1.10 produces the results listed in Table 1.1.

The data in the other two $V_{s30}$ will be examined in more detail in separate reports. Such an examination will incorporate the results of prior studies, such as those completed by Choi and Stewart (2005), Walling et al. (2008), and Kamai et al. (2012).

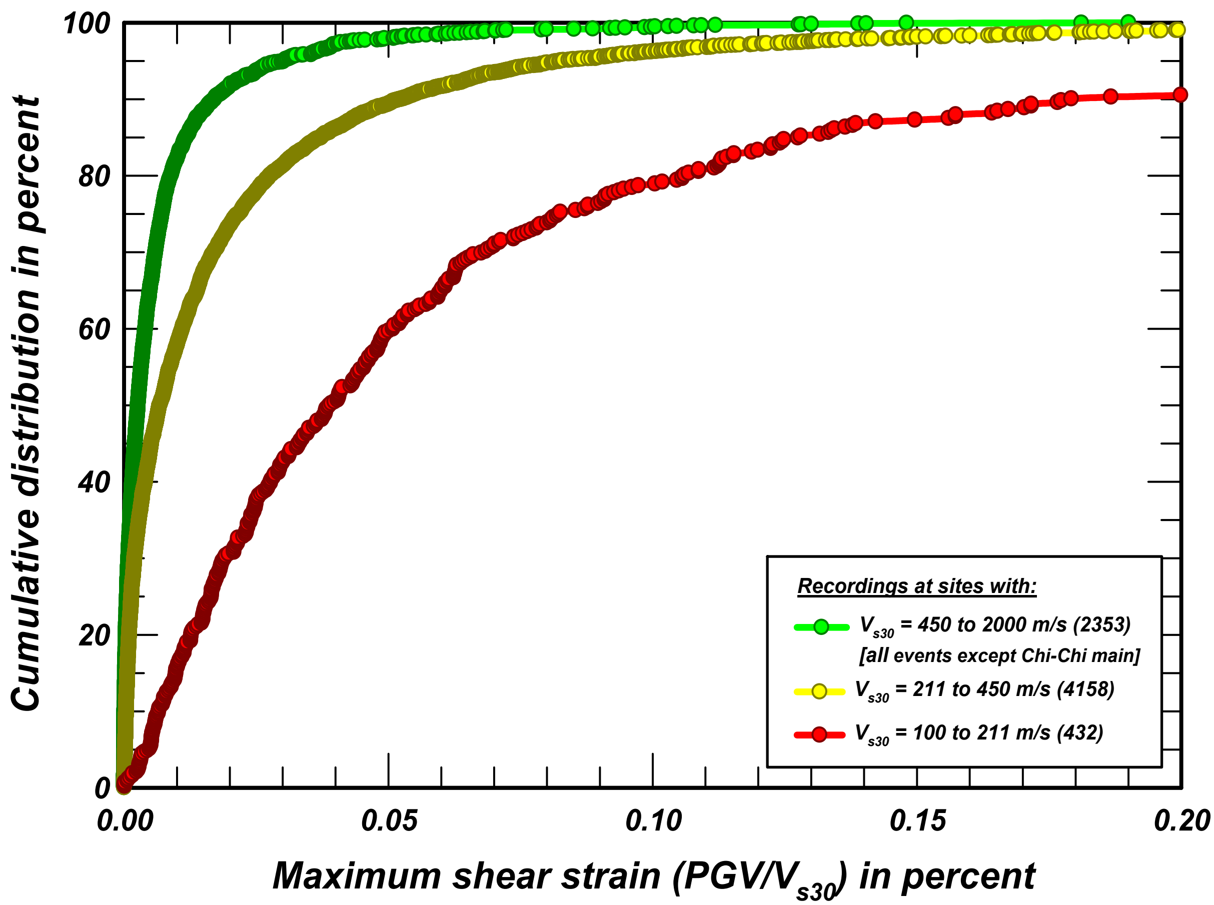


**Figure 1.8** **Distribution of maximum strain (PGV/$V_{s30}$) of NGA-West2 free-field recording stations at distances ≤ 175 km for the "quasi linear sites" ($V_{s30}$ = 450 to 2000 m/sec), the "NL soil sites" ($V_{s30}$ = 211 to 450 m/sec), and the "soft soil sites" ($V_{s30}$ = 100 to 211 m/sec).**

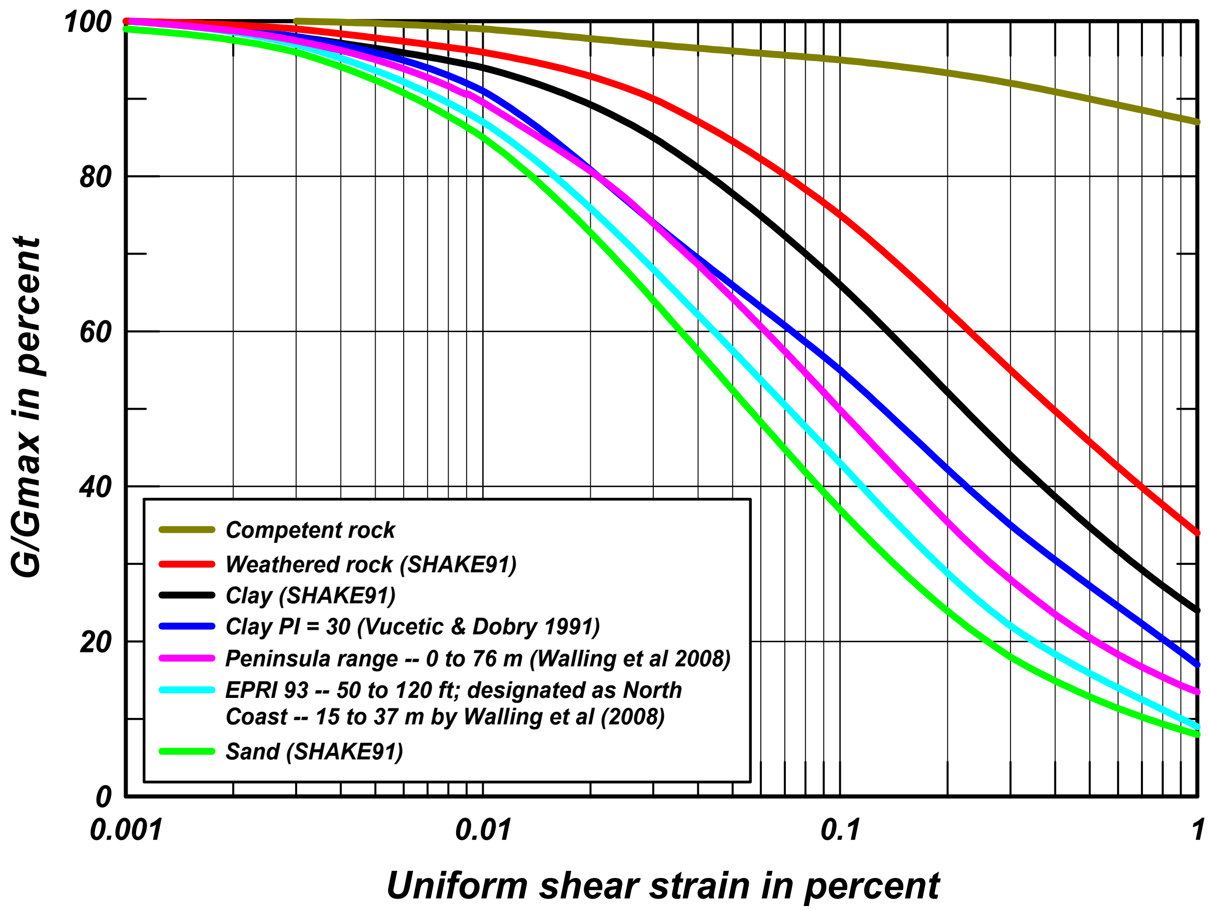


**Figure 1.9** **Variations of $G/G_{max}$ with uniform shear strain for various geotechnical materials.**

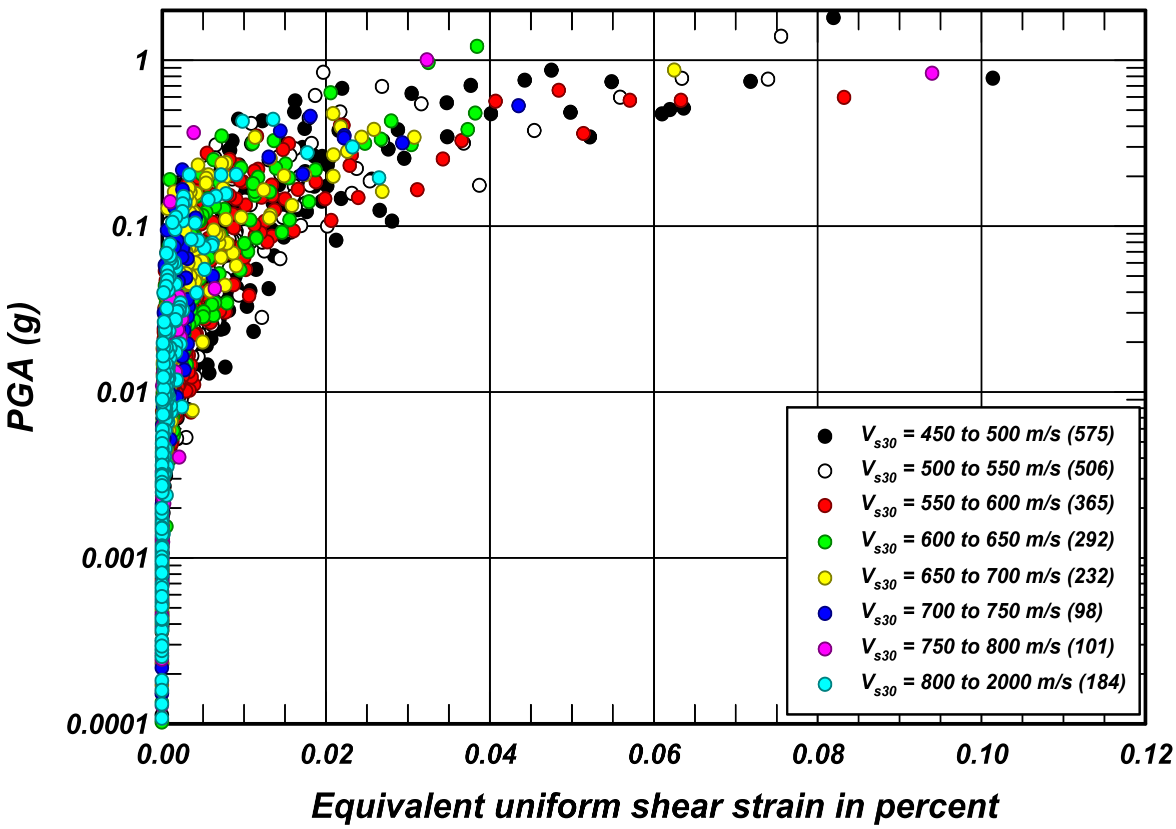


**Figure 1.10** **Distribution of equivalent uniform strain of NGA-West2 free-field recording stations with $V_{s30}$ ≥ 450 m/sec at distances ≤ 175 km and M ≥ 4.5 for all earthquakes except Chi-Chi mainshock, binned in 50 m/sec increments in $V_{s30}$ from $V_{s30}$ = 450 to 800 m/sec and for $V_{s30}$ ≥ 800 m/sec.**

**Table 1.1 Number of recordings, binned in 50 m/sec increments in $V_{s30}$ from $V_{s30}$ = 450 to 800 m/sec and for $V_{s30} \geq 800$ m/sec, and number of recordings at sites, within each $V_{s30}$ bin, where response can be considered nonlinear (NL).**

| Range of $V_{s30}$ within the bin | Number of recordings within bin | NL sites ** | Percent NL |
|---|---|---|---|
| 450 to 500 m/sec | 575 | 30 | 5.2 |
| 500 to 550 m/sec | 506 | 20 | 4.0 |
| 550 to 600 m/sec | 365 | 16 | 4.4 |
| 600 to 650 m/sec | 292 | 0 | 0 |
| 650 to 700 m/sec | 232 | 1 | 0.4 |
| 700 to 750 m/sec | 98 | 0 | 0 |
| 750 to 800 m/sec | 101 | 0 | 0 |
| 800 to 2000 m/sec | 184 | 0 | 0 |
| All recordings *<br>450 to 2000 m/sec | 2353 | 67 | 2.9 |

* NGA-West2 free field recording stations with $V_{s30} \geq 450$ m/sec at distances ≤ 175 km and M ≥ 4.5 for all earthquakes except Chi-Chi mainshock

** Number of recordings at sites where response can be considered nonlinear (NL)

# 2 EMPIRICAL MODEL FOR ESTIMATING AVERAGE HORIZONTAL VALUES OF PSEUDO-ABSOLUTE SPECTRAL ACCELERATIONS (PSA) GENERATED BY CRUSTAL EARTHQUAKES

## 2.1 GENERAL

Based on the considerations summarized in Sections 2.2 and 2.3, an empirical model for estimating the average horizontal values of PSA (5% spectral damping) is developed using only the recordings described above as being part of the "quasi-linear sites" $V_{s30}$ bin ($V_{s30}$ = 450 to 2000 m/sec). These recordings, totaling 2353, were obtained during 152 earthquakes, 73 of which occurred in California, one in Nevada, 5 in Japan, the Wenchuan main shock and its 53 aftershocks in Chica, 2 in New Zealand and 17 in other countries (Canada, Mexico, Taiwan, Italy, Turkey, and Iran). These earthquakes are listed in Appendix A; the earthquake identification number (EQID) identified in the flatfile, the earthquake name, magnitude, mechanism and number of recording are also listed in Appendix A.

The general form of the model adopted in this study is as follow:

$$Ln(PSA) = \alpha_1 + \alpha_2 M + \alpha_3 (8.5 - M)^2 - (\beta_1 + \beta_2 M) Ln(R_{rup} + 10) + \xi Ln(V_{s30}) + \gamma R_{rup} + \varphi F \quad (2.1)$$

The variables included in Equation (2.1) are defined as follows: PSA in *g*'s is the 5% damped pseudo-absolute spectral acceleration; $M$ is moment magnitude; $R_{rup}$ in km is the closest distance to the rupture surface; $V_{s30}$ in m/sec is the average shear wave velocity over the top 30 m below the ground surface; and $F$ refers to source mechanism, with $F$ = 0 referring to strike slip and $F$ =1 referring to reverse mechanisms. Note that the reverse mechanism data base used in this study includes all data from events with mechanism equal to 2, 3, and 4, and all strike slip mechanism data base includes all data from events with mechanism 0 and 1. The sparsity of data for mechanism 1 (normal faulting) precluded separating its data from the strike slip data base. The parameters $\alpha_1$, $\alpha_2$, $\beta_1$, $\beta_2$ …. $\varphi$ were determined from the regression results.

## 2.2 PARAMETERS

The parameters derived are listed in Table 2.1 for $M \leq 6.75$ and in Table 2.2 for $M \geq 6.75$. Note that for $V_{s30} > 1200$ m/sec, the PSA values calculated using $V_{s30} = 1200$ m/sec are used.

Table 2.1 Derived parameters for sites with $V_{s30}$ ≥ 450 m/sec and M ≤ 6.75.

| Period (sec) | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\beta_1$ | $\beta_2$ | $\xi$ | $\gamma$ | $\varphi$ |
|---|---|---|---|---|---|---|---|---|
| 0.01 | 7.0887 | 0.2058 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.02 | 7.1157 | 0.2058 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.03 | 7.2087 | 0.2058 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.04 | 7.3287 | 0.2058 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.05 | 6.2638 | 0.0625 | 0.0417 | 2.8664 | -0.2418 | -0.631 | -0.0061 | 0.08 |
| 0.075 | 5.9051 | 0.1128 | 0.0527 | 2.9406 | -0.2513 | -0.591 | -0.0056 | 0.08 |
| 0.1 | 7.5791 | 0.0848 | 0.0442 | 3.0190 | -0.2516 | -0.757 | -0.0042 | 0.08 |
| 0.15 | 8.0190 | 0.1713 | 0.0329 | 2.7871 | -0.2236 | -0.911 | -0.0046 | 0.08 |
| 0.2 | 9.2812 | 0.1041 | 0.0188 | 2.8611 | -0.2229 | -0.998 | -0.0030 | 0.08 |
| 0.25 | 9.5804 | 0.0875 | 0.0095 | 2.8289 | -0.2200 | -1.042 | -0.0028 | 0.08 |
| 0.3 | 9.8912 | 0.0003 | -0.0039 | 2.8423 | -0.2284 | -1.030 | -0.0029 | 0.08 |
| 0.4 | 9.5342 | 0.0027 | -0.0133 | 2.8300 | -0.2318 | -1.019 | -0.0028 | 0.08 |
| 0.5 | 9.2142 | 0.0399 | -0.0224 | 2.8560 | -0.2337 | -1.023 | -0.0021 | 0.08 |
| 0.75 | 8.3517 | 0.0689 | -0.0267 | 2.7544 | -0.2392 | -1.056 | -0.0029 | 0.08 |
| 1 | 7.0453 | 0.1600 | -0.0198 | 2.7339 | -0.2398 | -1.009 | -0.0032 | 0.06 |
| 1.5 | 5.1307 | 0.2429 | -0.0367 | 2.6800 | -0.2417 | -0.898 | -0.0033 | 0.04 |
| 2 | 3.3610 | 0.3966 | -0.0291 | 2.6837 | -0.2450 | -0.851 | -0.0032 | 0.02 |
| 3 | 0.1784 | 0.7560 | -0.0214 | 2.6907 | -0.2389 | -0.761 | -0.0031 | 0.02 |
| 4 | -2.4301 | 0.9283 | -0.0240 | 2.5782 | -0.2514 | -0.675 | -0.0051 | 0 |
| 5 | -4.3570 | 1.1209 | -0.0202 | 2.5468 | -0.2541 | -0.629 | -0.0059 | 0 |
| 7.5 | -7.8275 | 1.4016 | -0.0219 | 2.4478 | -0.2593 | -0.531 | -0.0057 | 0 |
| 10 | -9.2857 | 1.5574 | -0.0035 | 2.3922 | -0.2586 | -0.586 | -0.0061 | 0 |

Note that for $V_{s30}$ > 1200 m/s, the PSA values calculated using $V_{s30}$ = 1200 m/sec are used.

**Table 2.2 Derived parameters for sites with $V_{s30}$ ≥ 450 m/sec and M ≥ 6.75**

| Period (sec) | α1 | α2 | α3 | β1 | β2 | ξ | γ | φ |
|---|---|---|---|---|---|---|---|---|
| 0.01 | 9.0138 | -0.0794 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.02 | 9.0408 | -0.0794 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.03 | 9.1338 | -0.0794 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.04 | 9.2538 | -0.0794 | 0.0589 | 2.9935 | -0.2287 | -0.854 | -0.0027 | 0.08 |
| 0.05 | 7.9837 | -0.1923 | 0.0417 | 2.7995 | -0.2319 | -0.631 | -0.0061 | 0.08 |
| 0.075 | 7.7560 | -0.1614 | 0.0527 | 2.8143 | -0.2326 | -0.591 | -0.0056 | 0.08 |
| 0.1 | 9.4252 | -0.1887 | 0.0442 | 2.8131 | -0.2211 | -0.757 | -0.0042 | 0.08 |
| 0.15 | 9.6242 | -0.0665 | 0.0329 | 2.4091 | -0.1676 | -0.911 | -0.0046 | 0.08 |
| 0.2 | 11.1300 | -0.1698 | 0.0188 | 2.4938 | -0.1685 | -0.998 | -0.0030 | 0.08 |
| 0.25 | 11.3629 | -0.1766 | 0.0095 | 2.3773 | -0.1531 | -1.042 | -0.0028 | 0.08 |
| 0.3 | 11.7818 | -0.2798 | -0.0039 | 2.3772 | -0.1595 | -1.030 | -0.0029 | 0.08 |
| 0.4 | 11.6097 | -0.3048 | -0.0133 | 2.3413 | -0.1594 | -1.019 | -0.0028 | 0.08 |
| 0.5 | 11.4484 | -0.2911 | -0.0224 | 2.3477 | -0.1584 | -1.023 | -0.0021 | 0.08 |
| 0.75 | 10.9065 | -0.3097 | -0.0267 | 2.2042 | -0.1577 | -1.056 | -0.0029 | 0.08 |
| 1 | 9.8565 | -0.2565 | -0.0198 | 2.1493 | -0.1532 | -1.009 | -0.0032 | 0.06 |
| 1.5 | 8.3363 | -0.2320 | -0.0367 | 2.0408 | -0.1470 | -0.898 | -0.0033 | 0.04 |
| 2 | 6.8656 | -0.1226 | -0.0291 | 2.0013 | -0.1439 | -0.851 | -0.0032 | 0.02 |
| 3 | 4.1178 | 0.1724 | -0.0214 | 1.9408 | -0.1278 | -0.761 | -0.0031 | 0.02 |
| 4 | 1.8102 | 0.3001 | -0.0240 | 1.7763 | -0.1326 | -0.675 | -0.0051 | 0 |
| 5 | 0.0977 | 0.4609 | -0.0202 | 1.7030 | -0.1291 | -0.629 | -0.0059 | 0 |
| 7.5 | -3.0563 | 0.6948 | -0.0219 | 1.5212 | -0.1220 | -0.531 | -0.0057 | 0 |
| 10 | -4.4387 | 0.8393 | -0.0035 | 1.4195 | -0.1145 | -0.586 | -0.0061 | 0 |

Note that for $V_{s30}$ > 1200 m/sec, the PSA values calculated using $V_{s30}$ = 1200 m/sec are used.

## 2.3 RESIDUALS

The residuals for PGA (i.e., $T$ = 0.01 sec) are plotted in Figure 2.1 in terms of residuals versus magnitude, residuals versus distance, and residuals versus $V_{s30}$. The corresponding residuals for $T$ = 0.2 sec and for $T$ = 1 sec are presented in Figures 2.2 and 2.3, respectively. The results in these figures indicate that the fitted parameters provide an excellent representation of the data in the magnitude range of 5.2 to 7.9 for PGA, 5.2 to 7.3 for $T$ = 0.2 sec, and 5.2 to 7.5 for $T$ = 1 sec. The results also indicate that excellent representation is obtained for PGA, $T$ = 0.2 sec and $T$ = 1 sec essentially in the entire distance and $V_{s30}$ ranges.

## 2.4 STANDARD ERROR TERMS

The standard error (SE) terms were obtained as part of the regression analyses and were fitted to the following expression for ease of use:

$$SE = 1.18 + 0.035Ln(T) - 0.06M \tag{2.2}$$

Equation (2.2) shows a small dependence of the SE term on magnitude, which is obtained by minimizing the standardized residuals. The minimum value of SE is assumed equal to that for $M = 7.5$. Also, the values of SE at $T < 0.05$ sec is kept equal to that at $T = 0.05$ sec and that at $T > 3$ sec, SE is kept equal to that at $T = 3$ sec.

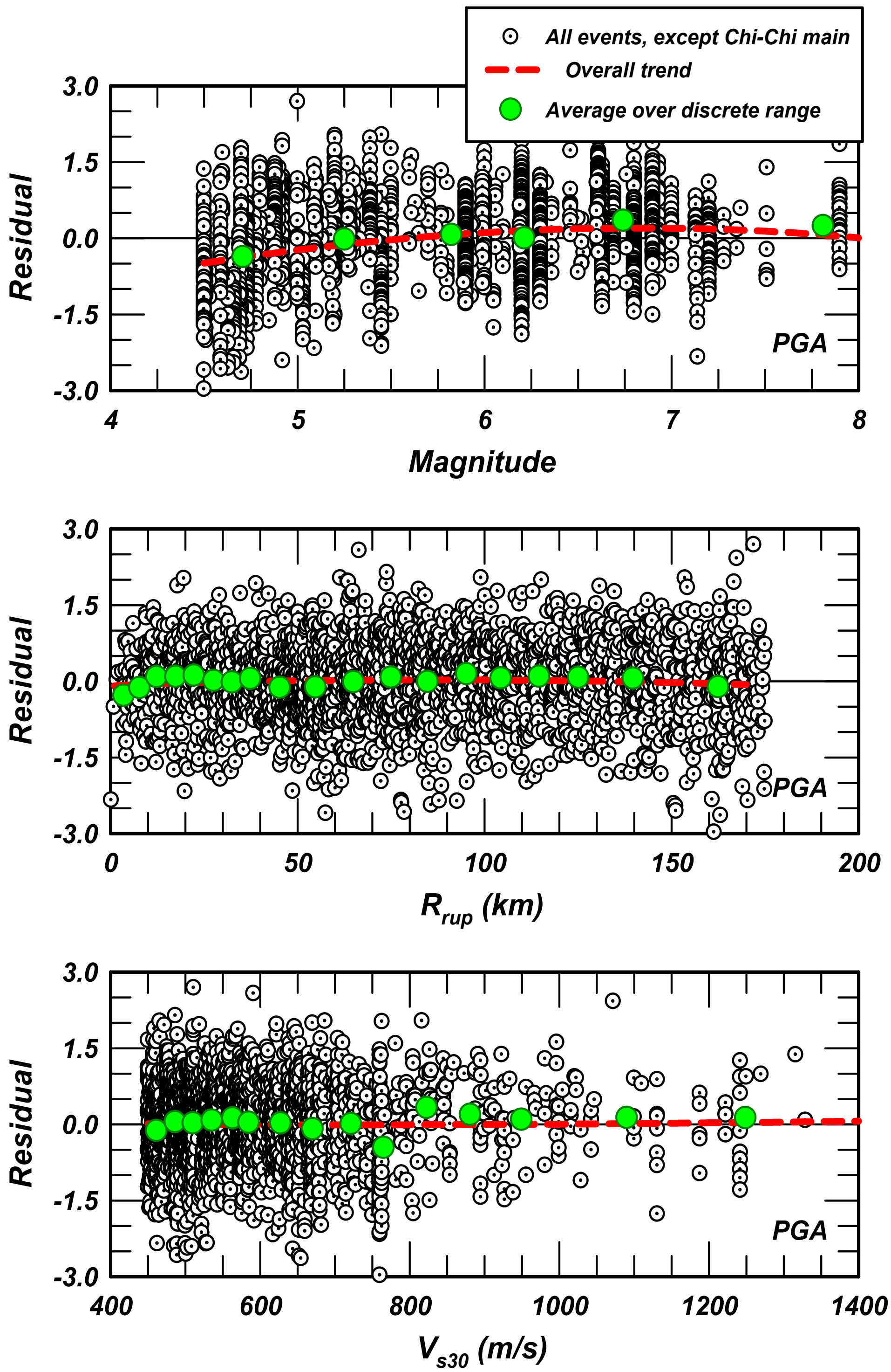


**Figure 2.1** Residuals versus magnitude, rupture distance and $V_{s30}$ using the derived equation for estimating PGA at sites with 450 m/sec ≤ $V_{s30}$ ≤ 1200 m/sec.

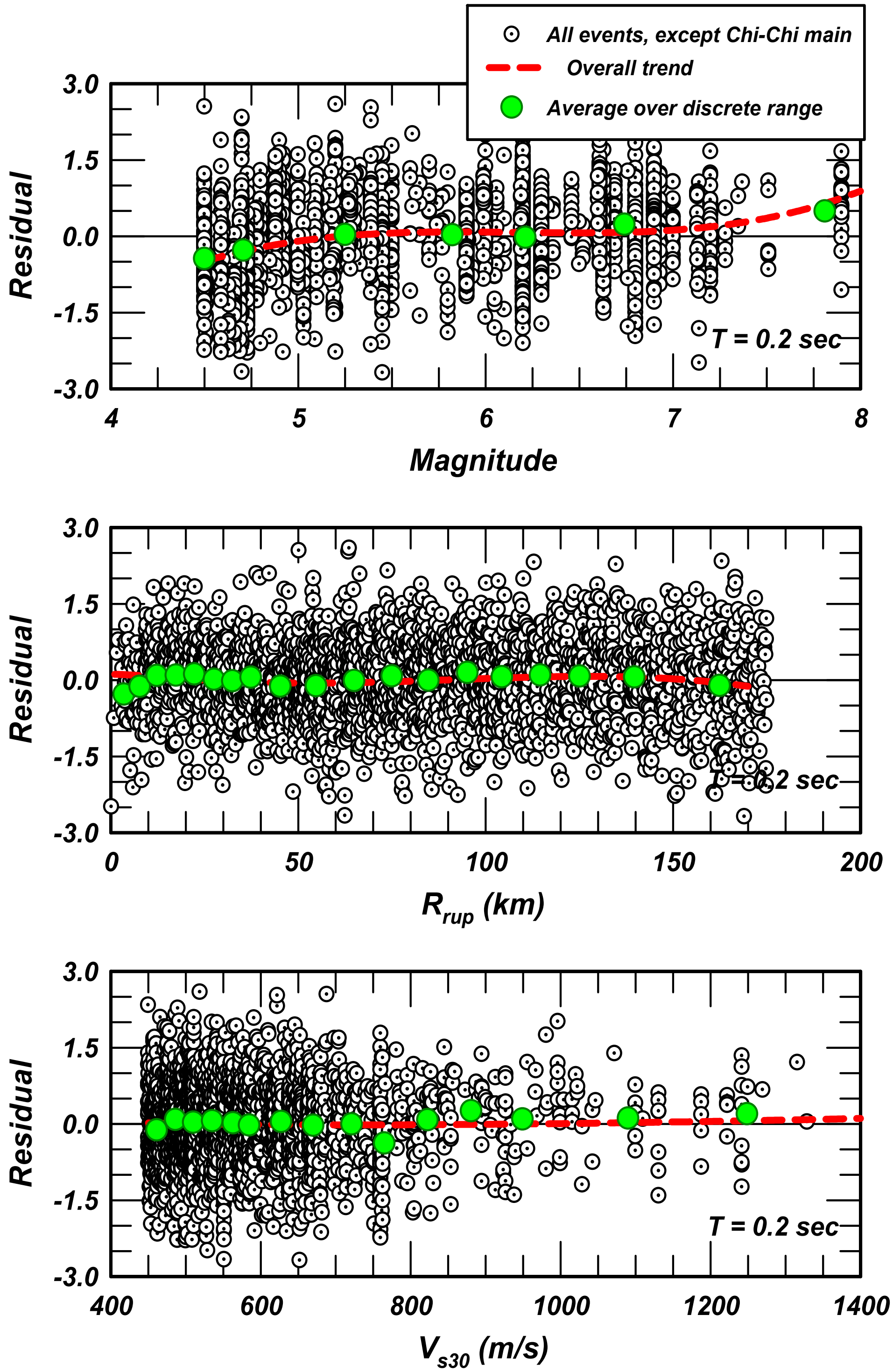


**Figure 2.2** **Residuals versus magnitude, rupture distance and $V_{s30}$ using the derived equation for estimating PSA for $T$ = 0.2 sec at sites with 450 m/sec ≤ $V_{s30}$ ≤ 1200 m/sec.**

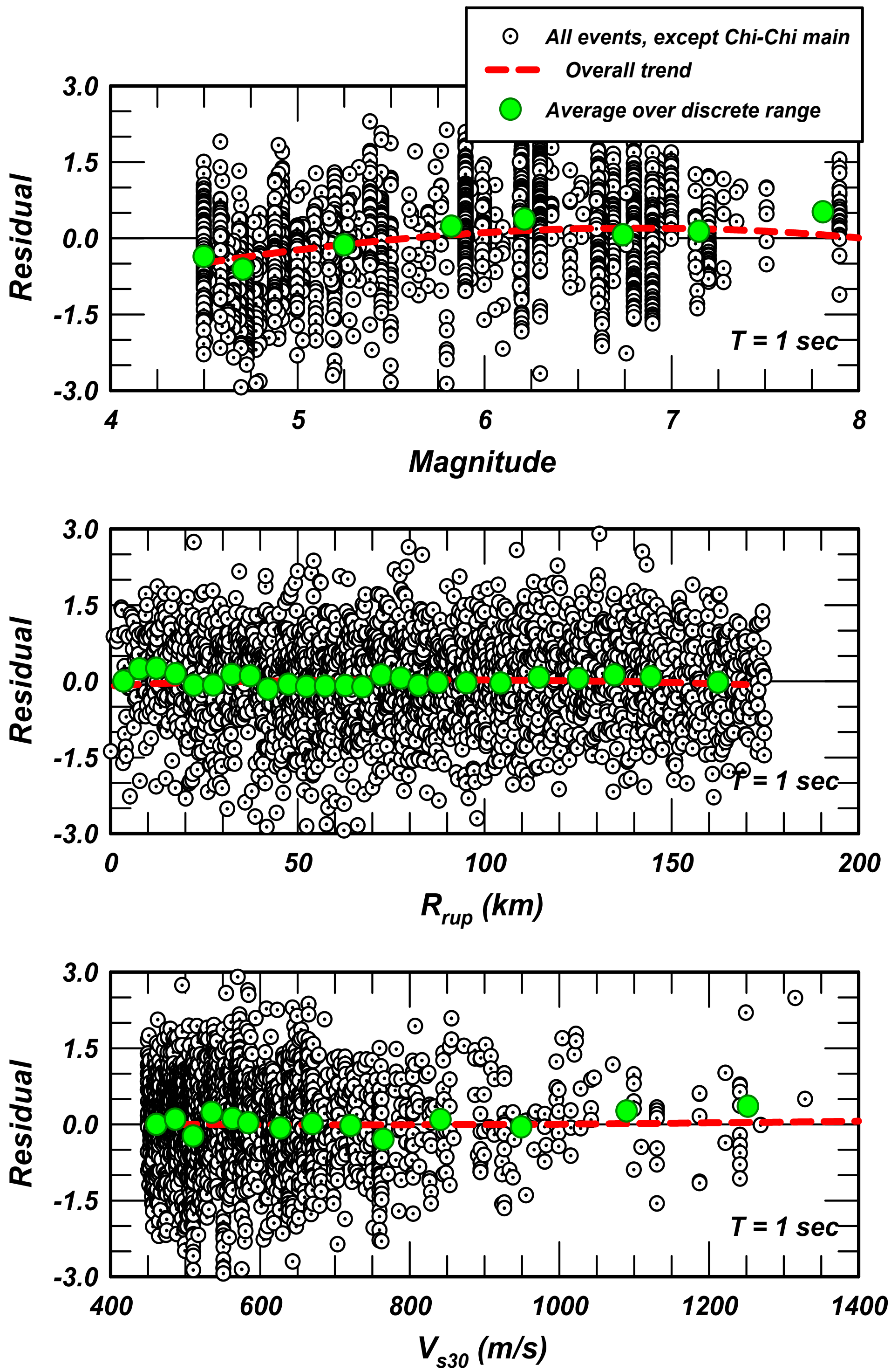


**Figure 2.3** **Residuals versus magnitude, rupture distance and $V_{s30}$ using the derived equation for estimating PSA for $T$ = 1 sec at sites with 450 m/sec ≤ $V_{s30}$ ≤ 1200 m/sec.**

## 2.5 COMPARISONS WITH 2008 NGA ATTENUATION RELATIONSHIPS

The median values of PGA as a function of $R_{rup}$ for M = 7, $V_{s30}$ = 450 m/sec and $V_{s30}$ = 900 m/sec, calculated using the parameters in Table 2.2, are presented in Figure 2.4 considering a strike slip event (mechanism 0). Also shown in Figure 2.4 are the median values of PGA as a function of $R_{rup}$ for $M$ = 7 using the parameters developed for the author's 2008 model (Idriss 2008). The parameters for the 2008 model were derived for the then-available data for sites with $V_{s30}$ = 450 to 900 m/sec to be independent of $V_{s30}$. The 2013 model includes $V_{s30}$ as an independent variable [see Equation (2.1)]. The results shown in Figure 2.4 highlight the effects of $V_{s30}$ on PGA. For a site with $V_{s30}$ = 450 m/sec, there is an overall increase in PGA averaging about 50% over a distance of about 100 km using the 2013 model in comparison to the 2008 model. On the other hand, a site with $V_{s30}$ = 900 m/sec there is an overall decrease of about 10% using the 2013 model in comparison to the 2008 model. Comparable observations are obtained for changes in PSA for almost all periods considered.

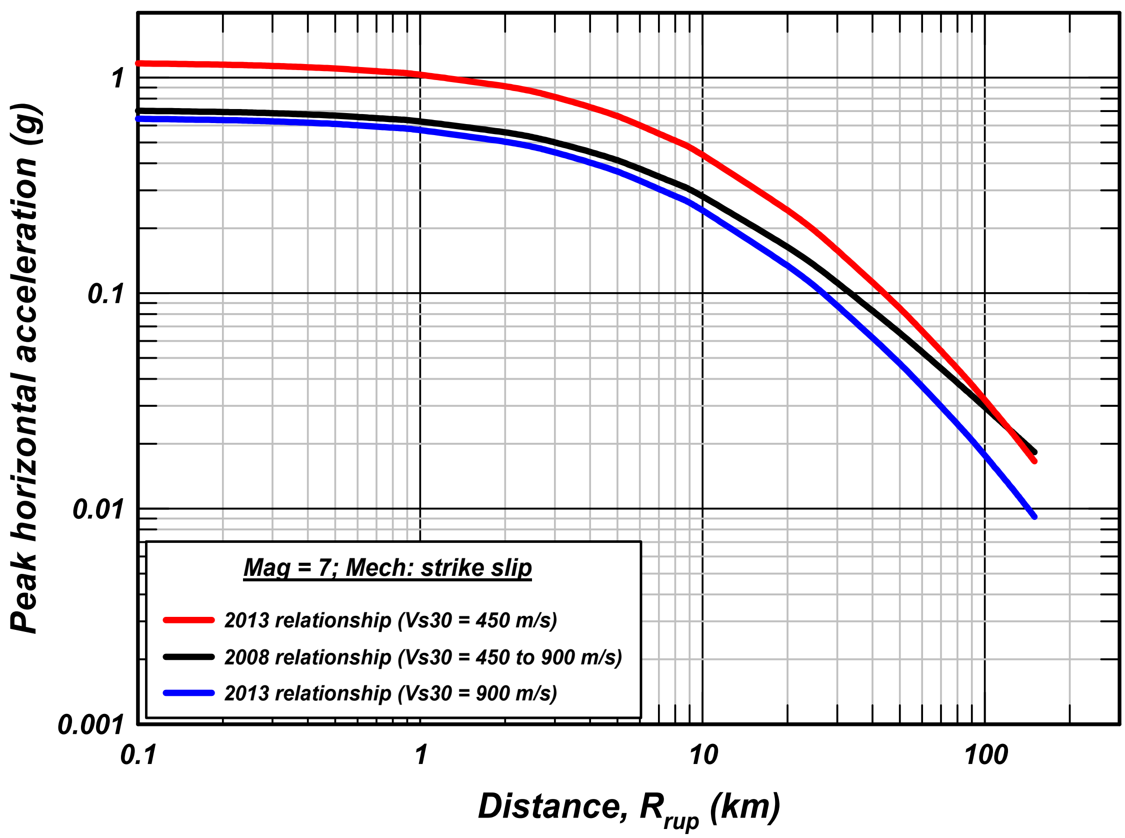


**Figure 2.4 PGA versus $R_{rup}$ for M = 7 occurring on a strike slip source calculated using the parameters derived for the 2008 model ($V_{s30}$ = 450 to 900 m/sec) and the parameters derived for the 2013 model for $V_{s30}$ = 450 m/sec and for $V_{s30}$ = 900 m/sec.**

# 3 CONCLUDING REMARKS

A model for estimating the average horizontal values of pseudo-absolute spectral accelerations (PSA) generated by crustal earthquakes has been developed for sites having $V_{s30}$ values ranging from 450 m/sec to 2000 m/sec. The fitted parameters, listed in Tables 2.1 and 2.2, provide a reasonable to excellent representation of the data in the magnitude range of about 5 to 8 and excellent representation essentially in the entire distance and $V_{s30}$ ranges.

The use of this model should be limited to M ≥ 5, to distances less than about 150 km, and to $V_{s30} \geq 450$ m/sec. For sites with $V_{s30} > 1200$ m/sec, the PSA values calculated using $V_{s30} =$ 1200 m/sec are used.

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# APPENDIX A: DATA USED IN DERIVING ATTENUATION EQUATIONS PARAMETERS

| EQID | Earthquake Name | Year | Magnitude | Mechanism | Number of recording |
|---|---|---|---|---|---|
| 1001 | 40204628 | 2007 | 5.45 | 0 | 64 |
| 1002 | 14383980 | 2008 | 5.39 | 3 | 55 |
| 1003 | 14151344 | 2005 | 5.20 | 0 | 36 |
| 1004 | 14346868 | 2008 | 5.10 | 0 | 5 |
| 1006 | 14095628 | 2004 | 5.03 | 0 | 28 |
| 1007 | 14155260 | 2005 | 4.88 | 3 | 43 |
| 1008 | 21465580 | 2005 | 4.77 | 0 | 3 |
| 1009 | 14462064 | 2009 | 4.73 | 0 | 5 |
| 1010 | 9086596 | 1999 | 4.93 | 0 | 5 |
| 1011 | 10410337 | 2009 | 4.70 | 0 | 21 |
| 1012 | 14186612 | 2005 | 4.69 | 3 | 27 |
| 1013 | 51182810 | 2007 | 4.60 | 0 | 6 |
| 1014 | 14138080 | 2005 | 4.59 | 4 | 31 |
| 1017 | 10347253 | 2008 | 4.63 | 0 | 12 |
| 1019 | 14312160 | 2007 | 4.66 | 2 | 35 |
| 1023 | 21530368 | 2006 | 4.50 | 0 | 61 |
| 1027 | 9064093 | 1998 | 4.78 | 0 | 19 |
| 1028 | 10275733 | 2007 | 4.73 | 0 | 53 |
| 1029 | 9154141 | 2000 | 4.51 | 1 | 9 |
| 1034 | 9069997 | 1998 | 4.50 | 0 | 21 |
| 1182 | 14517500 | 2009 | 5.00 | 0 | 12 |
| 1185 | 14519764 | 2009 | 4.50 | 0 | 8 |
| 1186 | 14519780 | 2009 | 5.19 | 0 | 13 |

| | | | | | |
|---|---|---|---|---|---|
| 1199 | 21401069 | 2004 | 5.00 | 0 | 3 |
| 1200 | 21401170 | 2004 | 4.88 | 0 | 4 |
| 1226 | 21351360 | 2004 | 4.51 | 2 | 4 |
| 0025 | Parkfield | 1966 | 6.19 | 0 | 1 |
| 0029 | Lytle Creek | 1970 | 5.33 | 3 | 5 |
| 0030 | San Fernando | 1971 | 6.61 | 2 | 12 |
| 0035 | Northern Calif-07 | 1975 | 5.20 | 0 | 3 |
| 0036 | Oroville-01 | 1975 | 5.89 | 1 | 1 |
| 0039 | Oroville-03 | 1975 | 4.70 | 1 | 4 |
| 0040 | Friuli, Italy-01 | 1976 | 6.50 | 2 | 2 |
| 0042 | Fruili, Italy-03 | 1976 | 5.50 | 2 | 2 |
| 0043 | Friuli, Italy-02 | 1976 | 5.91 | 2 | 1 |
| 0046 | Tabas, Iran | 1978 | 7.35 | 2 | 2 |
| 0048 | Coyote Lake | 1979 | 5.74 | 0 | 2 |
| 0049 | Norcia, Italy | 1979 | 5.90 | 1 | 2 |
| 0050 | Imperial Valley-06 | 1979 | 6.53 | 0 | 1 |
| 0053 | Livermore-01 | 1980 | 5.80 | 0 | 2 |
| 0054 | Livermore-02 | 1980 | 5.42 | 0 | 2 |
| 0055 | Anza (Horse Canyon)-01 | 1980 | 5.19 | 0 | 2 |
| 0061 | Mammoth Lakes-06 | 1980 | 5.94 | 0 | 1 |
| 0063 | Mammoth Lakes-08 | 1980 | 4.80 | 0 | 2 |
| 0064 | Victoria, Mexico | 1980 | 6.33 | 0 | 1 |
| 0065 | Mammoth Lakes-09 | 1980 | 4.85 | 0 | 3 |
| 0076 | Coalinga-01 | 1983 | 6.36 | 2 | 8 |
| 0077 | Coalinga-02 | 1983 | 5.09 | 2 | 12 |
| 0078 | Coalinga-03 | 1983 | 5.38 | 2 | 9 |
| 0080 | Coalinga-05 | 1983 | 5.77 | 2 | 6 |
| 0081 | Coalinga-06 | 1983 | 4.89 | 2 | 1 |
| 0082 | Coalinga-07 | 1983 | 5.21 | 2 | 1 |
| 0090 | Morgan Hill | 1984 | 6.19 | 0 | 5 |
| 0097 | Nahanni, Canada | 1985 | 6.76 | 2 | 3 |
| 0101 | N. Palm Springs | 1986 | 6.06 | 3 | 7 |
| 0102 | Chalfant Valley-01 | 1986 | 5.77 | 0 | 7 |
| 0113 | Whittier Narrows-01 | 1987 | 5.99 | 3 | 14 |
| 0114 | Whittier Narrows-02 | 1987 | 5.27 | 3 | 7 |
| 0118 | Loma Prieta | 1989 | 6.93 | 3 | 27 |

| | | | | | |
|---|---|---|---|---|---|
| 0125 | Landers | 1992 | 7.28 | 0 | 5 |
| 0126 | Big Bear-01 | 1992 | 6.46 | 0 | 10 |
| 0127 | Northridge-01 | 1994 | 6.69 | 2 | 39 |
| 0129 | Kobe, Japan | 1995 | 6.90 | 0 | 6 |
| 0136 | Kocaeli, Turkey | 1999 | 7.51 | 0 | 7 |
| 0138 | Duzce, Turkey | 1999 | 7.14 | 0 | 10 |
| 0144 | Manjil, Iran | 1990 | 7.37 | 0 | 1 |
| 0145 | Sierra Madre | 1991 | 5.61 | 2 | 2 |
| 0147 | Northridge-02 | 1994 | 6.05 | 2 | 5 |
| 0148 | Northridge-03 | 1994 | 5.20 | 2 | 2 |
| 0149 | Northridge-04 | 1994 | 5.93 | 3 | 3 |
| 0150 | Northridge-05 | 1994 | 5.13 | 3 | 3 |
| 0151 | Northridge-06 | 1994 | 5.28 | 2 | 18 |
| 0152 | Little Skull Mtn,NV | 1992 | 5.65 | 1 | 3 |
| 0157 | San Juan Bautista | 1998 | 5.17 | 0 | 2 |
| 0158 | Hector Mine | 1999 | 7.13 | 0 | 13 |
| 0160 | Yountville | 2000 | 5.00 | 0 | 3 |
| 0161 | Big Bear-02 | 2001 | 4.53 | 0 | 4 |
| 0162 | Mohawk Val, Portola | 2001 | 5.17 | 0 | 3 |
| 0163 | Anza-02 | 2001 | 4.92 | 4 | 48 |
| 0165 | CA/Baja Border Area | 2002 | 5.31 | 0 | 2 |
| 0166 | Gilroy | 2002 | 4.90 | 0 | 10 |
| 0170 | Big Bear City | 2003 | 4.92 | 0 | 19 |
| 0171 | Chi-Chi, Taiwan-02 | 1999 | 5.90 | 2 | 147 |
| 0172 | Chi-Chi, Taiwan-03 | 1999 | 6.20 | 2 | 130 |
| 0173 | Chi-Chi, Taiwan-04 | 1999 | 6.20 | 0 | 114 |
| 0174 | Chi-Chi, Taiwan-05 | 1999 | 6.20 | 2 | 150 |
| 0175 | Chi-Chi, Taiwan-06 | 1999 | 6.30 | 2 | 133 |
| 0176 | Tottori, Japan | 2000 | 6.61 | 0 | 79 |
| 0177 | San Simeon, CA | 2003 | 6.52 | 2 | 4 |
| 0178 | Bam, Iran | 2003 | 6.60 | 0 | 5 |
| 0179 | Parkfield-02, CA | 2004 | 6.00 | 0 | 23 |
| 0180 | Niigata, Japan | 2004 | 6.63 | 2 | 105 |
| 0202 | Basso Tirreno, Italy | 1978 | 6.00 | 0 | 2 |
| 0277 | Wenchuan, China | 2008 | 7.90 | 3 | 24 |
| 0278 | Chuetsu-oki | 2007 | 6.80 | 2 | 133 |

| | | | | | |
|---|---|---|---|---|---|
| 0279 | Iwate | 2008 | 6.90 | 2 | 90 |
| 0280 | El Mayor-Cucapah | 2010 | 7.20 | 0 | 45 |
| 0281 | Darfield, New Zealand | 2010 | 7.00 | 0 | 22 |
| 0282 | Wenchuan, China-01 | 2008 | 6.00 | 0 | 7 |
| 0283 | Wenchuan, China-02 | 2008 | 6.10 | 0 | 7 |
| 0284 | Wenchuan, China-03 | 2008 | 6.30 | 2 | 4 |
| 0285 | Wenchuan, China-04 | 2008 | 5.50 | 2 | 6 |
| 0286 | Wenchuan, China-05 | 2008 | 5.60 | 3 | 5 |
| 0287 | Wenchuan, China-06 | 2008 | 5.50 | 0 | 7 |
| 0288 | Wenchuan, China-07 | 2008 | 5.50 | 2 | 3 |
| 0289 | Wenchuan, China-08 | 2008 | 5.20 | 2 | 4 |
| 0290 | Wenchuan, China-09 | 2008 | 5.50 | 0 | 5 |
| 0291 | Wenchuan, China-10 | 2008 | 5.70 | 0 | 3 |
| 0292 | Wenchuan, China-11 | 2008 | 5.40 | 2 | 3 |
| 0293 | Wenchuan, China-12 | 2008 | 5.30 | 4 | 2 |
| 0294 | Wenchuan, China-13 | 2008 | 5.70 | 0 | 4 |
| 0295 | Wenchuan, China-14 | 2008 | 5.70 | 0 | 3 |
| 0296 | Wenchuan, China-15 | 2008 | 5.70 | 2 | 3 |
| 0297 | Wenchuan, China-16 | 2008 | 5.90 | 2 | 4 |
| 0298 | Wenchuan, China-17 | 2008 | 5.10 | 0 | 3 |
| 0299 | Wenchuan, China-18 | 2008 | 5.50 | 2 | 3 |
| 0300 | Wenchuan, China-19 | 2008 | 5.00 | 3 | 3 |
| 0301 | Wenchuan, China-20 | 2008 | 5.30 | 3 | 7 |
| 0302 | Wenchuan, China-21 | 2008 | 4.70 | 4 | 3 |
| 0303 | Wenchuan, China-22 | 2008 | 5.20 | 0 | 3 |
| 0304 | Wenchuan, China-23 | 2008 | 5.80 | 2 | 3 |
| 0305 | Wenchuan, China-24 | 2008 | 5.80 | 2 | 4 |
| 0306 | Wenchuan, China-25 | 2008 | 5.10 | 2 | 2 |
| 0307 | Wenchuan, China-26 | 2008 | 4.80 | 2 | 3 |
| 0308 | Wenchuan, China-27 | 2008 | 4.50 | 3 | 2 |
| 0309 | Wenchuan, China-28 | 2008 | 4.80 | 2 | 3 |
| 0310 | Wenchuan, China-29 | 2008 | 5.50 | 2 | 4 |
| 0311 | Wenchuan, China-30 | 2008 | 5.20 | 2 | 4 |
| 0312 | Wenchuan, China-31 | 2008 | 5.00 | 2 | 1 |
| 0313 | Wenchuan, China-32 | 2008 | 4.90 | 0 | 1 |
| 0314 | Wenchuan, China-33 | 2008 | 5.00 | 0 | 3 |

| | | | | | |
|---|---|---|---|---|---|
| 0315 | Wenchuan, China-34 | 2008 | 4.80 | 0 | 3 |
| 0316 | Wenchuan, China-35 | 2008 | 4.60 | 2 | 1 |
| 0317 | Wenchuan, China-36 | 2008 | 5.00 | 0 | 2 |
| 0318 | Wenchuan, China-37 | 2008 | 4.70 | 2 | 2 |
| 0319 | Wenchuan, China-38 | 2008 | 5.20 | 2 | 3 |
| 0320 | Wenchuan, China-39 | 2008 | 5.10 | 2 | 2 |
| 0321 | Wenchuan, China-40 | 2008 | 4.80 | 0 | 3 |
| 0323 | Wenchuan, China-42 | 2008 | 4.60 | 2 | 1 |
| 0324 | Wenchuan, China-43 | 2008 | 5.10 | 0 | 3 |
| 0325 | Wenchuan, China-44 | 2008 | 4.70 | 0 | 2 |
| 0326 | Wenchuan, China-45 | 2008 | 5.10 | 2 | 3 |
| 0328 | Wenchuan, China-47 | 2008 | 4.70 | 4 | 2 |
| 0329 | Wenchuan, China-48 | 2008 | 4.90 | 0 | 2 |
| 0333 | Wenchuan, China-52 | 2008 | 4.80 | 2 | 1 |
| 0334 | Wenchuan, China-53 | 2008 | 4.70 | 0 | 3 |
| 0335 | Wenchuan, China-54 | 2008 | 4.70 | 0 | 1 |
| 0337 | Wenchuan, China-56 | 2008 | 4.80 | 0 | 3 |
| 0338 | Wenchuan, China-57 | 2008 | 4.80 | 2 | 1 |
| 0341 | Wenchuan, China-60 | 2008 | 5.20 | 0 | 4 |
| 0342 | Wenchuan, China-61 | 2008 | 4.70 | 2 | 3 |
| 0346 | Christchurch, New Zealand | 2011 | 6.20 | 3 | 21 |

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