Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No

EMPIRICAL GROUND MOTION ATTENUATION RELATIONSHIPS FOR MAXIMUM INCREMENTAL VELOCITY

Jaime Guaman,[1] David Kirkner,[2] and Yahya Kurama[2]

ABSTRACT

This paper presents basic attenuation relationships for the maximum incremental velocity, *MIV*, of earthquake ground motion records. Multiple regression analyses were conducted to determine relationships between the *MIV* and the relevant independent earthquake parameters, such as magnitude, and site parameters, such as distance. The PEER-NGA (2009) ground motion database was expanded for the purposes of the study, to include the "orientation-independent" geometric mean *MIV* of the two orthogonal horizontal components of a given record. The proposed attenuation relationship can be used to estimate the *MIV* at a given site, similar to currently available models for other ground motion intensity parameters such as the peak acceleration and velocity, as well as spectral acceleration values.

Introduction

The development of attenuation models for various measures of ground motion has been an active area of research for more than 60 years (e.g., Gutenberg and Richter 1942; Kawasumi 1951; Trifunac 1976; Joyner and Boore, 1981; Campbell 1981; Fukushima and Tanaka 1990; Boore and Atkinson 2007). The primary focus to date has been on relationships for the peak ground acceleration, *PGA*, peak ground velocity, *PGV*, and spectral acceleration, *SA*. The current paper builds on this previous work to develop a basic attenuation relationship for the maximum incremental velocity, *MIV*, which is defined as the maximum area under the acceleration time-history of a ground motion record between two consecutive zero acceleration crossings.

The maximum incremental velocity is an important ground motion intensity parameter that can be used in the seismic design of building structural systems. As performance-based considerations have become requisite in recent years, the use of nonlinear time-history analysis in the seismic design and evaluation of building structures has gained increased importance (e.g., for tall or irregular structures, and/or structures on soft soil). The selection and scaling of ground motion histories has a large impact on the results from nonlinear time-history analyses. In particular, recent research (Kurama and Farrow 2003) has shown that ground motion records scaled to a constant value of the *MIV* result in a significantly reduced amount of dispersion in the peak nonlinear lateral displacement demands for a wide range of site and structure characteristics. Under these conditions, the reduced scatter in the seismic demands, together with its simplicity, make

[1]Graduate Student, Civil Engineering and Geological Sciences, Univ. of Notre Dame, Notre Dame, Indiana 46556
[2]Associate Professor, Civil Engineering and Geological Sciences, Univ. of Notre Dame, Notre Dame, Indiana 46556

MIV-based scaling of ground motion records advantageous over many other scaling methods (e.g., spectral acceleration at the fundamental period of the structure).

The current disadvantage to the use of the *MIV* as a ground motion intensity parameter in seismic design and analysis is the lack of methods to estimate the *MIV* at a specific site. To address this limitation, the current paper: (1) develops an extensive *MIV* database by expanding the PEER-NGA (2009) earthquake ground motion database to include the *MIV*; (2) develops basic attenuation relationships for the *MIV* by conducting multiple regression analyses on a subset of this database; and (3) assesses the adequacy of the proposed attenuation relationships in predicting the trends in the ground motion data.

Previous Ground Motion Attenuation Models

The general approach in developing a ground motion attenuation model is to determine a predictive equation for the parameter of interest (e.g., *PGA*, *MIV*) as a function of the ground motion characteristics such as the earthquake moment magnitude m and distance r of the recording site from the earthquake source. The significant variability in ground motion and site parameters makes deterministic prediction of attenuation relationships difficult. As a result, the bulk of the research in this area is based on statistical regression analysis of the available empirical data. Many of the previous models have begun with the simple assumption of inelastic attenuation (Aki and Richards 2002). For example, taking *PGA* as the response variable,

$$PGA = (c/r)\,\mathrm{e}^{-kr} \tag{1}$$

with c and k being coefficients to be determined from the data. Often, the logarithm of the response variable is used because that transformation yields a model in the form of standard multiple linear least-squares regression,

$$\ln(PGA) = b_1 + b_2 r + b_3 \ln(r) \tag{2}$$

where, b_i are coefficients to be determined from the regression analysis. In addition to the distance, r, the principle predictor variable in all existing models is the earthquake moment magnitude, m, which yields the most basic ground motion attenuation equation as

$$\ln(PGA) = b_1 + b_2 m + b_3 r + b_4 \ln(r) \tag{3}$$

The form of the model in Eq. (3) or variations to it have been used in many studies (e.g., Joyner and Boore 1981; Campbell 1981; Brillinger and Preisler 1984, 1985). In an important paper, Joyner and Boore (1993) used the following model first proposed by Brillinger and Preisler (1984):

$$\ln(PGA) = b_1 + b_2(m-6) + b_3 r - \ln r + e_r + e_e, \quad \text{with } r = \sqrt{d_{JB}^2 + b_4^2} \tag{4}$$

where, d_{JB} is the “Joyner-Boore distance” (defined as the shortest distance from the recording site to the vertical projection of the fault rupture on the surface of the Earth) and the regression coefficient b_4 is a depth measure to be determined from the regression analysis. In Eq. (4), the error e_r measures the uncertainty in each record, whereas e_e is the earthquake-to-earthquake component of uncertainty. The error e_r is a zero-mean (over the population of records) random variable with constant variance σ_r^2 and the error e_e is a zero-mean (over the population of earthquakes) random variable with constant variance σ_e^2. It is further assumed that the covariance between records in the same earthquake is σ_e^2 whereas the covariance between records from different earthquakes is zero (Joyner and Boore 1993). This error structure implies that the variance-covariance matrix of the error vector is not diagonal, suggesting that a solution based on generalized least-squared regression is required (Seber and Wild 1989) as discussed later in the paper.

In an attempt to quantify the effects of earthquake fault type and site soil type, Boore et al. (1997) extended the model in Eq. (4) to the following form.

$$\ln\left(PGA\right) = b_1 + b_2(m-6) + b_3(m-6)^2 + b_4 \ln r\left(d_{JB}, b_6\right) + b_5 \ln(V_S) + b^{FT} + e_r + e_e \qquad (5)$$

where, V_S is the soil shear-wave velocity and the fault-type coefficient is defined as

$$b^{\mathrm{FT}} = \begin{cases} b_7, & \text{if the fault type is strike-slip} \\ b_8, & \text{if the fault type is reverse-slip} \\ b_9, & \text{if the fault type is otherwise} \end{cases} \qquad (6)$$

A slightly more complicated model than that in Eq. (5) was recently proposed by Akkar and Bommer (2007) to predict the peak ground velocity from an ensemble of European and Middle Eastern earthquakes. This equation takes the following form.

$$\ln\left(PGV\right) = b_1 + b_2 m + b_3 m^2 + b_4 \ln r\left(d_{JB}, b_6\right) + b_5 m \ln r\left(d_{JB}, b_6\right) + b^S + b^{FT} + e_r + e_e \qquad (7)$$

Eq. (7) includes a dummy variable to measure the site effect, b^S, with coefficient b_7 for soft soil and b_8 for stiff soil. Only two classifications were used for the fault-type coefficient; b_9 for normal and reverse faulting and b_{10} otherwise.

Also, recently, Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) developed regression models that are special cases of the following equation.

$$y = f_{\mathrm{mag}} + f_{\mathrm{dist}} + f_{\mathrm{fault}} + f_{hng} + f_{\mathrm{site}} + f_{sed} + e_r + e_e \qquad (8)$$

In Eq. (8), the response variable y is the natural logarithm of the *PGA*, *PGV*, or *SA*. Similar to the b^{FT} term in Eq. (5), each of the terms in Eq. (8) breaks into conditional equations that depend on parameters such as magnitude, distance, fault type, hanging-wall effect, site soil effect, and sediment depth. An evaluation of the number of terms and the conditional equations in the regression models developed by Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) shows a higher level of complexity compared to the other models reviewed above.

It should be noted that including a depth measure by introducing a regression coefficient in the distance parameter ($r = \sqrt{d_{JB}^2 + b^2}$) makes all of the above regression models inherently nonlinear. In addition, the selected error structure for e_r and e_e leads to a non-diagonal variance-covariance matrix as stated above. Joyner and Boore (1993) proposed two approaches for solving the nonlinear regression problem with an unknown variance-covariance matrix of known structure. The first method, referred to as a one-stage algorithm, is based on the method of maximum likelihood to determine all regression coefficients and error measures simultaneously. Basically, the regression problem is solved by a generalized nonlinear least-squares algorithm with an assumed value of the correlation coefficient, and then, the likelihood is evaluated. A search is conducted and the values of the regression coefficients and of the correlation coefficient giving the maximum likelihood are the estimates of the regression parameters and error terms. In the second approach, Joyner and Boore proposed a two-stage algorithm wherein the distance coefficients and a set of earthquake coefficients are determined in the first stage and the magnitude coefficient(s) are determined in the second stage regression.

According to Joyner and Boore (1993), while the two-stage and one-stage approaches produce similar results, the two-stage method is computationally less burdensome (although it was also noted that this is really not an issue). Subsequently, however, Spudich et al. (1999) found that the two-stage method can underestimate the variance of the error for data sets containing a significant number of earthquakes with a single record. Noting this, Akkar and Bommer (2007) carried out their regression analyses using the one-stage algorithm. The *MIV* relationships described in the current paper were also developed using a one-stage approach. Note that this is different from a significant number of other attenuation models that have been developed recently (e.g., Boore et al. 1997; Boore and Atkinson 2007; Campbell and Bozorgnia 2007), which used the two-stage method as the solution technique.

Maximum Incremental Velocity Database

An extensive maximum incremental velocity, *MIV* database was developed by expanding the PEER-NGA (2009) ground motion database to include the *MIV*. This database has 3551 records from 175 earthquakes. Each ground motion record measured at a site in the NGA database consists of two orthogonal horizontal components and a vertical component. The *MIV* was calculated for each horizontal component by numerically integrating the corresponding acceleration time-history between two successive zero crossings, and then, by taking the maximum absolute value of these "incremental velocities" over the entire time-history.

Several methods have been proposed to express the two horizontal components of a ground motion record into a single component. For instance, Joyner and Boore (1981, 1993) used the larger of the two as-recorded components for *PGA* and *PGV*. Boore et al. (1997) used the geometric mean, which, for *MIV*, can be written as

$$MIV = \sqrt{(MIV_1)(MIV_2)} \tag{9}$$

In Eq. (9), MIV_1 and MIV_2 are computed from the two orthogonal horizontal acceleration time-history components and MIV is the geometric mean. Recognizing that the sensors at the recording sites are randomly oriented, Boore et al. (2006) proposed a measure of the geometric mean, referred to as *GMRotDpp*, that attempts to remove the uncertainty in the ground motion measure due to the sensor orientation. The geometric means of the earthquake measure under study, in this case of the *MIV*, are computed from the two recorded orthogonal acceleration time-history components rotated through θ=0° to 90° from the sensor orientation at the site. The calculated geometric means are then rank ordered. Boore et al. (2006) define *GMRotDpp* as the pp^{th} percentile of this rank-ordered list. Therefore, the level of uncertainty due to sensor orientation can be selected.

The attenuation relationships in this paper were developed both for *GMRotD50* and *GMRotD100*; the median MIV over all sensor orientations (referred to as MIV_{50} in this paper) as well as the maximum MIV (referred to as $MIV_{\max}$). Note that the relationships were developed using the ground motion ensemble from Boore and Atkinson (2007), which is a subset (containing 1574 records from 58 earthquakes) of the PEER-NGA (2009) database. Fig. 1 plots the available $\widehat{MIV}_{\max}$ data for this subset against the Joyner-Boore distance, d_{JB} as well as the earthquake moment magnitude, m. The $\widehat{MIV}_{50}/\widehat{MIV}_{\max}$ ratio is also plotted against d_{JB} and m. A general trend for the MIV with d_{JB} and m can be observed. Also, for a large number of records, there are considerable differences between the $\widehat{MIV}_{50}$ and $\widehat{MIV}_{\max}$ values calculated from the two orthogonal horizontal components.

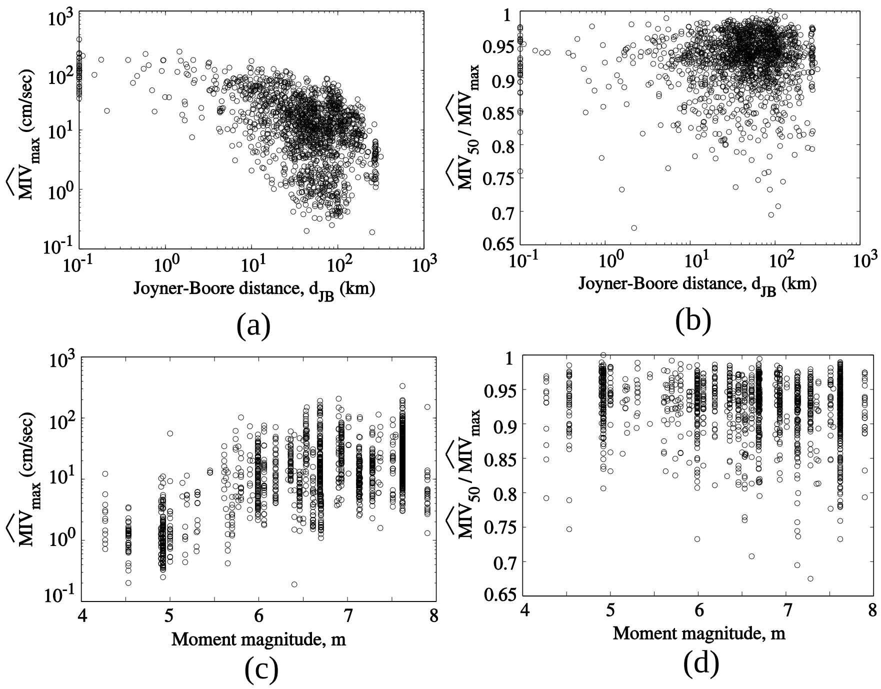


Figure 1. MIV data: (a) $\widehat{MIV}_{\max}-d_{JB}$; (b) $\widehat{MIV}_{50}/\widehat{MIV}_{\max}-d_{JB}$; (c) $\widehat{MIV}_{\max}-m$; (d) $\widehat{MIV}_{50}/\widehat{MIV}_{\max}-m$

Fig. 2 provides more information on the MIV database by plotting $\widehat{MIV}_{\max}$ against the $\widehat{PGA}_{\theta_{MIV\max}}$ of the entire time-history as well as of the MIV pulse, where $\widehat{PGA}_{\theta_{MIV\max}}$ is the geometric mean PGA of the rotated time-history components at the same orientation angle, θ as that for $\widehat{MIV}_{\max}$ (referred to as $\theta_{MIV\max}$). An additional plot shows $\widehat{MIV}_{50}$ versus the median geometric mean of the peak ground velocity, $\widehat{PGV}_{50}$ as obtained from the PEER-NGA database. As may be expected, there is a very strong correlation between the MIV and the

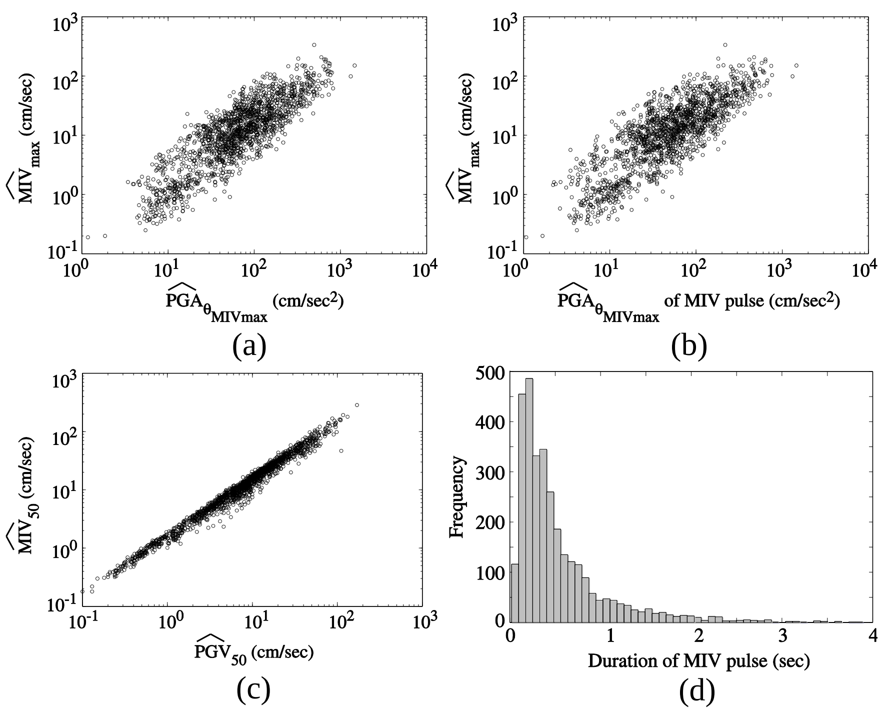


Figure 2. MIV data: (a) $\widehat{MIV}_{\max}-\widehat{PGA}_{\theta_{MIV\max}}$; (b) $\widehat{MIV}_{\max}-\widehat{PGA}_{\theta_{MIV\max}}$ of MIV pulse; (c) $\widehat{MIV}_{50}-\widehat{PGV}_{50}$; (d) duration of MIV pulse, $t_{\theta_{MIV\max}}$

PGV. Finally, the duration of the *MIV* pulse, $t_{\theta_{MIV\max}}$ is plotted for the two orthogonal acceleration components (without taking the geometric mean) of each record rotated at $\theta_{MIV\max}$.

Solution Methodology

All the previous attenuation relationships described above can be written in the following general form (Gallant 1987).

$$\mathbf{y} = \mathbf{f}\left(\mathbf{X};\mathbf{b}\right) + \mathbf{e} \equiv \mathbf{f}\left(\mathbf{b}\right) + \mathbf{e} \tag{10}$$

where, $\mathbf{y}$ is an $n \times 1$ vector containing the response variable (e.g., *PGA*, *MIV*), n is the number of records, $\mathbf{X}$ is an $n \times p$ matrix containing the earthquake data, $\mathbf{f}$ is an $n \times 1$ nonlinear function of the regression coefficients, $\mathbf{b}$ is a $p \times 1$ vector of regression coefficients to be determined, and $\mathbf{e}$ is an $n \times 1$ vector containing the residuals. Note that in Eq. (10) and in the following, the explicit dependence of the functions on the matrix $\mathbf{X}$ is suppressed. Also, as stated previously, $\mathbf{e}$ is assumed to be a vector of normally distributed random variables with zero mean and variance-covariance matrix, $\mathbf{V}$. The assumed structure of $\mathbf{V}$ is given in Joyner and Boore (1993) and discussed further below.

The problem defined by Eq. (10) can be converted into a standard nonlinear least-squares problem (with diagonal variance-covariance matrix) as follows (Seber and Wild 1989). Let $\mathbf{V} = \mathbf{U}^T\mathbf{U}$ be the Cholesky decomposition of the matrix $\mathbf{V}$, where $\mathbf{U}$ is upper triangular. Multiplying the nonlinear model by $\mathbf{R} = \left(\mathbf{U}^T\right)^{-1}$ yields

$$\mathbf{z} = \mathbf{k}\left(\mathbf{b}\right) + \mathbf{g} \tag{11}$$

with, $\mathbf{z} = \mathbf{R}\mathbf{y}, \mathbf{k}\left(\mathbf{b}\right) = \mathbf{R}\mathbf{f}\left(\mathbf{b}\right)$, and $\mathbf{g} = \mathbf{R}\mathbf{e}$. Then, $E\left[\mathbf{g}\right] = 0$, where E is the expected-value operator and $E\left[\mathbf{g}\mathbf{g}^T\right] = \sigma^2\mathbf{I}$, that is, the elements of $\mathbf{g}$ are now uncorrelated, normally distributed, zero-mean random variables with constant variance, σ^2. The model given by Eq. (11) can be solved in a straight-forward manner by Newton iteration, if the elements of $\mathbf{V}$ are known. As shown in Joyner and Boore (1993), the matrix $\mathbf{V}$ can be expressed as $\sigma^2\mathbf{v}$, where the matrix $\mathbf{v}$ contains the unknown constant, $\gamma = \sigma_e^2 / \left(\sigma_r^2 + \sigma_e^2\right)$. Joyner and Boore solve for the best estimates, $\hat{\sigma}^2$ and $\hat{\gamma}$, by using the maximum likelihood method. Basically, Eq. (11) is solved for the vector $\mathbf{b}$ that minimizes the sum of the errors squared, for an assumed value of γ. The corresponding estimate of the variance is given by

$$\sigma^2 = \frac{\left(\mathbf{z} - \mathbf{k}\left(\mathbf{b}\right)\right)^T \left(\mathbf{z} - \mathbf{k}\left(\mathbf{b}\right)\right)}{n - q} \tag{12}$$

Here, q is the number of regression coefficients (p) or the rank of $\mathbf{K}\left(\mathbf{b}\right) = \partial\mathbf{k} / \partial\mathbf{b}^T$, the Jacobian matrix of the nonlinear function, $\mathbf{k}\left(\mathbf{b}\right)$, whichever is smaller. A search is conducted over $\gamma \in \left[0,1\right]$ to find the value $\hat{\gamma}$ and the corresponding values of $\hat{\mathbf{b}}$ and $\hat{\sigma}^2$ that maximize the likelihood function [see Joyner and Boore (1993) for details]. This procedure was employed in the subsequent simulations.

Model Selection and Evaluation

In this first attenuation study of the *MIV*, the simpler regression models reviewed above were evaluated using the one-stage solution methodology described in the previous section. The attenuation models that were studied are: (1) Joyner and Boore (1993) model in Eq. (4), referred to as the JB93 model in the remainder of this paper; (2) Boore et al. (1997) model in Eq. (5), referred to as the BJF97 model; and (3) Akkar and Bommer (2007) model in Eq. (7), referred to as the AB07 model. The more complex Boore and Atkinson (2007) and Campbell and Bozorgnia (2007) models were not included in the study.

Consistent with the finding in Boore et al. (1997), the coefficient, b_3 of the distance measure r in the JB93 model was found to be almost zero [and statistically not significant based on a Student's *t*-test (Mendenhall and Sincich 2007)] using the MIV database, and thus, this term was eliminated from this model. Also, unlike the JB93 model (which used $\log_{10}$), natural logarithms of the regression parameters were used in the current study. Furthermore, the AB07 model was modified as follows to make it more compatible with the other models: (1) a centered moment magnitude term of (m–6) was used; (2) since the shear-wave velocities, V_S of all of the records were available in the database, the soil effect was included using a term proportional to $\ln(V_S)$; and (3) the fault-type classification from the BJF97 model was also used in the AB07 model. Thus, the models were evaluated in the following equation forms.

$$y = b_1 + b_2(m-6) + b_3 r - \ln r(d_{JB}, b_4), \quad \text{JB93} \tag{13}$$

$$y = b_1 + b_2(m-6) + b_3(m-6)^2 + b_4 \ln r\left(d_{JB}, b_6\right) + b_5 \ln(V_S) + b^{FT}, \quad \text{BJF97} \tag{14}$$

$$\begin{aligned} y = {} & b_1 + b_2\left(m-6\right) + b_3\left(m-6\right)^2 + b_4 \ln r\left(d_{JB}, b_6\right) + b_5\left(m-6\right)\ln r\left(d_{JB}, b_6\right) \\ & + b_7 \ln\left(V_S\right) + b^{FT}, \quad \text{AB07} \end{aligned} \tag{15}$$

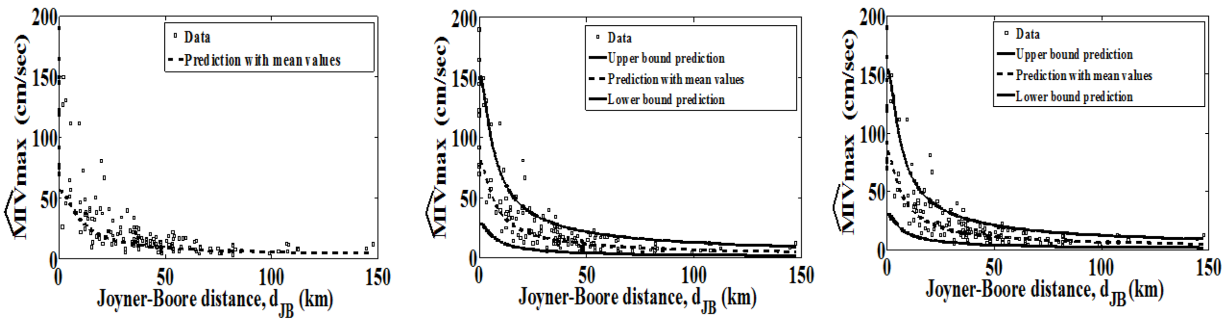
where $y = \ln\left(MIV\right)$ in all cases.

Table 1. Regression statistics and coefficients

	JB93		BJF97		AB07	
	$MIV_{\max}$	MIV_{50}	$MIV_{\max}$	MIV_{50}	$MIV_{\max}$	MIV_{50}
b_1	5.26	5.09	6.967	6.923	6.57	6.48
b_2	0.959	0.949	1.028	1.021	0.630	0.540
b_3	0.00	0.00	-0.168	-0.172	-0.176	-0.187
b_4	6.80	7.98	-0.758	-0.753	-0.843	-0.850
b_5	-	-	-0.653	-0.659	0.108	0.130
b_6	-	-	3.898	3.905	3.76	4.41
b_7	-	-	1.617	1.601	-0.637	-0.640
b_8	-	-	1.768	1.755	2.20	2.15
b_9	-	-	1.281	1.268	2.37	2.33
b_{10}	-	-	-	-	1.90	1.89
σ_r	0.583	0.609	0.534	0.534	0.531	0.557
σ_e	0.416	0.418	0.273	0.274	0.252	0.245
$\hat{\sigma}^2$	0.513	0.546	0.361	0.361	0.346	0.367

Using the Boore and Atkinson (2007) ensemble, Table 1 shows the numerical results for the regression coefficients and the error terms determined from the one-stage algorithm on both the MIV_{50} as well as the $MIV_{\max}$. All regression coefficients were found to be significant at the 5% level using a Student's *t*-test (Mendenhall and Sincich 2007). Based on the calculated variances, it can be seen that the AB07 model provides the best fit to the total MIV data.

The variance values in Table 1 provide an overall evaluation of each regression model to the entire data set containing 1574 records from 58 earthquakes. Of considerable interest is how well the models predict the MIV for large-magnitude, near-source events. Thus, to supplement the comparisons in Table 1, Fig. 3 shows the data fit for only the records from the 1994 Northridge, California earthquake (154 □ markers). The dashed line in each plot depicts the corresponding regression curve using the mean values of the parameters from the Northridge ensemble (i.e., V_S = 420 m/sec) and the solid lines provide the upper and lower boundaries of the prediction, which were generated by maximizing and minimizing the prediction line using the available data ranges from the Northridge ensemble (i.e., $V_{S,\min}$ = 160 m/sec to generate the upper curve, and $V_{S,\max}$ = 2,016 m/sec to generate the lower curves). Northridge had a reverse-slip fault type. Note that the smallest value of the shear-wave velocity, V_S is used to generate the upper boundary since the sign of the V_S coefficient is negative reflecting that softer soils predict a larger MIV response. Note also that upper and lower boundary lines are not provided for the JB93 model since the only parameters in this regression equation are distance, d_{JB} (which is plotted on the horizontal axis in Fig. 3) and magnitude (which is constant, m = 6.69 for the Northridge earthquake).

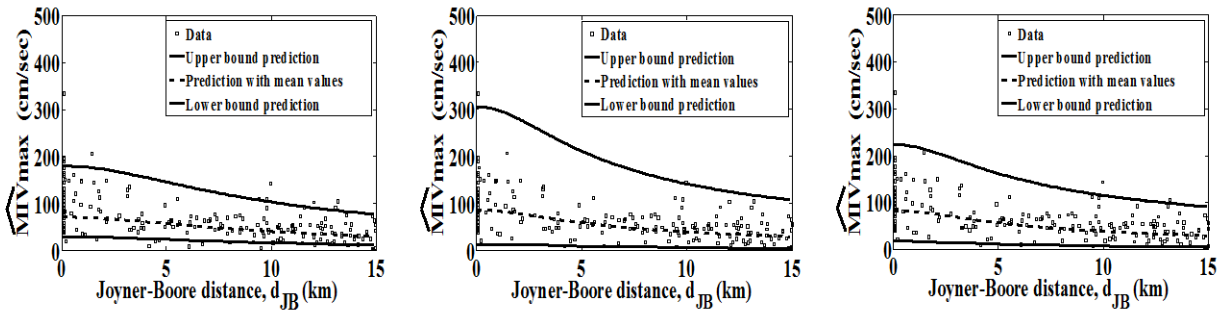


(a) (b) (c)

Figure 3. $MIV_{\max}$ data set and regression predictions for the 1994 Northridge earthquake: (a) JB93 model; (b) BJF97 model; (c) AB07 model

From the comparisons in Fig. 3, it can be seen that while most of the data falls within the corresponding prediction band, high outliers indicate improvements may be needed to the regression models. The BJF97 and AB07 models yield similar results, whereas the JB93 model seems not as good indicating the contribution of the soil effect and the fault type. Further evaluation of the models is made in Fig. 4 where only the records from earthquakes with magnitudes greater than 6.0 and recording distances less than 15 kilometers (187 □ markers) in the Boore and Atkinson (2007) ensemble are plotted. The prediction lines in Fig. 4 were obtained as follows. The dashed line uses the mean values of the parameters from this subset of records (m = 6.95, V_S = 453 m/sec, mean of b^{FT}). The solid lines were obtained by choosing the maximum magnitude, minimum shear-wave velocity ($m_{\max}$ = 7.9, $V_{S,\min}$ = 162 m/sec) and reverse-slip fault type to generate the upper curve, and then the minimum magnitude, maximum velocity ($m_{\min}$ = 6.06, $V_{S,\min}$ = 2,016 m/sec) and strike-slip fault type to generate the lower curve.

Out of the 187 data points, all except for three are contained within the upper and lower boundaries in the AB07 model prediction. Although the error variance is certainly significantly greater for the JB93 model, the model is much simpler yet captures the data fairly well. The BJF97 model results in Fig. 4 are somewhat different. Although the mean prediction equation is very similar to the other two models, the upper boundary curve (generated by using the maximum magnitude, minimum shear-wave velocity and reverse fault type) is higher and over predicts the MIV in this data set significantly. The upper bound is very close to the overall maximum value of the MIV subset (1999 Chi-Chi, Taiwan earthquake with a magnitude of 7.62, and one record with a distance of 0.1 km, shear-wave velocity of 487 m/sec, and a MIV of 334 cm/sec). The high magnitude, low shear-wave velocity, reverse fault type and close distance cause the BJF97 model to predict an excessive MIV value. The negative coefficient of the m^2 term in the AB07 model, however, somewhat mitigates the effect of a large magnitude and so the AB07 does not show as high a prediction for this case, yet captures all of the data except for three points.



(a) (b) (c)

Figure 4. MIV_{max} data set and regression predictions for all records with m > 6.0 and d < 15 km: (a) JB93 model; (b) BJF97 model; (c) AB07 model

Summary and Conclusions

This paper presents a first attempt at developing a predictive attenuation relationship for the maximum incremental velocity (*MIV*) from data on recorded earthquake ground acceleration time-histories. The PEER-NGA (2009) ground motion database was extended to include the geometric mean of the maximum incremental velocity, providing values for the maximum as well as the median geometric mean over all possible sensor orientations. Several attenuation relationships existing in the literature for other ground motion measures, such as *PGA* and *PGV*, were evaluated for use with *MIV*. It was found that the simple model proposed by Joyner and Boore (1993) compares favorably with the more complicated 1997 version of their model and a variation of the model recently proposed by Akkar and Bommer (2007). For large-magnitude, near-source records, the BJF97 model may overestimate considerably the *MIV*. Based on this preliminary analysis, it appears that, overall, the model based on the AB07 equation best represents the data. However, more in-depth studies using these and other attenuation models are currently underway.

Acknowledgments

Support for the graduate studies of the first author was provided by a Fulbright scholarship. This support is gratefully acknowledged. The authors would also like to acknowledge David Boore and Yousef Bozorgnia for providing their ground motion databases. The opinions, findings, and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the individuals and organizations acknowledged above.

References

Aki, K. and P. Richards, 2002. *Quantitative Seismology*, University Science Books, Sausalito, California.

Akkar, S. and J. Bommer, 2007. Empirical prediction equations for peak ground velocity derived from strong-motion records from Europe and the Middle East, *Bulletin of the Seismological Society of America* 97(2), 511-530.

Boore, D. and G. Atkinson, 2007. Boore-Atkinson NGA Ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters, PEER Report No. 2007/01, *Pacific Earthquake Engin. Research Center*, Univ. of California, Berkeley, 242 pp.

Boore, D., W. Joyner, and T. Fumal, 1997. Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work (with 2005 erratum), *Seismological Research Letters* 68(1), 128-153.

Boore, D., J. Watson-Lamprey, and N. Abrahamson, 2006. Orientation-independent measures of ground motion, *Bulletin of the Seismological Society of America* 96(4A), 1502-1511.

Brillinger, D. and H. Preisler, 1984. An exploratory analysis of the Joyner-Boore attenuation data, *Bulletin of the Seismological Society of America* 74(4), 1441-1450.

Brillinger, D. and H. Preisler, 1985. Further analysis of the Joyner-Boore attenuation data, *Bulletin of the Seismological Society of America* 75(2), 611-614.

Campbell, K., 1981. Near-source attenuation of peak horizontal acceleration, *Bulletin of the Seismological Society of America* 71(6), 2039-2070.

Campbell, K. and Y. Bozorgnia, 2007. Campbell-Bozorgnia NGA Ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters, PEER Rep. No. 2007/02, *Pacific Earthquake Engin. Res. Center*, Univ. of California, Berkeley, 238 pp.

Fukushima, Y. and T. Tanaka, 1990. A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan, *Bulletin of the Seismological Society of America* 80(4), 757-783, Tokyo, Japan.

Gallant, A., 1987. *Nonlinear Statistical Models*, John Wiley & Sons Inc., Raleigh, North Carolina.

Gutenberg, B. and C. Richter, 1942. Earthquake magnitude, intensity, energy and acceleration, *Bulletin of the Seismological Society of America* 32(3), 163-191.

Joyner, W. and D. Boore, 1981. Peak horizontal acceleration and velocity from strong- motion records including records from the 1979 Imperial Valley, California, earthquake, *Bulletin of the Seismological Society of America* 71(6), 2011-2038.

Joyner, W. and D. Boore, 1993. Methods for regression analysis of strong-motion data, *Bulletin of the Seismological Society of America* 83(2), 469-487.

Kawasumi, H., 1951 Measures of Earthquake danger and expectancy of maximum intensity throughout Japan as inferred from the seismic activity in historical times, Bulletin Earthquake Res. Inst., Tokyo University 29(3), 469-482.

Kurama, Y. and K. Farrow, 2003. Ground motion scaling methods for different site conditions and structure characteristics, *Earthquake Engineering and Structural Dynamics* 32(15), 2425-2450.

Mendenhall, W. and T. Sincich, 2007. *Statistics for Engineering and the Sciences*, Prentice Hall Inc., Upper Saddle River, New Jersey.

PEER, 2009. *Pacific Earthquake Engineering Research Center*: NGA Database, http://peer.berkeley.edu/nga/

Seber, G. and C. Wild, 1989, *Nonlinear Regression*, John Wiley & Sons Inc., Hoboken, New Jersey.

Spudich P., W. Joyner, A. Lindh, D. Boore, B. Margaris, and J. Fletcher, 1999. SEA99: A revised ground motion prediction relation for use in extensional tectonic regimes, *Bulletin of the Seismological Society of America* 89(5), 1156-1170.

Trifunac, M., 1976. Preliminary empirical model for scaling Fourier amplitude spectra of strong ground acceleration in terms of earthquake magnitude, source-to-station distance, and recording site conditions, *Bulletin of the Seismological Society of America* 66(4), 1343-1373.