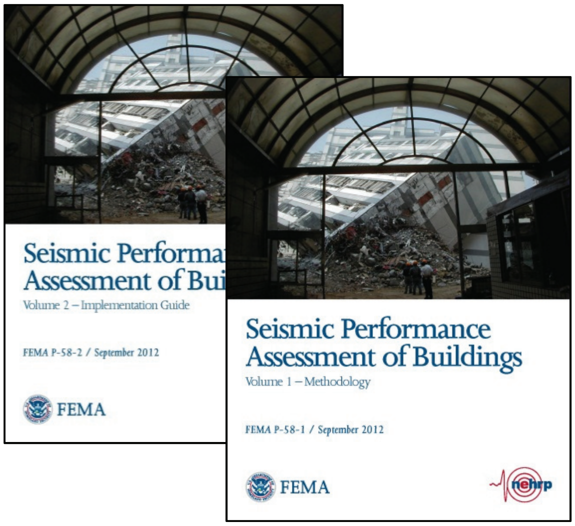

Background Document

FEMA P-58/BD-3.7.5

Calculation of Peak Ground Velocity From One-Second Pseudo-Spectral Velocity

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Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Users of information in this document assume all liability arising from such use.

Notice

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Calculation of Peak Ground Velocity From One-Second Pseudo-Spectral Velocity

Yin-Nan Huang[a] and Andrew S. Whittaker[b]

INTRODUCTION

The ATC-58 project is developing a *Guideline for Seismic Performance Assessment of Buildings*, hereafter termed the *ATC-58 Guideline* (ATC 2012). The *ATC-58 Guideline* presents the next generation of procedures and tools for performance-based earthquake engineering. The procedures and tools use the probability of incurring direct and indirect economic loss and casualties as measures of performance. The computation of loss requires the analyst to first perform structural analysis to establish distributions of structural response quantities including peak story drift, floor velocity and floor acceleration. These distributions of demands are then used to assess probable damage and the resulting consequences of this damage in terms of repair costs, occupancy interruption and casualties.

The *ATC-58 Guideline* provides two alternative analysis procedures to estimate distributions of key structural response parameters. The first is nonlinear response-history analysis, which should be used when a comprehensive assessment is required for a building. The second is a simplified procedure, which is valid only for regular structures with limited nonlinear response and provides values for peak transient floor acceleration, floor velocity and story drift. The procedure for estimating the median peak floor velocity in the simplified analysis requires a value of peak ground velocity (PGV), which can be calculated by seismic hazard analysis for intensity- and time-based assessments or using a ground-motion prediction equation for a scenario-based assessment.

The objective of the study presented herein is to provide an alternative procedure to develop a value of PGV for use in simplified analysis when hazard data for PGV are not available. The procedure should be easy to implement and supported by trends observed in ground-motion records.

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Newmark and Hall (1982) computed amplification factor between PGV and pseudo-spectral velocity (termed R_V) in the velocity-sensitive period range using ground-motion records available at that time. The factor provides a method to estimate PGV. A significant number of ground-motion records have been acquired since the seminal study of Newmark and Hall was published. In the study presented in this report, we compute values of R_V for selected ground motions in the PEER NGA Strong Motion Database (http://peer.berkeley.edu/nga/) and develop empirical models for R_V. The results of this study provide the technical basis for a procedure presented in the *ATC-58 Guideline* to estimate PGV by scaling the pseudo-spectral velocity at a period of 1 second.

GROUND-MOTION SETS

The ground motions used in this study were selected from the PEER NGA Strong Motion Database. Each pair of time series was rotated to be strike-normal (SN) and strike-parallel (SP) to the causative fault shaking by members of the NGA project team. Records without clear information in the NGA Database Flatfile (http://peer.berkeley.edu/nga/flatfile.html) for closest site-to-fault distance and average shear wave velocity (V_{S30}) are not included in this study. A total of 5594 time series (2798 pairs of records) were selected and termed Bin 1 ground motions. To study values of R_V for ground motions with high intensity, we developed a second bin of ground motions, Bin 2, by excluding all the records in Bin 1 with one or more of the following: 1) peak ground acceleration smaller than 0.1 g, 2) moment magnitude smaller than 6, and 3) closest site-to-fault distance greater than 50 km. Bin 2 includes 916 time series from 38 earthquakes. Table 1 presents the names, years and moment magnitudes of the earthquakes included in Bin 2.

NORMALIZED PSEUDO-SPECTRAL VELOCITY

AMPLIFICATION FACTOR R_V AS A FUNCTION OF PERIOD

Pseudo-spectral velocity was computed and normalized by PGV for each record in Bins 1 and 2. Median and 84th percentile (through counting) values of normalized pseudo-spectral velocity (i.e., R_V) for Bins 1 and 2 are presented in Figure 1 and Figure 2 using log-log and linear scales, respectively. As a point of reference, the median and 84th percentile of R_V reported in Newmark and Hall (1982) for a damping ratio of 5% are 1.65 and 2.3, respectively. The two values are plotted in Figure 1 and Figure 2 as red dotted lines and agree well with the results of this study in the intermediate period range (around 1 second). Figure

3 presents the dispersion (β) in R_V for Bins 1 and 2 as a function of period. The value of β at a given period was computed using the following equations:

$$\theta = \exp\left(\frac{1}{n}\sum_{i=1}^{n}\ln R_{V,i}\right) \tag{1}$$

$$\beta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\ln R_{V,i} - \ln\theta)^2} \tag{2}$$

where $R_{V,i}$ is the value of normalized pseudo-spectral velocity at the period for the *i*-th ground-motion time series; and n is the number of ground motions used in the analysis. In this study, the value of n is 5594 for Bin 1 and 916 for Bin 2.

The dispersion of Figure 3 in the intermediate period range is much smaller than that in the shorter and longer period ranges: an expected observation since pseudo-spectral velocity is more stable in the intermediate period range than in the short and long period ranges.

AMPLIFICATION FACTOR R_V AVERAGED OVER THE VELOCITY-SENSITIVE PERIOD RANGE

In Figure 1 and Figure 2, the value of R_V for Bin 2 is smaller than Bin 1 at periods between 0.5 and 3 seconds. This observation implies that the value of R_V may depend on magnitude and distance. Figure 4 and Figure 5 present the values of R_V as a function of magnitude and distance, respectively, for the Bin 2 ground motions and the results of linear regression. In Figure 4 through Figure 9, R_V is computed as the normalized pseudo-spectral velocity averaged over the period range of 0.5 and 2 seconds. This period range is determined based on the results of Figure 1, where the dependency of normalized pseudo-spectral velocity on period is moderate at periods between 0.5 and 2 seconds. Hereafter, we focus on the results for Bin 2 only.

Per Figure 4 and Figure 5, R_V tends increase with distance and decrease with magnitude. A two-stage regression (Boore and Atkinson 2008) was used to study the relationship between R_V, magnitude and distance. In the first stage, the (inter-)event term was determined for each earthquake used in the study. The event term was computed as the average of the nature logarithm of R_V ($\ln R_V$) for a given event. The event term was subtracted from the value of $\ln R_V$ for each record in Bin 2 for the given event. The resultant residual is termed the "intra-event residual". The intra-event residuals for Bin 2 are presented in Figure 6 as a function of distance. The dependency of the intra-event residuals on distance is insignificant.

In the second stage, a linear regression was performed to determine the dependency of the event terms obtained in the first stage on moment magnitude (M_W). Figure 7 presents the event terms for Bin 2 as a function of M_W. The regression results for the data of Figure 7 suggest a model of $Y = 1.4 - 0.14X$, where X and Y are the axes in the figure. Figure 8 presents the inter-event residuals (the residuals between the event terms and their regression results) as a function of M_W. Note that only three events have a M_W greater than 7.5. Based on the data of Figure 6 through Figure 8, a relationship between R_V and M_W is proposed:

$$R_V = e^{1.4-0.14M_W} \tag{3}$$

The relationship of (3) is valid only for M_W between 6 and 8. The values of R_V computed using (3) are presented in Figure 9 and range roughly between 1.3 and 1.8. The intra-event and inter-event standard deviations identified using the data of Figure 6 and Figure 8 are 0.29 and 0.16, respectively. The total logarithmic standard deviation for R_V is about 0.33 ($= \sqrt{0.29^2 + 0.16^2}$).

AMPLIFICATION FACTOR R_V AT A PERIOD OF ONE SECOND

The use of the R_V of (3) to estimate PGV will require the value of pseudo-spectral velocity averaged over a period range of 0.5 to 2 seconds. The procedure can be further simplified if R_V is computed as the ratio of pseudo-spectral velocity at a period of one second to PGV (termed $R_{V,1s}$ hereafter) assuming this change does not greatly increase the dispersion in R_V.

To investigate 1) the relationship between $R_{V,1s}$, distance, and M_W, and 2) the dispersion in $R_{V,1s}$, the analyses of Figure 4 through Figure 9 were repeated for $R_{V,1s}$ and the results are presented in Figure 10 through Figure 15, respectively. The trends observed in Figure 10 through Figure 15 are similar to those in Figure 4 through Figure 9. The results of Figure 12 indicate the intra-event residuals are independent of distance. The equation for the regression results of Figure 13 is $Y = 1.3 - 0.13X$ and following model is proposed for $R_{V,1s}$:

$$R_{V,1s} = e^{1.3-0.13M_W} \tag{4}$$

The values of $R_{V,1s}$ computed using (4) are presented in Figure 15 and range between 1.3 and 1.7. The intra-event and inter-event standard deviations identified using the data of Figure 12 and Figure 14 are 0.39 and 0.19, respectively. The total logarithmic standard deviation for $R_{V,1s}$ is about 0.43 ($= \sqrt{0.39^2 + 0.19^2}$). The dispersion in $R_{V,1s}$ is higher than in R_V averaged over a period range of 0.5 to 2 seconds: an expected result since R_V averaged over the intermediate period range is more stable than $R_{V,1s}$.

The procedures of estimating PGV for a given (acceleration) spectrum using $R_{V,1s}$ of (4) are summarized below:

1. Compute pseudo-spectral velocity at a period of one second, $S_v(1)$, using the following equation:

$$S_v(1) = \frac{S_a(1)}{2\pi} g \tag{5}$$

   where $S_a(1)$ is the spectral acceleration at a period of one second in the unit of gravity (g).

2. Compute PGV using the following equation:

$$\text{PGV} = \frac{S_v(1)}{R_{V,1s}} \tag{6}$$

   where $R_{V,1s}$ can be computed using (4) when the given spectral acceleration is associated with an earthquake magnitude; if not, the data of Figure 1 and Figure 2 support the use of a factor of 1.65 (the recommendation of Newmark and Hall (1982)) in lieu of (4) to estimate the median value of PGV for the given spectral acceleration.

3. The dispersion in $R_{V,1s}$ (a logarithmic standard deviation of 0.43) should be considered in a seismic performance assessment when it is used to estimate PGV.

CONCLUSIONS

Amplification factors between PGV and pseudo-spectral velocity 1) averaged over the period range of 0.5 to 2 seconds, and 2) at a period of one second were computed using hundreds of ground-motion records. The dependency of the factors on earthquake magnitude and distance was investigated. The results enable an alternative approach to estimate PGV for performance assessment of buildings when hazard data for PGV is unavailable. The following conclusions are drawn:

1. The amplification factors developed in this study agree well with those reported in Newmark and Hall (1982).
2. For moment magnitude between 6 and 8, the inter-event term decreases moderately as moment magnitude increases and the intra-event residuals do not depend on distance.

3. The logarithmic standard deviation in the amplification factor averaged over the period range of 0.5 to 2 seconds (at a period of one second) is about 0.33 (0.43). The dispersion should be properly included in the process of performance assessment when the amplification factor is used to estimate PGV.

REFERENCES

Applied Technology Council. (ATC). (2011). "Seismic Performance Assessment of Buildings Volume 1 - Methodology" *ATC-58-1 100% Draft*, Applied Technology Council, Redwood City, California.

Boore, D. M., and Atkinson, G. M. (2008). "Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s." *Earthquake Spectra*, 24(1), 99-138.

Newmark, N. M., and Hall, W. J. (1982). *Earthquake spectra and design*, Earthquake Engineering Research Institute, Berkeley, California.

Table 1. Earthquakes used in this study for the Bin 2 ground motions

Earthquake	Year	Moment Magnitude
Imperial Valley-02	1940	6.95
Kern County	1952	7.36
Parkfield	1966	6.19
San Fernando	1971	6.61
Managua, Nicaragua-01	1972	6.24
Friuli, Italy-01	1976	6.50
Gazli, USSR	1976	6.80
Imperial Valley-06	1979	6.53
Mammoth Lakes-01	1980	6.06
Victoria, Mexico	1980	6.33
Irpinia, Italy-01	1980	6.90
Irpinia, Italy-02	1980	6.20
Coalinga-01	1983	6.36
Morgan Hill	1984	6.19
Nahanni, Canada	1985	6.76
N. Palm Springs	1986	6.06
Chalfant Valley-02	1986	6.19
New Zealand-02	1987	6.60
Superstition Hills-01	1987	6.22
Superstition Hills-02	1987	6.54
Loma Prieta	1989	6.93
Griva, Greece	1990	6.10
Erzican, Turkey	1992	6.69
Cape Mendocino	1992	7.01
Landers	1992	7.28
Northridge-01	1994	6.69
Kobe, Japan	1995	6.90
Dinar, Turkey	1995	6.40
Kocaeli, Turkey	1999	7.51
Chi-Chi, Taiwan	1999	7.62
Duzce, Turkey	1999	7.14
Manjil, Iran	1990	7.37
Hector Mine	1999	7.13
Denali, Alaska	2002	7.90
Chi-Chi, Taiwan-03	1999	6.20
Chi-Chi, Taiwan-04	1999	6.20
Chi-Chi, Taiwan-05	1999	6.20
Chi-Chi, Taiwan-06	1999	6.30

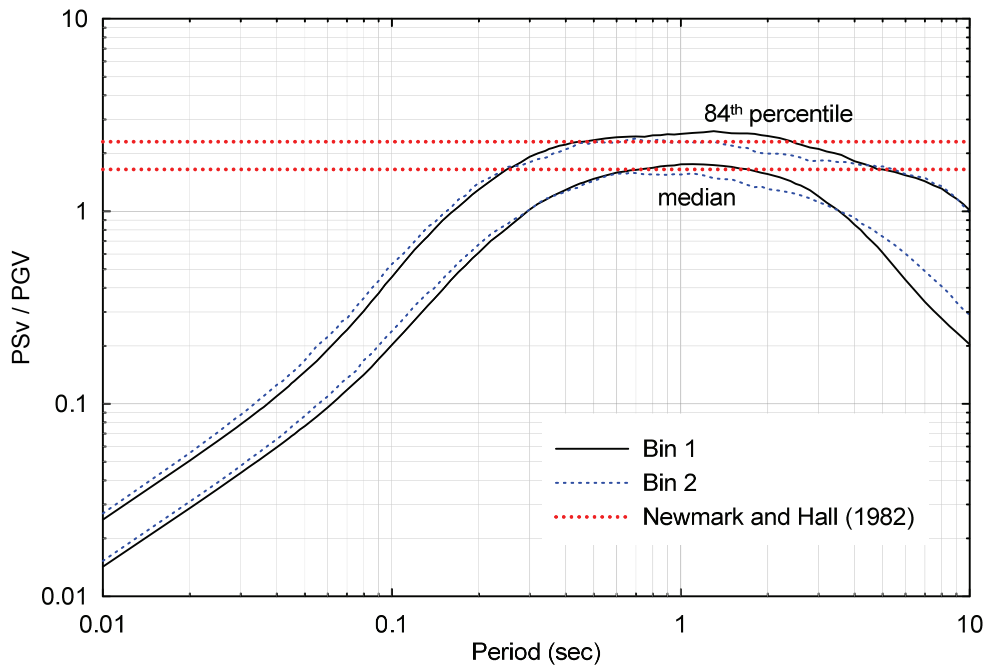

Figure 1. Median and 84th percentile of pseudo-spectral velocity normalized by *PGV* for Bin 1 and 2 ground motions (log-log scale)

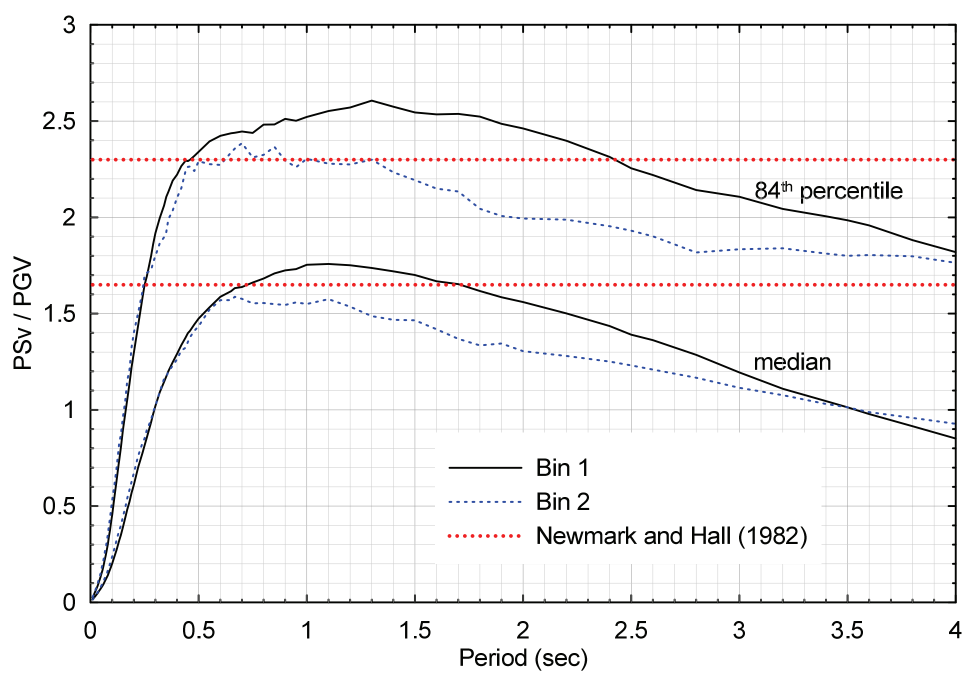

Figure 2. Median and 84th percentile of pseudo-spectral velocity normalized by *PGV* for Bin 1 and 2 ground motions (normal scale)

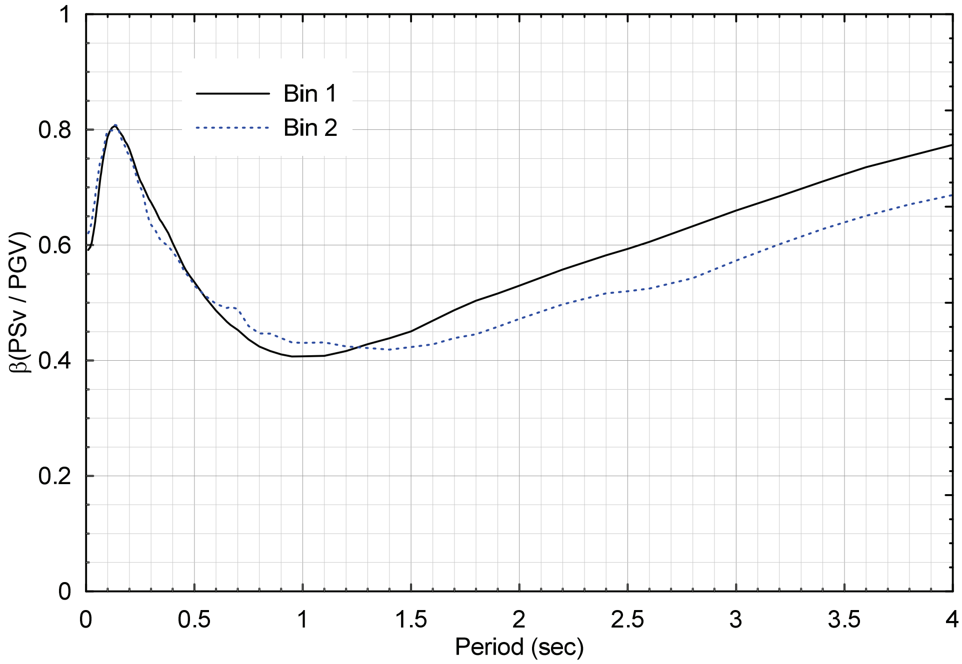

Figure 3. Dispersions in pseudo-spectral velocity normalized by *PGV* for Bin 1 and 2 ground motions

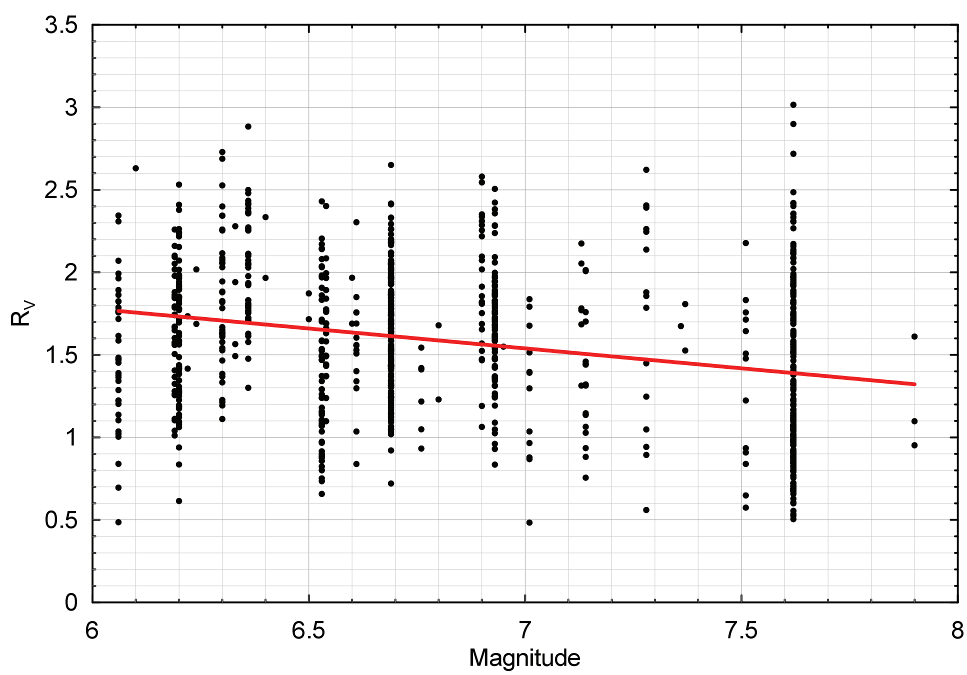

Figure 4. Normalized spectral velocity R_V and the regression results as a function of magnitude for Bin 2 ground motions

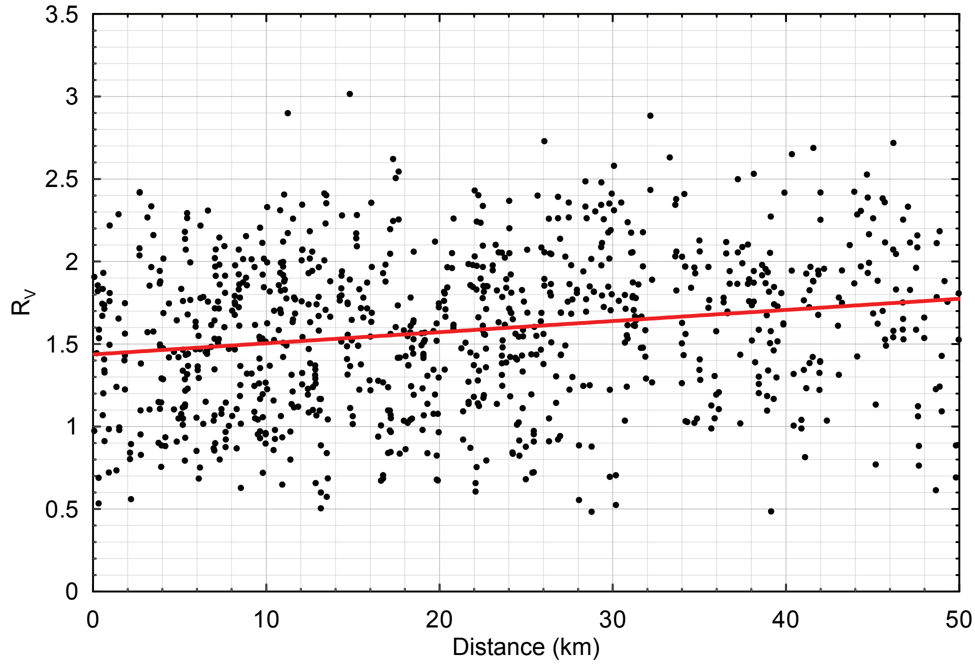

Figure 5. Normalized spectral velocity R_V and the regression results as a function of distance for Bin 2 ground motions

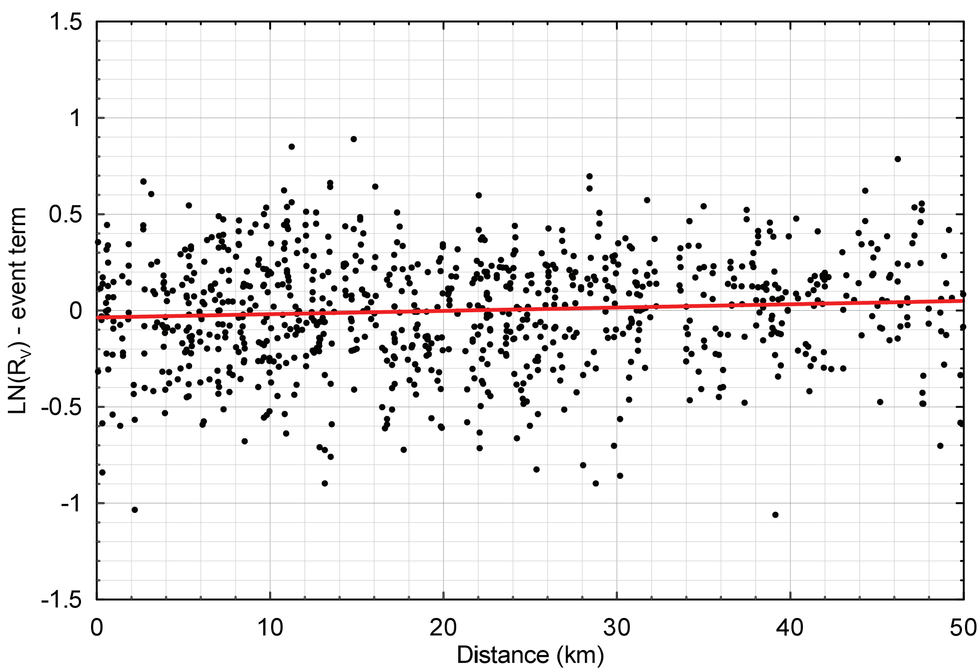

Figure 6. Intra-event residuals as a function of distance for R_V and Bin 2 ground motions

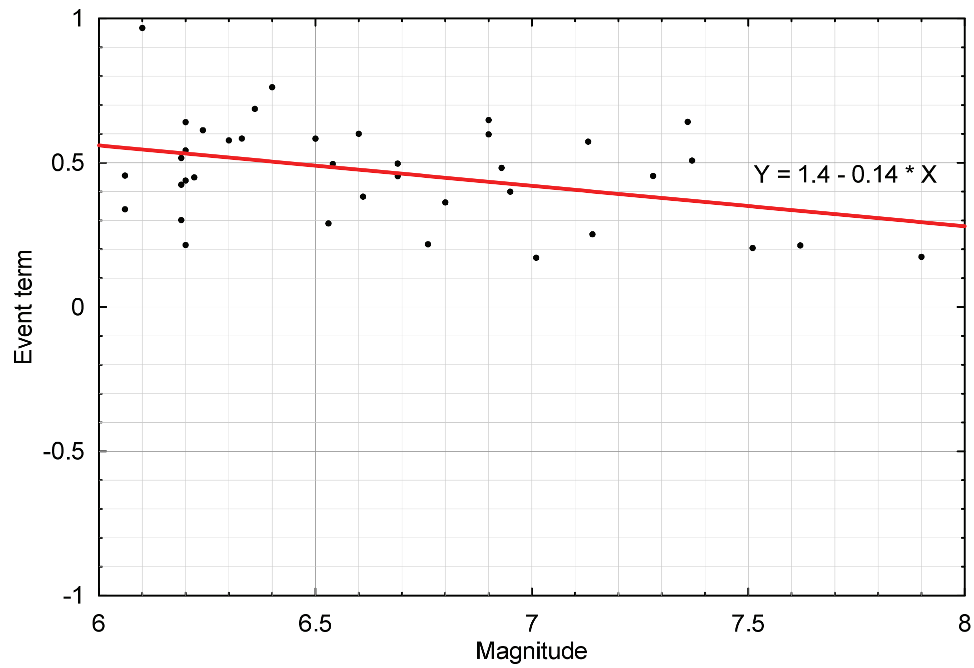

Figure 7. Inter-event terms and the regression results as a function of magnitude for R_V and Bin 2 ground motions

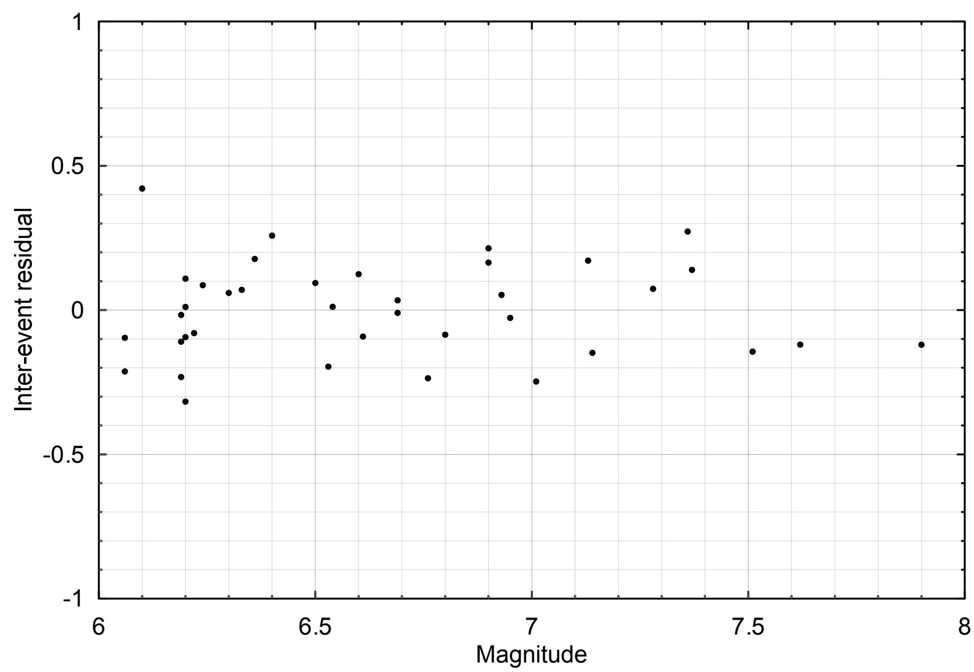

Figure 8. Inter-event residuals as a function of magnitude for R_V and Bin 2 ground motions

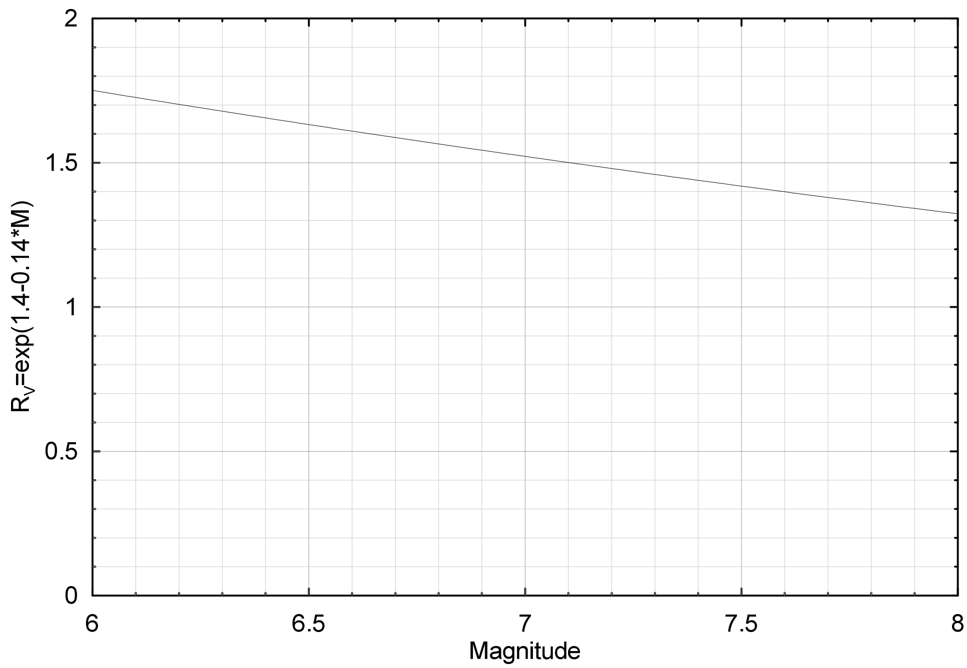

Figure 9. Normalized spectral velocity R_V and computed using (3) as a function of magnitude

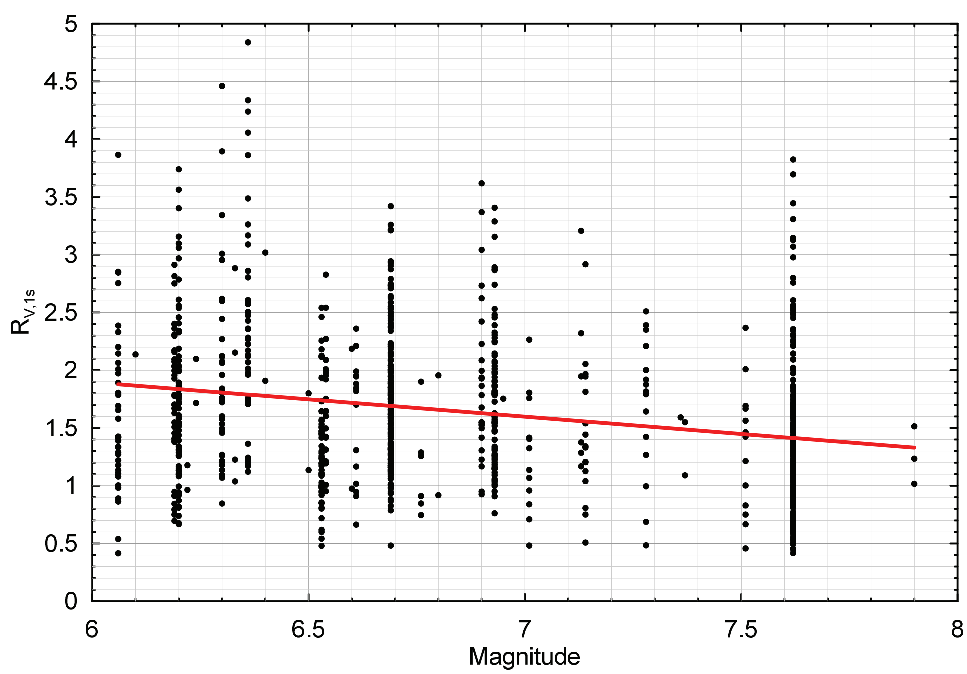

Figure 10. Normalized spectral velocity $R_{V,1s}$ and the regression results as a function of magnitude for Bin 2 ground motions

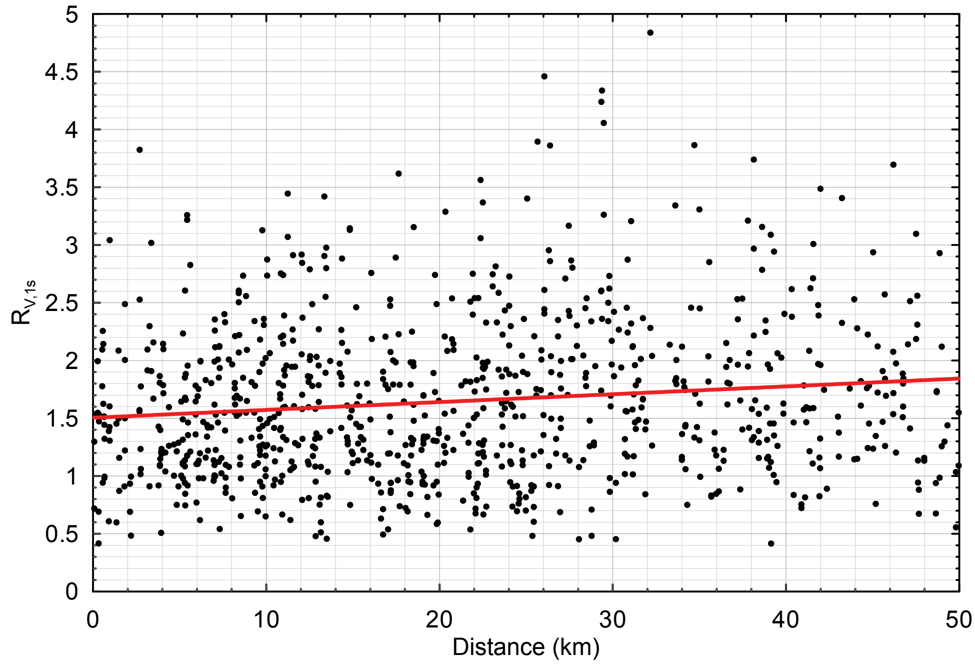

Figure 11. Normalized spectral velocity $R_{V,1s}$ and the regression results as a function of distance for Bin 2 ground motions

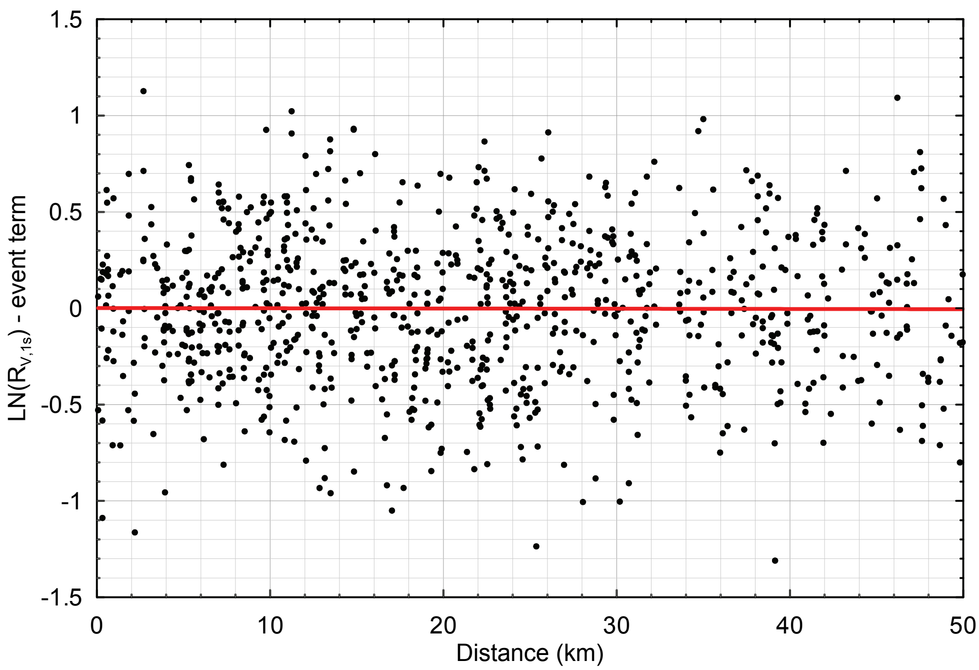

Figure 12. Intra-event residuals as a function of distance for $R_{V,1s}$ and Bin 2 ground motions

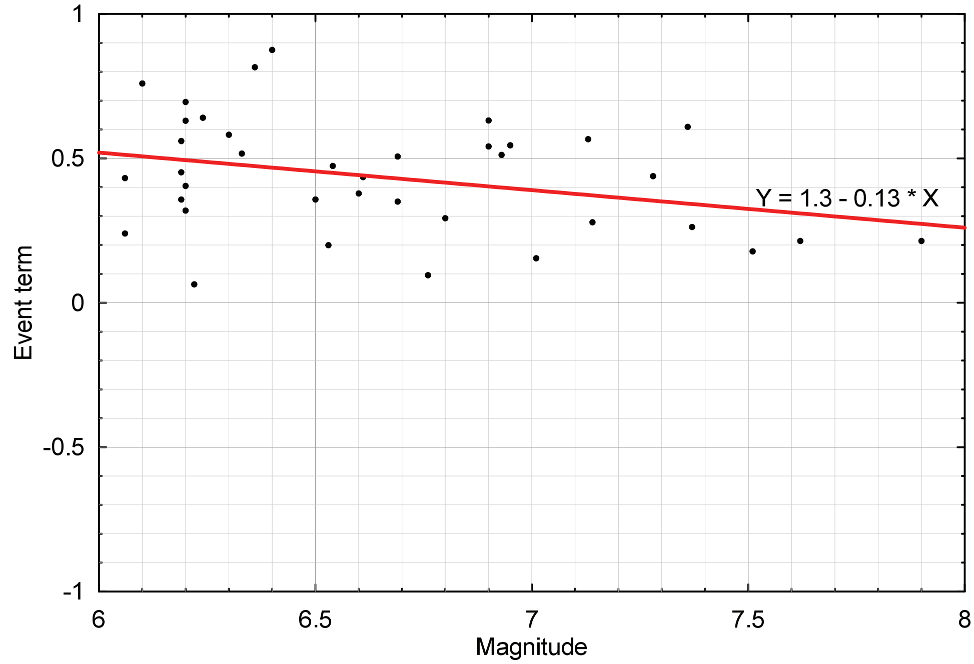

Figure 13. Inter-event terms and the regression results as a function of magnitude for $R_{V,1s}$ and Bin 2 ground motions

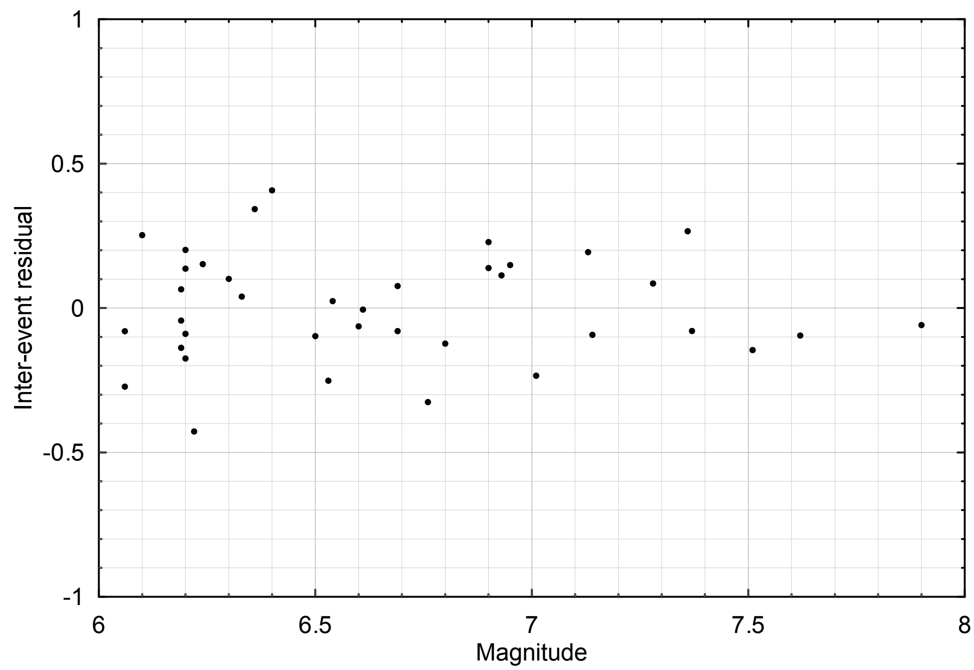

Figure 14. Inter-event residuals as a function of magnitude for $R_{V,1s}$ and Bin 2 ground motions

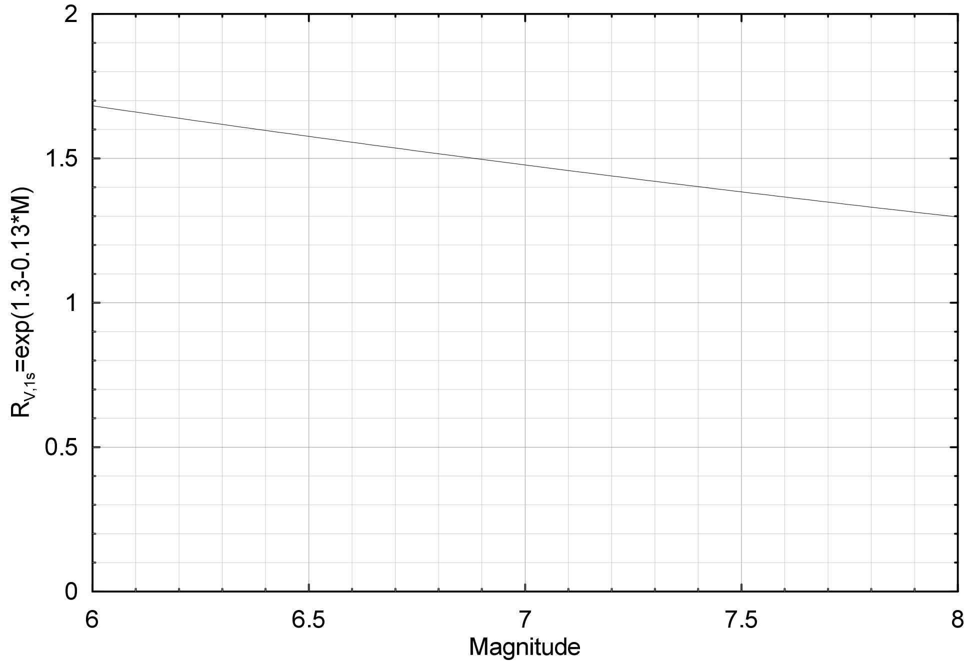

Figure 15. Normalized spectral velocity $R_{V,1s}$ computed using (4) as a function of magnitude