

PGA Correlation with the Mercalli scale

The [United States Geological Survey](#) developed an Instrumental Intensity scale which maps peak ground acceleration and peak ground velocity on an intensity scale similar to the felt [Mercalli scale](#). These values are used to create shake maps by seismologists around the world.

Instrumental Intensity	MMI	Acceleration (g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I		< 0.0017	< 0.1	Not felt	None
II-III		0.0017 - 0.014	0.1 - 1.1	Weak	None
IV		0.014 - 0.039	1.1 - 3.4	Light	None
V		0.039 - 0.092	3.4 - 8.1	Moderate	Very light
VI		0.092 - 0.18	8.1 - 16	Strong	Light
VII		0.18 - 0.34	16 - 31	Very strong	Moderate
VIII		0.34 - 0.65	31 - 60	Severe	Moderate to heavy
IX		0.65 - 1.24	60 - 116	Violent	Heavy
X+		> 1.24	> 116	Extreme	Very heavy

Comparison of Two Versions of Modified Mercalli Intensity- MSc 2012

Even knowing when PGA or PGV is more appropriate for using in place of MMI is not sufficient to assign an MMI class. PGA or PGV values must be converted to MMI using one of four formulae developed by looking at the relationship between MMI, PGA, and PGV for eight earthquakes in Southern California (Wald et. al., 1999). The four formulae in combination most completely approximate MMI using PGA and PGV:

- (1) $I_{mm} = 3.66 \log (PGA) - 1.66$ when $MMI V \leq I_{mm} \leq VIII$;
- (2) $I_{mm} = 3.47 \log (PGV) + 2.35$ when $MMI V \leq I_{mm} \leq IX$;
- (3) $I_{mm} = 2.20 \log (PGA) + 1.00$ when $MMI I_{mm} < V$ or;
- (4) $I_{mm} = 2.10 \log (PGV) + 3.40$ when $MMI I_{mm} < V$

Formula (1) is used first to convert PGA (in cm/s²) to MMI. If the resulting intensity value I_{mm} is greater than VII then Formula (2) is used to convert PGV (in cm/s) to MMI instead. If the result from Formula (1) is less than V then the result from Formula (3) or (4) replaces Formula (1). In practice, Formula (3) is used rather than Formula (4) since PGA is more representative than PGV of low-level shaking intensity. These formulae reveal that even though a relationship between PGA and MMI has been established, the relationship is not perfect. Resulting MMI and PGA outputs from ShakeMap will therefore produce different results when doing a spatial exposure analysis.

Wald et al. (1999) demonstrated in their analysis of historical California earthquakes that a perfect positive relationship between PGA or PGV and MMI does not exist.

Comparison of instrumental and felt intensity

Peak ground acceleration provides a measurement of *instrumental intensity*, that is, ground shaking recorded by [seismic instruments](#). Other intensity scales measure *felt intensity*, based on eyewitness reports, felt shaking, and observed damage. There is correlation between these scales, but not always absolute agreement since experiences and damage can be affected by many other factors, including the quality of earthquake engineering. Generally speaking,

- 0.001 g (0.01 m/s²) – perceptible by people
- 0.02 g (0.2 m/s²) – people lose their balance
- 0.50 g – very high; well-designed buildings can survive if the duration is short.^[4]

Table 1. Modified Mercalli Intensity (MMI) classes, including relations to PGA values (Wald and others, 1999) and impact descriptions (abridged from U.S. Geological Survey, 1989).

MMI Class	PGA Range	Description of Societal Impact
I	< 0.0017g	Not felt except by a very few under especially favorable conditions.
II	0.0017–0.014g	Felt only by a few persons at rest, especially on upper floors of buildings.
III	0.0017–0.014g	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	0.014–0.039g	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	0.039–0.092g	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	0.092–0.18g	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	0.18–0.34g	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	0.34–0.65g	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	0.65–1.24g	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	> 1.24g	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

Approximate Relationship between Mercalli Intensity and PGA

MMI	PGA (g)
IV	0.03 and below
V	0.03 – 0.08
VI	0.08 – 0.15
VII	0.15 – 0.25
VIII	0.25 – 0.45
IX	0.45 – 0.60
X	0.60 – 0.80
XI	0.80 – 0.90
XII	0.90 and above

2.2. Recent statistical data

The wealth of macroseismic and instrumental information which became available more recently made it possible to develop a statistical study on the relationships between macroseismic intensity and kinematic parameters (Aptikaev 2005). They refer essentially to the outcome of statistical analysis of instrumental data on ground motion, for cases when macroseismic intensity estimates were at hand. The wealth of data used was considerable: 84 records for intensity 9, 178 records for intensity 8, 212 records for intensity 7, 353 records for intensity 6, 391 records for intensity 5, 172 records for intensity 4, 75 records for intensity 3 and 75 records for intensity 2. The results obtained stood at the basis of the specification of instrumental criteria adopted in the frame of the draft new Russian Macroseismic Scale, *RMS-04* (Aptikaev, 2005), (Aptikaev, 2006), (Shebalin & Aptikaev, 2003).

The empirical relations determined on a statistical basis are (with some updating with respect to (Aptikaev, 2005), (Aptikaev, 2006)): for peak ground accelerations, “*A*”; for peak ground velocities, “*V*”; for peak ground displacements “*D*”; and for peak wave kinematic power, “*P*” respectively:

$$\lg A (^{\circ} PGA), \text{ cm/s}^2 = - 0.755 + 0.4 I \pm 0.39 (0.25) \text{ (correlation coefficient: 0.82)} \quad (1)$$

$$\lg V (^{\circ} PGV), \text{ cm/s} = - 2.23 + 0.47 I \pm 0.33 (0.20) \text{ (correlation coefficient: 0.84)} \quad (2)$$

$$\lg D (^{\circ} PGD), \text{ cm} = - 4.26 + 0.68 I \pm 0.65 (0.33) \text{ (correlation coefficient: 0.81)} \quad (3)$$

$$\lg P, \text{ cm}^2/\text{s}^3 = - 2.22 + 0.87 I \pm 0.49 (0.41) \text{ (correlation coefficient: 0.89)} \quad (4)$$

Quantities under “ $\pm$ ” mean standard deviations, related both to intensity and ground motion parameters estimations. In parentheses are given values for intensities $I > 6$.

It turns out, on the basis of these relations, that the average values obtained for a jump of one intensity unit are:

- for peak ground accelerations, $100.4 \gg 2.51$;
- for peak ground velocities, $100.47 \gg 2.95$;
- for peak ground displacements, $100.68 \gg 4.79$;
- for peak wave kinematic power (as also for the product of peak ground acceleration and peak ground velocity), $100.87 \gg 7.41$.

The facts that the factor 0.47 of relation (2) is higher than the homologous factor 0.40 of relation (1), while the factor 0.68 of relation (3) is higher than the homologous factor 0.47 of relation (2), correspond to a rather well known trend of increase of dominant oscillation periods of ground motion with increasing intensity (this trend was quite systematically observed, on the basis of instrumental data obtained at a same location during different earthquakes, in Romania too). These results, which correspond to reality, are in direct contradiction with the features of the MSK scale criteria, which relied on the assumption of fixed corner periods, irrespective of intensity.

Looking at the values of kinematic parameters derived on the basis of previous relations, it turns out that one obtains reasonable values even for lowest intensities, for which the assumption of a fixed value of 2.0 for a jump of one intensity unit did no longer work. So, it appears to be reasonable to adopt such values, perhaps with a minor rounding up (e.g.: 2.5 for accelerations, 3.0 for velocities, 4.8 for displacements, 7.5 for peak kinematic power). These results could eventually be combined with the need of revising the logarithm basis $b = 4$, adopted initially (Sandi, 1986), (Sandi & Floricel, 1998), referred to further on. In case the rounded up values suggested are accepted, the result would be a value $b = 7.5$, which would make it possible to cover in a satisfactory manner an extensive interval of intensities, going e.g. downwards up to intensity 2.

ESTIMATION OF MACROSEISMIC INTENSITY – NEW ATTENUATION AND INTENSITY VS. GROUND MOTION RELATIONS FOR DIFFERENT PARTS OF EUROPE, M.B. Sørensen¹, D. Stromeyer² and G. Grünthal³, 2008

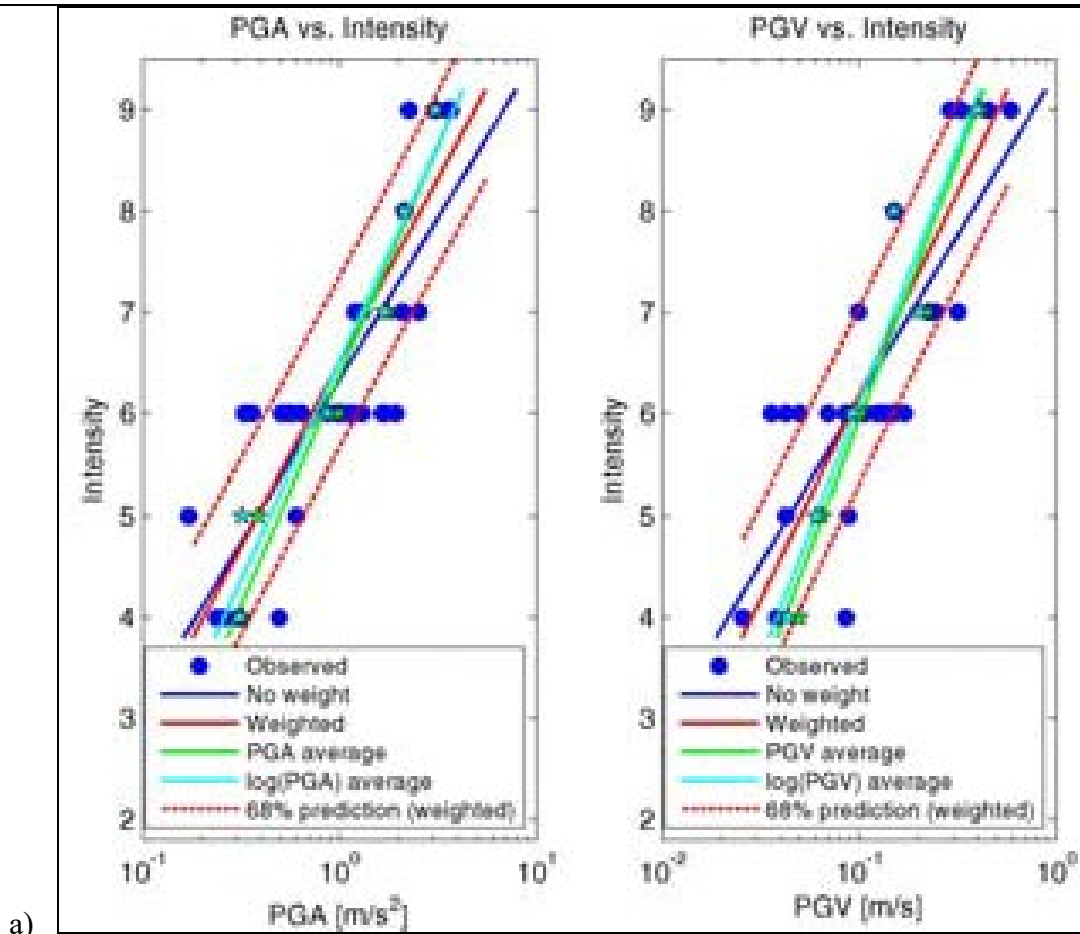
4.2. PGM vs. intensity relations

The PGMI relations obtained with different weighting schemes for the three regions of interest, including mean regression errors, are listed in Table 4.2 and presented in Figure 3.

In Figure 3 we see that the different weighting schemes lead to significantly different relations between peak ground motion and intensity. The mean regression errors are generally lower for the regressions based on average values, which is as expected as these regressions are performed for fewer data points, and outliers may cancel each other due to the averaging. The weighted regression solutions seem to represent an average of the derived solutions and the 68% prediction bounds have been included for these relations. All other relations fall within these prediction bounds which again illustrates that the variation between the different relations is a measure of the limitations in our dataset. Based on our relations we can predict the intensity with an uncertainty of ca. one intensity unit in all three studied regions.

Table 2 PGMI relations for the three regions of interest. MRE: mean regression error(PGA in m/s²)

Region	Weighting	PGA relation	MRE	PGV relation	MRE
Marmara Sea	Raw data	$I=3.20 \cdot \log(\text{PGA})+6.33$	0.8062	$I=3.23 \cdot \log(\text{PGV})+9.37$	0.8267
	Weighted data	$I=3.62 \cdot \log(\text{PGA})+6.51$	0.8062	$I=4.00 \cdot \log(\text{PGV})+10.18$	0.8267
	Average	$I=4.52 \cdot \log(\text{PGA})+6.38$	0.4469	$I=5.14 \cdot \log(\text{PGV})+11.08$	0.7068
	Log average	$I=4.29 \cdot \log(\text{PGA})+6.51$	0.4859	$I=5.04 \cdot \log(\text{PGV})+11.15$	0.6245
Vrancea	Raw data	$I=1.76 \cdot \log(\text{PGA})+6.56$	0.6726	$I=2.10 \cdot \log(\text{PGV})+8.42$	0.5359
	Weighted data	$I=2.76 \cdot \log(\text{PGA})+6.63$	0.6726	$I=2.33 \cdot \log(\text{PGV})+8.58$	0.5359
	Average	$I=4.48 \cdot \log(\text{PGA})+6.55$	0.3572	$I=2.84 \cdot \log(\text{PGV})+8.93$	0.3587
	Log average	$I=4.24 \cdot \log(\text{PGA})+6.70$	0.3748	$I=2.77 \cdot \log(\text{PGV})+8.97$	0.3398
Campania	Raw data	$I=1.07 \cdot \log(\text{PGA})+6.40$	0.7259	$I=0.97 \cdot \log(\text{PGV})+7.29$	0.7087
	Weighted data	$I=1.35 \cdot \log(\text{PGA})+6.43$	0.7259	$I=1.26 \cdot \log(\text{PGV})+7.62$	0.7087
	Average	$I=2.39 \cdot \log(\text{PGA})+6.45$	0.5802	$I=2.31 \cdot \log(\text{PGV})+8.57$	0.4562
	Log average	$I=1.98 \cdot \log(\text{PGA})+6.51$	0.7318	$I=2.02 \cdot \log(\text{PGV})+8.44$	0.5977



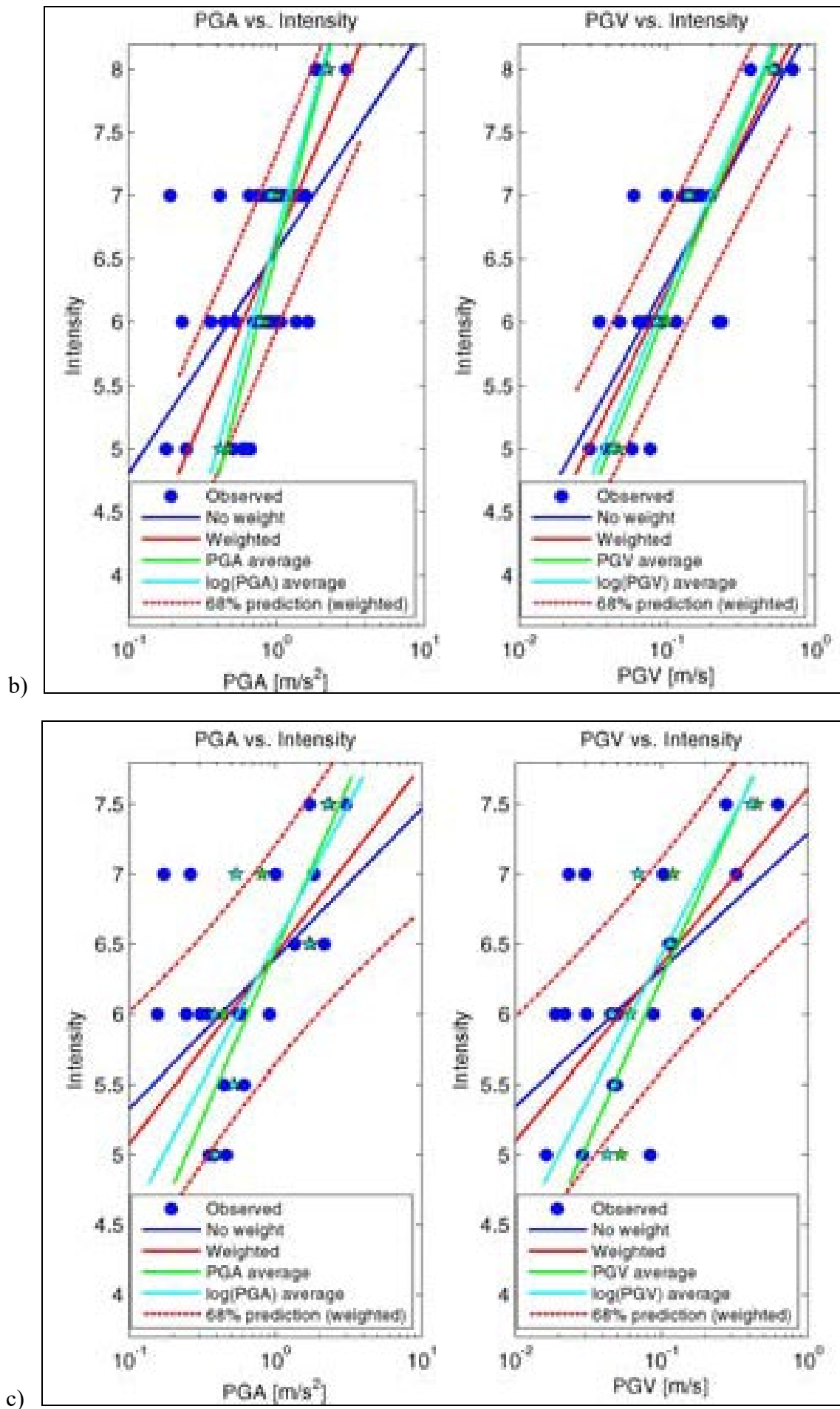


Figure 3 PGMI relations derived applying different weighting schemes for a) the Marmara Sea region, b) the Vrancea region and c) the Campania region.

GROUND MOTION PREDICTION AND INTENSITY CONVERSION RELATIONS FOR THE EUROPEAN REGION

Mathilde B. Sørensen and the SAFER WP4 team

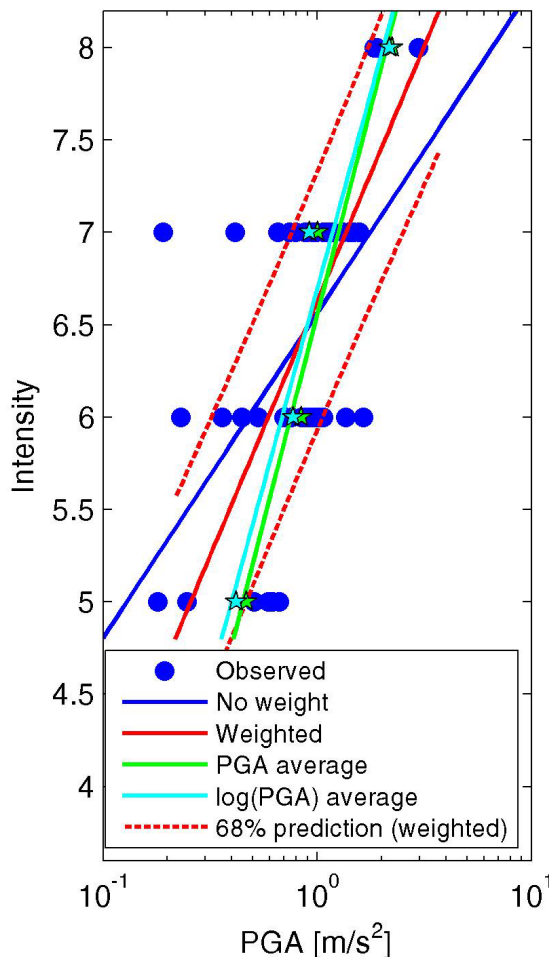
ATHENS: Selected 397 records from 73 events recorded to more than 4 stations

- $\log_{10}(\text{PGA}) = 0.65M - 1.61 \log_{10}X + 0.20S + 0.71$
- $\log_{10}(\text{PGV}) = 0.83M - 1.44 \log_{10}X + 0.15S - 1.74$
- $\log_{10}(\text{PSA0.1}) = 0.55M - 1.57 \log_{10}X + 0.13S + 1.24$
- $\log_{10}(\text{PSA0.2}) = 0.59M - 1.23 \log_{10}X + 0.15S + 0.54$
- $\log_{10}(\text{PSA0.5}) = 1.16M - 2.12 \log_{10}X + 0.16S - 0.54$
- $\log_{10}(\text{PSA1}) = 1.14M - 1.63 \log_{10}X + 0.23S - 1.74$
- $\log_{10}(\text{PSA2}) = 1.2M - 1.46 \log_{10}X + 0.21S - 2.88$
- $\log_{10}(\text{PSA3}) = 1.15M - 1.37 \log_{10}X + 0.23S - 3.25$

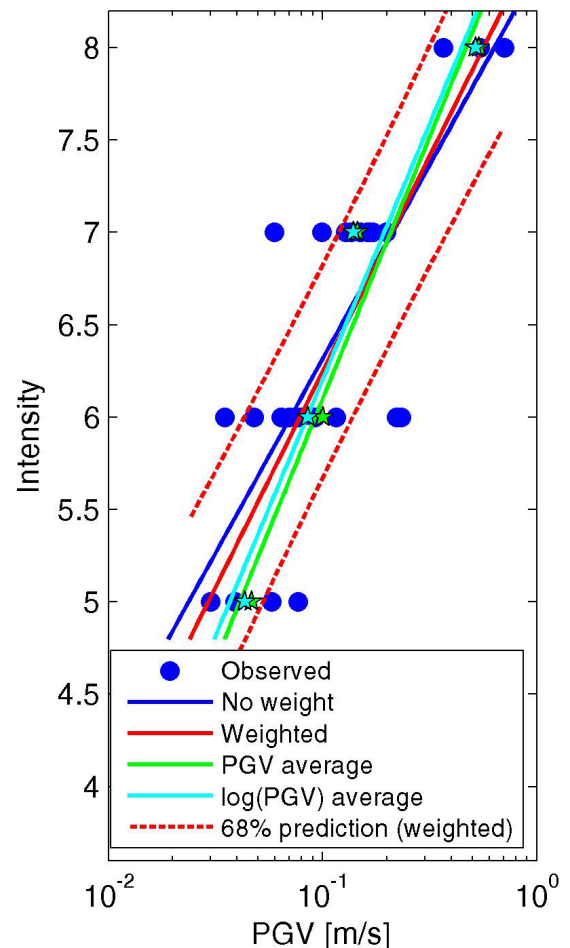
VRANCEA REGION – PGX VS. I Strong motion data from 1977 (ESD), 1986, 1990a, 1990b (NIEP- Uni Karlsruhe) events. Test four weighting schemes (unweighted, weighted, $\log(\text{mean}(\text{PGM}))$, $\text{mean}(\log(\text{PGM}))$)

Parameter	Relation	Mean Regression error
<i>PGA</i> , raw data	$I = 1.76 \cdot \log(PGA) + 6.56$	0.6726
<i>PGA</i> , weighted data	$I = 2.76 \cdot \log(PGA) + 6.63$	0.6726
<i>PGA</i> , average	$I = 4.48 \cdot \log(PGA) + 6.55$	0.3572
<i>PGA</i> , log average	$I = 4.24 \cdot \log(PGA) + 6.70$	0.3748
<i>PGV</i> , raw data	$I = 2.10 \cdot \log(PGV) + 8.42$	0.5359
<i>PGV</i> , weighted data	$I = 2.33 \cdot \log(PGV) + 8.58$	0.5359
<i>PGV</i> , average	$I = 2.84 \cdot \log(PGV) + 8.93$	0.3587
<i>PGV</i> , log average	$I = 2.77 \cdot \log(PGV) + 8.97$	0.3398

PGA vs. Intensity



PGV vs. Intensity



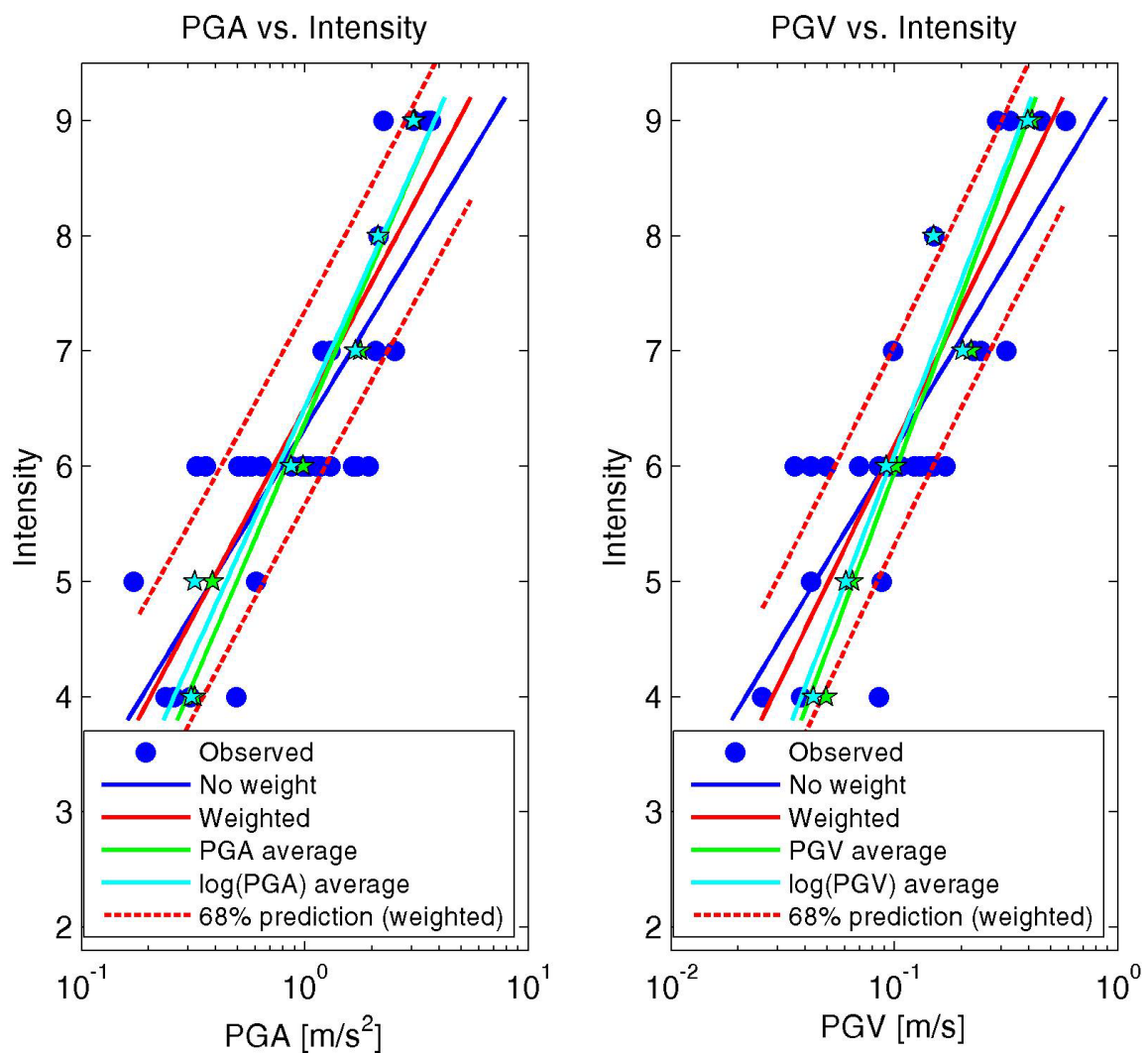
ISTANBUL, MARMARA SEA REGION – INTENSITY PREDICTION RELATION

Marmara Sea region – PGX VS. I

Strong motion data from 1983 Biga and 1999 Izmit earthquake from the European Strong-Motion Database (ESD)

Test four weighting schemes (unweighted, weighted, log(mean(PGM)), mean(log(PGM)))

Parameter	Relation	Mean regression error
<i>PGA</i> , raw data	$I=3.20 \cdot \log(PGA)+6.33$	0.8062
<i>PGA</i> , weighted data	$I=3.62 \cdot \log(PGA)+6.51$	0.8062
<i>PGA</i> , average	$I=4.52 \cdot \log(PGA)+6.38$	0.4469
<i>PGA</i> , log average	$I=4.29 \cdot \log(PGA)+6.51$	0.4859
<i>PGV</i> , raw data	$I=3.23 \cdot \log(PGV)+9.37$	0.8267
<i>PGV</i> , weighted data	$I=4.00 \cdot \log(PGV)+10.18$	0.8267
<i>PGV</i> , average	$I=5.14 \cdot \log(PGV)+11.08$	0.7068
<i>PGV</i> , log average	$I=5.04 \cdot \log(PGV)+11.15$	0.6245



MARMARA SEA REGION – PGX VS. I

DERIVE PGX VS. I RELATION BASED ON

Observed intensities from 58 earthquakes

Estimated PGA or PGV from ground motion prediction equations of Akkar and Bommer, Boore and Atkinson, Campbell and Bozorgnia and Gülkan and Kalkan

$$I_{akkar}=4.9 * \log(PGV) + 0.02 \quad \sigma=0.8$$

$$I_{boore}=4.35 * \log(PGV) + 1.57 \quad \sigma=0.7$$

$$I_{campbell}=4.24 * \log(PGV) + 1.96 \quad \sigma=0.7$$

$$I_{kalkan}=6.6 * \log(PGA) - 7.28 \quad \sigma=0.9$$

$$I_{boore}=4.5 * \log(PGA) - 2.73 \quad \sigma=0.8$$

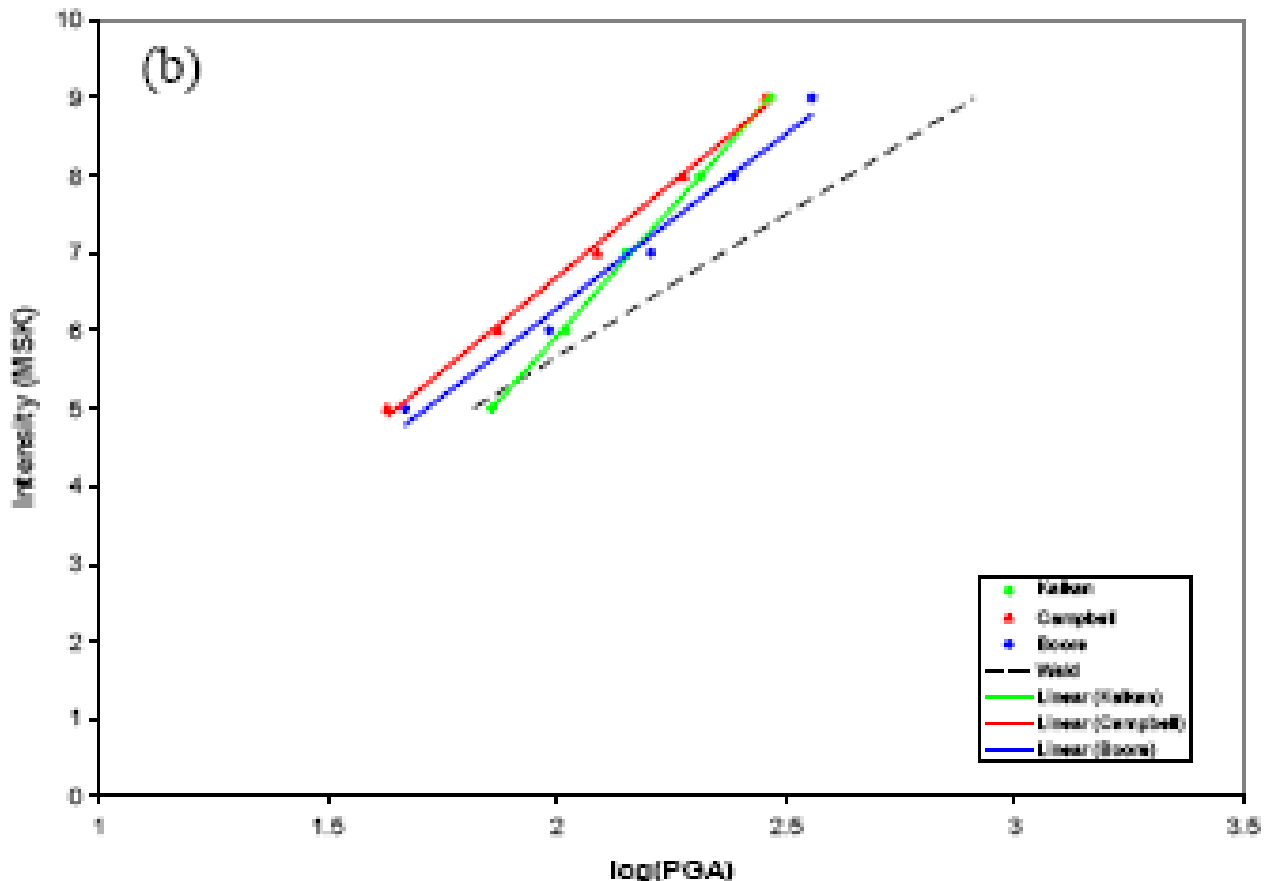
$$I_{campbell}=4.8 * \log(PGA) - 2.98 \quad \sigma=0.7$$

MARMARA SEA REGION – PGX VS. I

The PGV-Intensity relationships obtained by Boore and Atkinson (2006) and Campbell and Bozorgnia (2006) attenuation relationships agree well with the Wald et al. (1999)'s PGV-Intensity relationship for $I < 6$,

The PGV-Intensity relationship obtained by Akkar and Bommer (2006) attenuation relationship is considerably different than Wald et al. (1999)'s PGV Intensity relationship for $I < 8$.

All PGA-Intensity relationships obtained in this study are considerably different than Wald et al. (1999)'s PGA-Intensity relationship.!!!!



**LESSONS FOR THE FRAGILITY OF CANADIAN HYDROPOWER COMPONENTS
UNDER SEISMIC LOADING** L. Lin¹ and J. Adams², 2007, Ninth Canadian Conference on
Earthquake Engineering Ottawa, Ontario, Canada

Currently, the seismic hazard is normally represented by peak ground acceleration (PGA), spectral acceleration (S_a), or spectral displacement (S_d), rather than by MMI. In this study, the PGA was used as a hazard parameter, and fragility curves were developed as a function of PGA. This was done by applying the relationships between MMI and PGA (shown in Table 3) as used in the HAZUS software. Table 3. Conversion table for MMI to PGA (NIBS 1999).

Table 3. Conversion table for MMI to PGA (NIBS 1999).							
MMI	VI	VII	VIII	IX	X	XI	XII
PGA (g)	0.12	0.21	0.36	0.53	0.71	0.86	1.15

Conclusions

Seismic vulnerability analysis was conducted for major hydropower components (i.e. dams, power plants, transmission towers, and substations) at a number of selected locations in western and eastern Canada. The main conclusions that can be drawn from this study are as follows:

- The most vulnerable components of a hydropower system, when subjected to seismic motions, are the switchyards and the power plants.
- The highest vulnerability for switchyards and power plants is associated with seismic motions having peak ground accelerations (PGA) between 0.1g and 0.35g.
- The seismic vulnerability for dams and transmission towers is dominated by PGA values between 0.2g and 0.35g.
- The damage probabilities expressed as a function of peak ground accelerations are appropriate values for the vulnerability ranking of hydropower systems, even though this neglects the inter-actions among the individual components of the system.

Figure 6 shows comparison between MMI calculated by formula (3) and PGA. In this figure relationship between MMI and PGA proposed by Richter [6], Bolt [7] and Wald [8] are shown. By this after the definition of Richter, PGA corresponding to MMI increases and relationship between instrumental MMI and PGA is including the relationship between PGA and MMI defined by Richter, Bolt and Wald.

Figure 7 shows relationship between instrumental MMI and 5HzPGA and this relationship well matches with relationship Richter's first definition. These figures can be interpreted as follows; the maximum acceleration is able to measure for high frequency range recently, since high frequency does not contribute well to damage, PGA including high frequency range deviated from seismic intensity. Generally strong motion of higher than 5Hz is not effective to damage. In past, the observation range was about lower than 5Hz, so the relationship between the instrumental MMI and 5HzPGA is expected to be similar to the relationship between MMI and PGA in original.

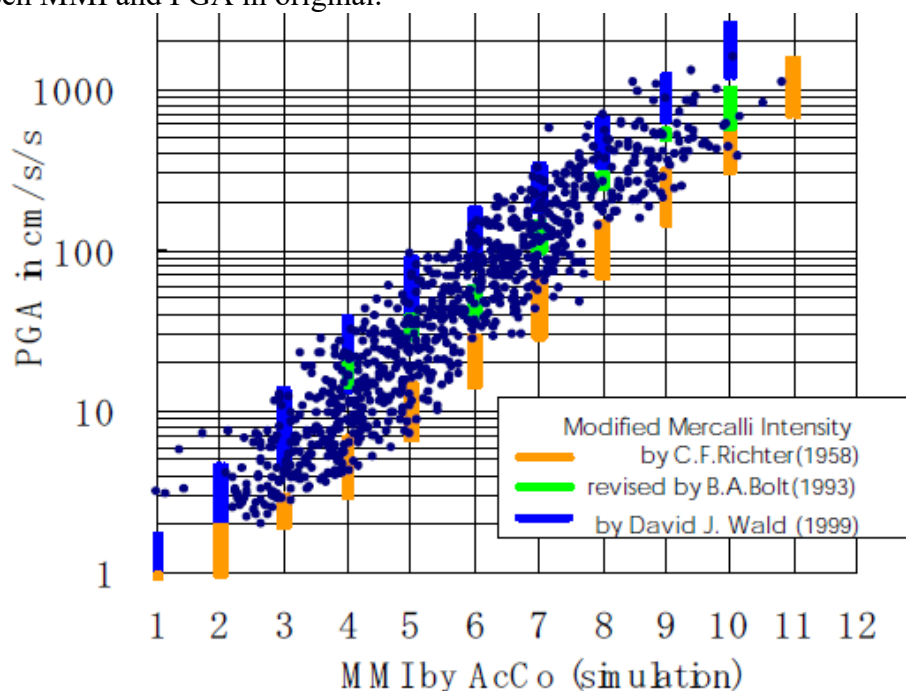


Figure 6 The comparison between MMI and PGA.

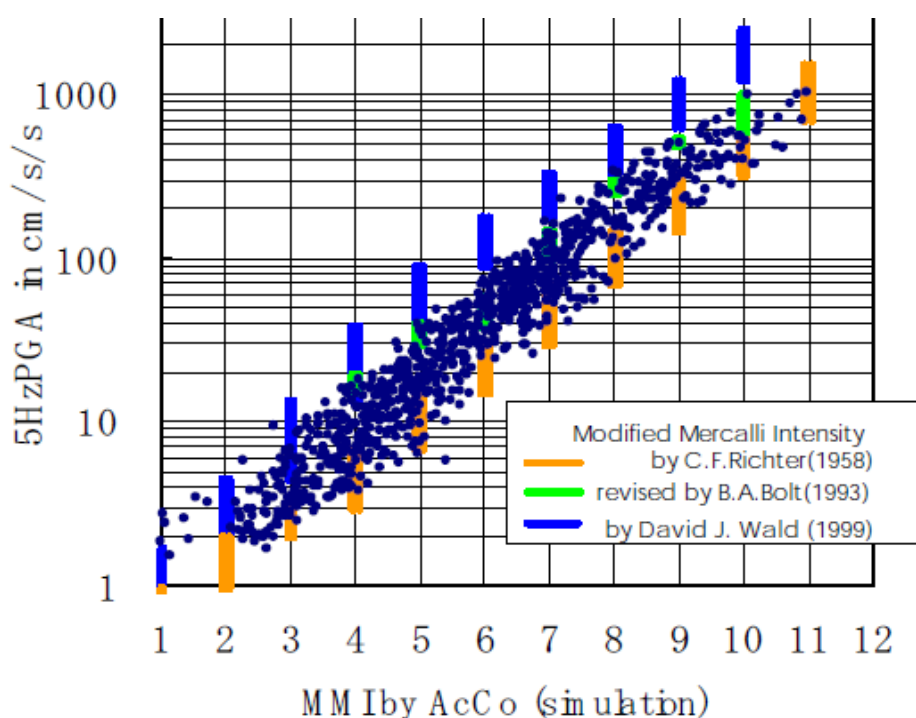


Figure 7 The relationship between instrumental MMI and 5HzPGA

The Relationship between Macroseismic Intensity and the Physical Parameters of Ground Motion

A viewpoint by B. Mohammadioun and G. Mohammadioun

Furthermore, with the passage of time and as the density of the networks increased, larger numbers of the accelerograms retrieved concerned lower-magnitude events, which may well behave differently from larger-magnitude ones, and the proportion of near-field data in the total database grew. All these elements are important sources of variability: high frequencies are not very predictable, influenced as they are by many factors, stress drop being prominent, but which also include effects only significant in the near field, such as fault geometry and directivity. As proof of the impact of this evolution, every few years witness new record-breaking peak accelerations that would have been deemed physically impossible just a few decades back. Initially believed to be limited to about 0.3 g, values today may top out at some eight times that figure, as in the most recent events in Japan (Oct. 28, 2004, $M=6.8$) and particularly at Parkfield, California (Sept. 28, 2004, $M=6.0$)!

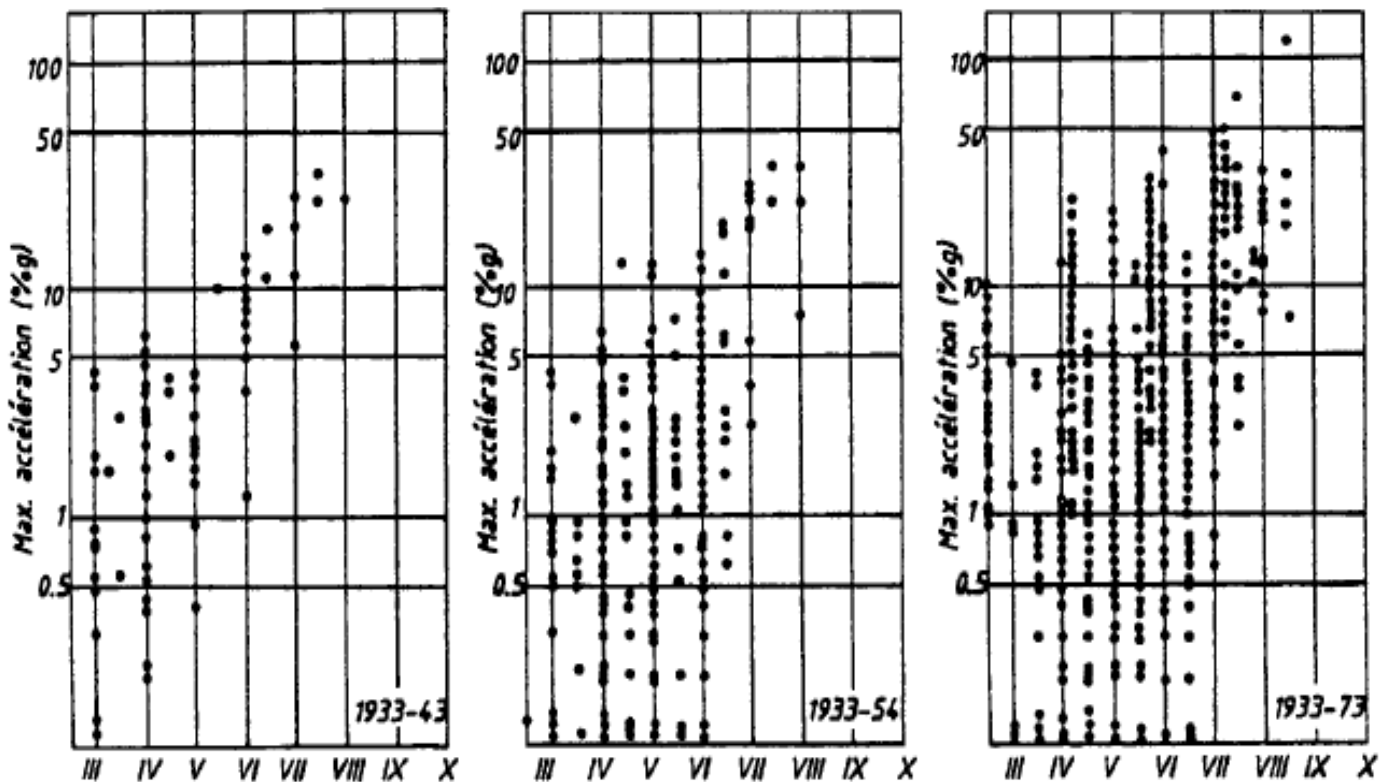


Figure 1. The evolution of acceleration/intensity correlation over time (from Ambraseys, 1974).

Synthetic ground-motion spectra are calculated from attenuation models derived from strong-motion data, now plentiful enough to support statistical correlations (Boore & *al.*, 1997, among others). This approach again seemingly bypasses the wealth of historical data essential in regions lacking accelerometric data, for whatever reason (absence of networks or low levels of seismic activity). However, there is an approach allowing this gap to be bridged: if a data bank can be established where the parameters of magnitude, M , recording-site intensity, I , and focal distance, R , have been determined in a uniform manner, correlations can be established linking the three parameters, as in Mohammadioun, 1995:

$$ML = 0.54 I + 1.40 \log R + 0.57$$

or Ambraseys, 1991:

$$MS = A + B (Ii) + C (Ri) + D \log Ri$$

based on 20th century crustal earthquakes, where teleseismic MS values were correlated with observed macroseismic estimates of Ri and Ii . In this study, sets of constants were computed for three different regions of Europe, as shown on the following table:

	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	r^2	<i>n</i>
Balkans	-0.902	0.578	1.10×10^{-3}	2.11	0.78	354
Turkey	-0.529	0.528	1.96×10^{-3}	1.83	0.94	494
NE Europe	-1.100	0.620	1.30×10^{-3}	1.62	0.92	300

where r^2 is the coefficient of correlation and n , the sample size.

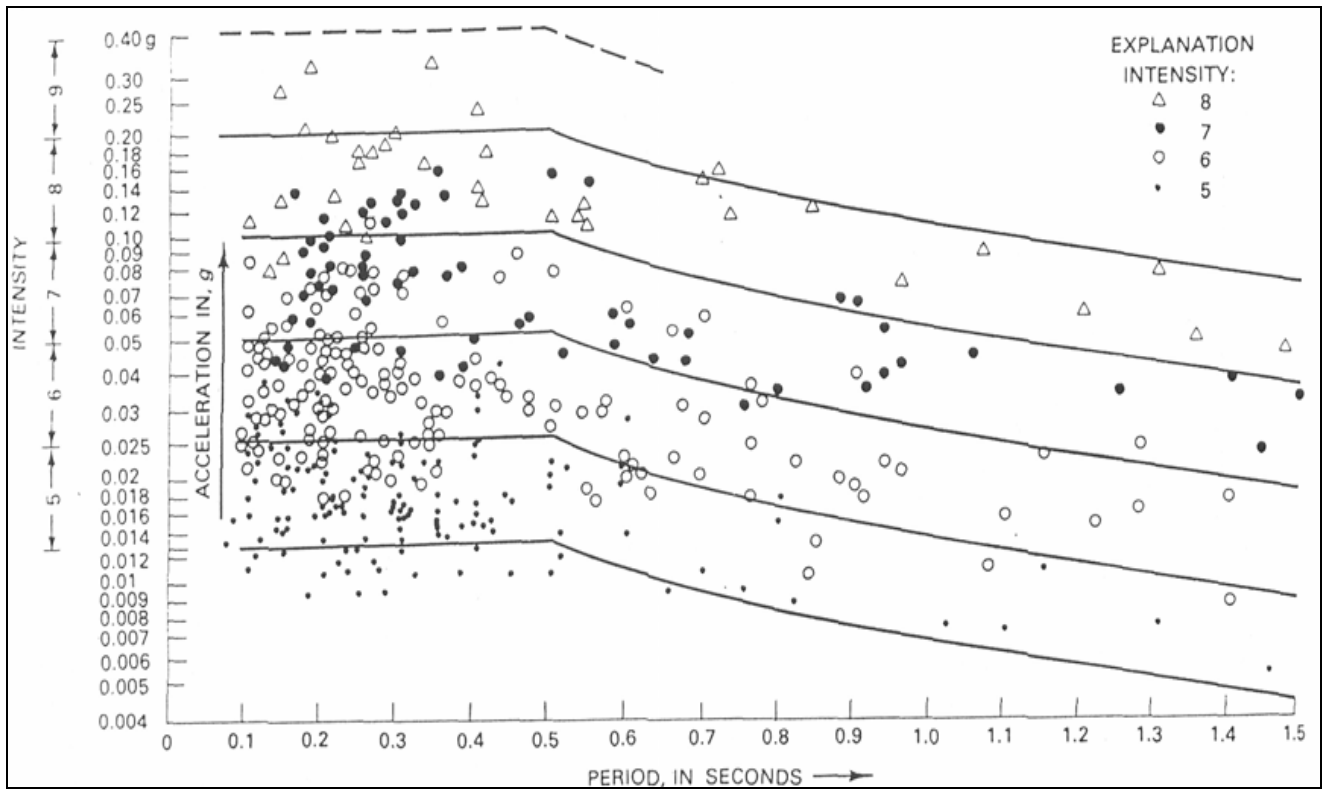


Fig.2. Correl betw intensity and acceleration corrected by the predominant period of the structures.

CONCLUSION—WHICH GROUND-MOTION PARAMETER? As will have been understood from the foregoing discussion, *PGA* is actually a very imperfect parameter to use in earthquake-resistant design. If it still continues to be in demand amongst the engineering community, the simple reason is that the static calculation of conventional structures requires it. For the more sophisticated treatment of engineered structures, a dynamic analysis is performed using response spec-tra or acceleration time histories, which do provide important information on signal duration. The suitability of velocity as a parameter was looked into above, and a tendency is currently emerging that resorts to displacement-based design.

AND WHICH INTENSITY? As stated above, the evaluation of whichever ground motion parameter is chosen, whether this is performed directly, from classical intensities, or by using a magnitude/intensity correlation, cannot avoid being biased notably by structural response (*cf.* Figure 2) and the influence of the magnitude/distance pair (*cf.* Figure 4). In contrast, the INQUA intensity scale, since it relies mainly on source effects in the near field, will in all probability prove to be a better “candidate” for establishing a correlation between intensity and either a ground motion parameter or magnitude.

RELATIONSHIP BETWEEN MM INTENSITY AND PEAK GROUND ACCELERATION IN MYANMAR

Santi Pailoplee

DISCUSSION AND CONCLUSION

A new relationship between macroseismic intensity and engineering ground-motion parameter is contributed for the Myanmar region by comparing the MMI gathered from 10 isoseismal maps with the inferred PGA..

From the result of this regression (**Figure 2**), it appears that there is a slight trend of MMI to be a linear function in relationship to the , which can be represented by Equation (2) with a standard deviation of 0.33.

$$\log_{10}(\text{PGA}) = 0.2526\text{MMI} - 3.1006 \quad (2)$$

where PGA is the peak ground acceleration (cm/s²) and MMI is the level of macroseismic intensity in terms of MMI scale.

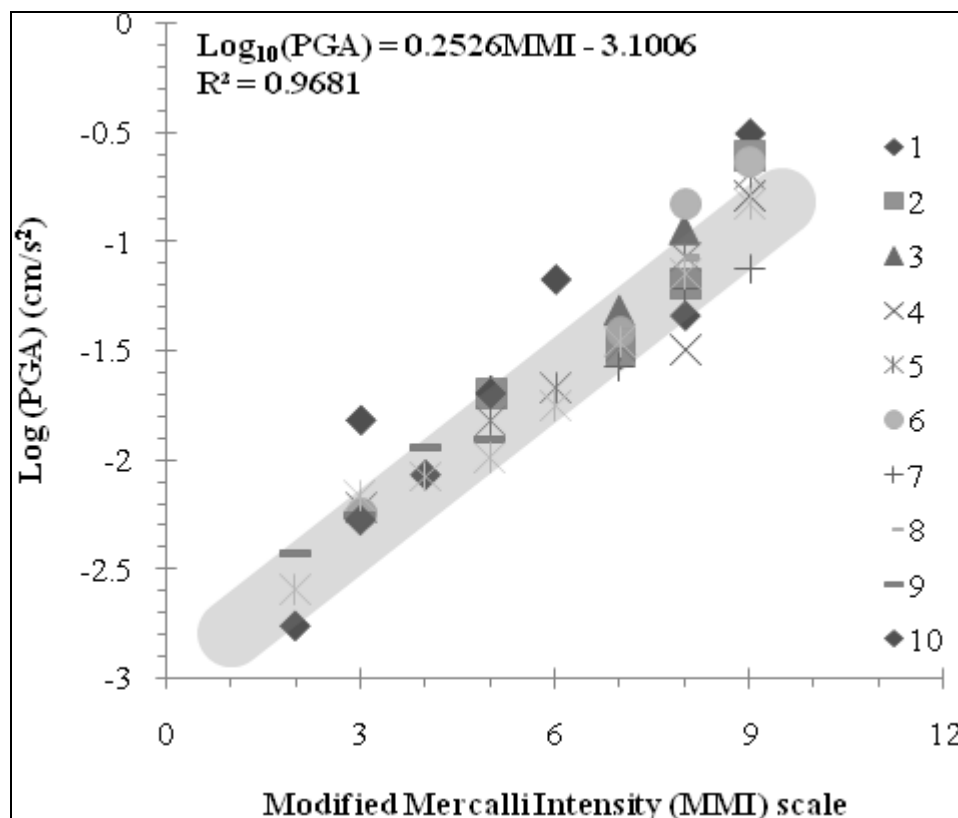
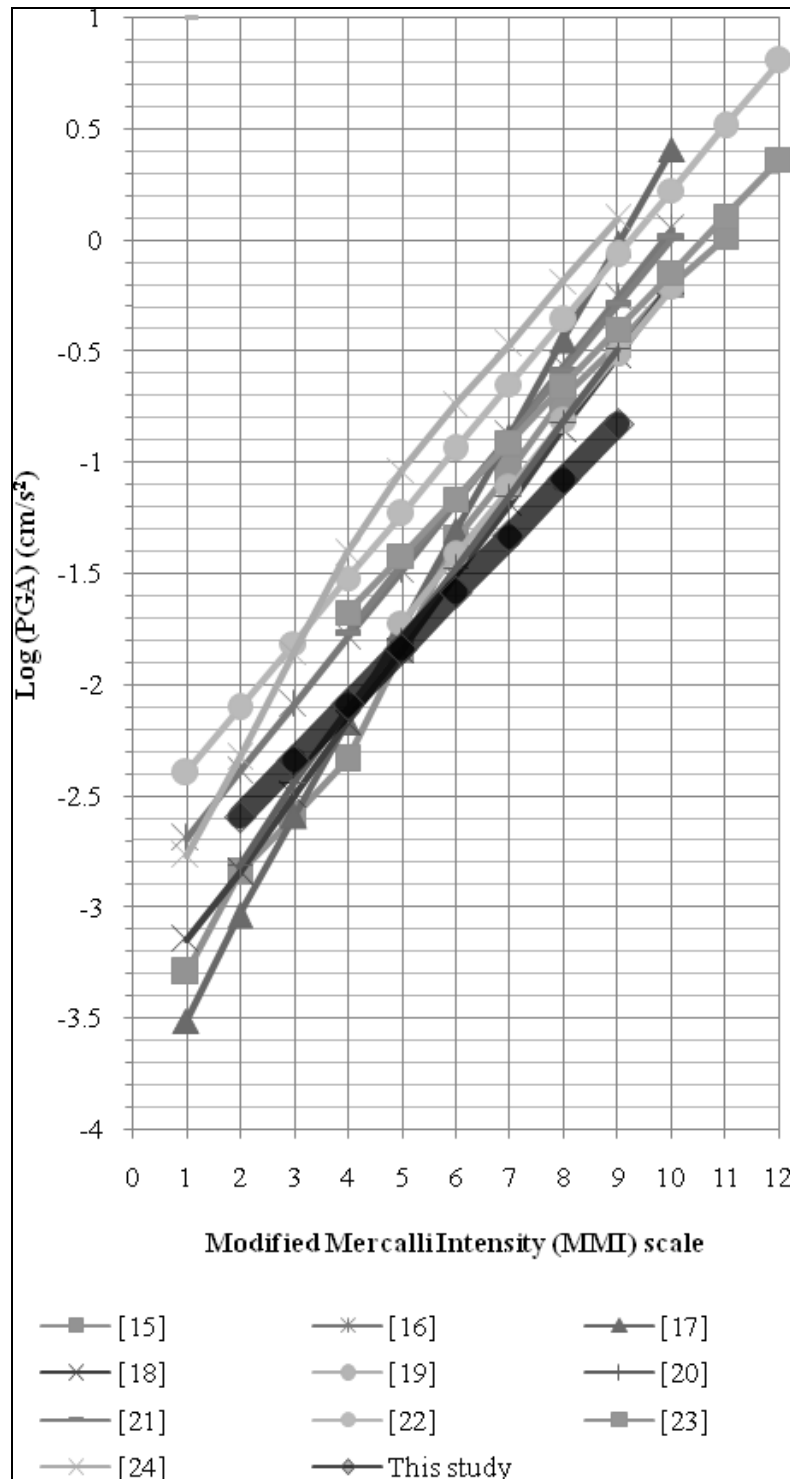


Figure 2. Relationship between the PGA (cm/s²) and the MMI scale. The series of MMI-PGA data are distinguished by different symbols and the numbers correspond to the isoseismal maps in **Figure 1**. The correlation coefficient (R²) for the shown linear regression is 0.9681.

This relationship, if substantiated, will be particularly useful in real-time applications for damage prediction or engineering parameter determination for earthquake ground shaking posed in or nearby to Myanmar.

Focusing to the other region, many empirical equations have been proposed to relate the MMI with PGA (**Figure 3**). In comparison with these, the MMI-PGA relationship for Myanmar reported here illustrates that in the same engineering ground-motion level, that is the same PGA level, the MMI of Myanmar is reported at a lower level than those for the other region until level V of the MMI scale (*i.e.*, felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop). However, for MMI values of equal to or larger than level VI, which mainly represent the destruction of infrastructures or buildings, the same PGA generates a higher MMI level than the other regions. This implies that the standard of building construction in Myanmar, in terms of withstanding earthquake hazards, is not high enough such that low ground motions contribute to a high degree of structure damage, particularly at higher levels of ground shaking. Thus, for the reduction of earthquake

hazards in Myanmar, earthquake hazard situations should be real-ized and the standard building code should be modified accordingly to withstand such ground movement.



[15] Kawasumi, H. (1951), [16] Neumann, F. (1954), [17], Hershberger, J. (1956), [18], Richter, C.F. (1958), [19] Medvedev, S.V. and Sponheuer, W. (1969), [20] Okamoto, S. (1973), [21] Trifunac, M.D. and Brady, A.G. (1975), [22] Theodulides, N.P. and Papazachos, B.C. (1992), [23] Shabestari, K.T. and Yamazaki, F. (2001), [24] Kaka, S. and Atkinson, G. (2004)

Figure 3. Comparison of MMI-PGA relationship determined from this study (thick black line) and the others proposed previously for different regions.

However, it is recognized that there is a significant level of uncertainty in estimating ground motions (*i.e.*, PGA) from the existing isoseismal maps by this process. Therefore, further work is required to check these PGA values carefully for consistency with those of the instrumentally recorded data. The uncertainties in the variables used in the damage estimation should also be discussed.

RELATIONSHIP BETWEEN PEAK GROUND ACCELERATION AND MODIFIED MERCALLI INTENSITY IN COSTA RICA

Limitations of the PGA vs. MMI correlation

The nature of the two ground shaking parameters that are correlated may explain the wide scatter. PGA only refers to a maximum value at single point and MMI refers to a maximum or average level of earthquakes effects throughout an area.

The PGA vs. MMI correlation calculated here is biased on the **observation period from 1983 to 2004**. At present there is little data to correlate intensity levels of VI and VII to PGA and there is no data available for $\text{MMI} \geq \text{VIII}$ to make correlations. Additional data may change the correlation as observed in California **by Wald et al. (1999a)** who, using earthquakes from 1971 to 1992, found a different correlation as the relationship presented by Trifunac & Bradly (1975), who used earthquakes prior to 1971. Also, the data set is biased to local earthquakes (depth < 40 km, hypocentral distance < 150 km) recorded at stations located at soft soil sites (Fig. 3). Currently, there is not sufficient data to determine if the PGA vs. MMI correlation is different for particular ranges of focal depth, hypocentral distance or soil type.

Recent analyses favor the correlation of MMI with Peak Ground Velocity (PGV) instead of PGA. Wald et al. (1999a) showed that for higher intensities ($\text{MMI} > \text{VII}$) PGV provides a more appropriate estimate of intensity. Boatwright et al. (2001) and Wu et al. (2003) **found that earthquake damage statistics give a closer correlation with PGV than with PGA**. The response spectra of 5%-damped pseudoacceleration is also proposed as an instrumental parameter to correlate with MMI (Atkinson & Boore, 1995; Atkinson 2001).

For $\text{MMI} < \text{VI}$ Wald et al. (1999a) support the use of PGA to estimate MMI, since lower intensities are mostly based on **human response to ground shaking and people are more sensitive to ground accelerations than velocity**. This supports the use of the correlations presented in this study that are valid in the MMI range II to VII.

CONCLUSIONS

The first relationship between MMI and the horizontal component of PGA was developed for Costa Rica using **regression analysis of 330 MMI - PGA observations from 108 earthquakes ($2.8 < \text{Mw} < 7.7$) that took place between 1983 and 2004**. The data set is mostly composed of local earthquakes (depth < 40 km, hypocentral distance < 150 km) recorded at stations located at soft soil sites.

There is a tendency of PGA to increas as MMI increases, however, there is a significant PGA scatter for a given intensity unit. Best-fit lines showing this tendency were calculated between MMI and both the largest of the two horizontal components (PGAm_{ax}) and the average of the two horizontal components (PGA_{ave}). **Predicted PGA intervals for each MMI value were proposed based on these equations (Table 3.**

The relationships obtained are:

$$\begin{aligned} & \text{MMI} = 2.30 \log(\text{PGAm}_{\text{ax}}) + 0.92 \\ \text{and} \quad & \text{MMI} = 2.33 \log(\text{PGA}_{\text{ave}}) + 0.76 \quad \text{for II} > \text{MMI} > \text{V} \end{aligned}$$

$$\begin{aligned} & \text{MMI} = 3.82 \log(\text{PGAm}_{\text{ax}}) - 1.78 \\ \text{and} \quad & \text{MMI} = 4.60 \log(\text{PGA}_{\text{ave}}) - 3.38 \quad \text{for V} > \text{MMI} > \text{VII}. \end{aligned}$$

Table 3 Proposed ranges of PGA for each MMI in Costa Rica

Intensity (MM)	PGAm _{ax} range (cm/s ²)	PGAm _{ax} range (% g)	PGAm _{ax} range (cm/s ²)	PGAm _{ax} range (% g)
II	< 4.9	< 0.5	< 5.6	< 0.6
III	4.9-13.3	0.5-1.4	5.6-15.0	0.6-1.5
IV	13.3-36.0	1.4-3.7	15.0-40.3	1.5-4.1
V	36.0-80.3	3.7-8.2	40.3-84.7	4.1-8.6
VI	80.3-146.7	8.2-15.0	84.7-139.6	8.6-14.2
VII	146.7-268.0	15.0-27.3	139.6-230.2	14.2-23.5

There is a remarkable agreement between the PGAm_{ax} vs. MMI correlation obtained in this study and the correlation calculated by Wald et al. (1999a) for California. The PGA_{ave} vs. MMI correlation indicates lower intensity levels associated with the same PGA with respect to previous correlations. Sufficient data are not yet available to explain these differences.

Relationships between Peak Ground Acceleration, Peak Ground Velocity, and Modified Mercalli Intensity in California

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We have developed regression relationships between Modified Mercalli Intensity (I_{mm}) and peak ground acceleration (PGA) and velocity (PGV) by comparing horizontal peak ground motions to observed intensities for eight significant California earthquakes. For the limited range of Modified Mercalli intensities (I_{mm}), we find that for peak acceleration with $V \leq I_{mm} \leq VIII$, $I_{mm} = 3.66 \log(PGA) - 1.66$, and for peak velocity with $V \leq I_{mm} \leq IX$, $I_{mm} = 3.47 \log(PGV) + 2.35$. From comparison with observed intensity maps, we find that a combined regression based on peak velocity for intensity $> VII$ and on peak acceleration for intensity $< VII$ is most suitable for reproducing observed I_{mm} patterns, consistent with high intensities being related to damage (proportional to ground velocity) and with lower intensities determined by felt accounts (most sensitive to higher-frequency ground acceleration). These new I_{mm} relationships are significantly different from the Trifunac and Brady (1975) correlations, which have been used extensively in loss estimation.

Table 1 gives the peak ground motion ranges that correspond to each unit Modified Mercalli intensity value according to our regression of the observed peak ground motions and intensities for California earthquakes.

Table 1. Ranges of ground motions for Modified Mercalli Intensities

Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Peak Accel. (% g)	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Peak Velocity (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116

DISCUSSION

For a given ground motion level, our intensities are lower than the commonly used relationships of Trifunac and Brady (1975), which are also displayed on Figures 3 and 4. Only data from the 1971 San Fernando earthquake are common; our data are from 1971 forward, while that of Trifunac and Brady (1975) contains data from the San Fernando and prior earthquakes. In general, the main differences are due to the addition of new data since the Trifunac and Brady (1975) study. However, for acceleration, part of the difference is that we do not include the intensity IX (or larger) values in the regression, due to the evidence of amplitude saturation, whereas Trifunac and Brady (1975) used an intensity X value. Likewise, for velocity, we did not use lower intensity values ($I_{mm} \leq IV$) for the regression whereas Trifunac and Brady (1975) did so.

It is notable that the relationship of Trifunac and Brady (1975) indicated lower intensities for a given ground motion level than most earlier estimates (see Trifunac and Brady, 1975, Figure 3), and now our relationship indicates yet lower intensity levels associated with the same peak ground motion. There are a number of factors that may influence this trend, and certainly more densely spaced recordings in the near-fault region of the recent events, particularly for the Northridge earthquake, do presumably favor a more accurate portrayal of the relationship. However, building practices have certainly improved since the earlier events, altering the association of shaking and damage, and there are fewer brittle structures that are easily damaged at moderate levels of ground acceleration. Hence, it may be natural that such empirical relationships change with time, though further examination of this trend is in order.

The relationships we have developed are now used to generate maps of estimated shaking intensities within a few minutes of the event based on the recorded peak motions (see Wald et al., 1999a). In practice, we compute the I_{mm} from the I_{mm} versus PGA relationship; if the intensity value determined from peak acceleration is $\geq$ VII, we then use the value of I_{mm} derived from the I_{mm} versus PGV relationship. These maps provide a rapid portrayal of the extent of potentially damaging shaking following an earthquake and can be used for emergency response, loss estimation, and for public information through the media.

RELATIONSHIPS BETWEEN FELT INTENSITY AND RECORDED GROUND MOTION PARAMETERS FOR TURKEY

3.6 Comparison of the Proposed Equations with Previous Studies

The results of this study are compared with the results of previous studies worldwide. The MMI-PGA equation obtained in this study is compared with the following studies: Arıoğlu et al. (2001), Tselentis and Danciu (2008), Faenza and Michelini (2010), Murphy and O'Brien (1977), Trifunac and Brady (1975) and Wald et al. (1999).

The proposed equation corresponding to each of these past studies is given in Table 3.5. Figure 3.16 to Figure 3.21 present the comparison of each study with the equation proposed in this thesis. Dataset used in this thesis is as well shown in these figures.

Table 3.5: Equations proposed for MMI-PGA relationships

No.	Name	Equation
1	This Study	$MMI=0.287+3.625*\log(PGA)$
2	Arıoğlu et al. (2001)	$MMI=1.748*\ln(PGA)-1.078$
3	Tselentis and Danciu (2008)	$MMI=-0.946+3.563*\log(PGA)$
4	Faenza and Michelini (2010)	$MMI=1.68+2.58*\log(PGA)$
5	Murphy and O'Brien (1977)	$MMI=(\log(PGA)-0.25)/0.25$
6	Trifunac and Brady (1975)	$MMI=(\log(PGA)-0.14)/0.30$
7	Wald et al. (1999)	$MMI=3.66*\log(PGA)-1.66$

Table 3.6: Equations proposed for MMI-PGV relationships

No.	Name	Equation
1	This Study	$MMI=0.319+5.021*\log(PGV)$
2	Atkinson and Kaka (2004)	$MMI=3.96+1.79*\log(PGV)$
3	Atkinson and Kaka (2007)	$MMI=4.37+1.32*\log(PGV)$ if $\log(PGV) \geq 0.48$ cm/sec $MMI=3.54+3.03*\log(PGV)$ if $\log(PGV) \leq 0.48$ cm/sec
4	Tselentis and Danciu (2008)	$MMI=3.30+3.358*\log(PGV)$
5	Atkinson and Kaka (2006)	$MMI=4.40+1.92*\log(PGV)+0.28*(\log(PGV))^2$
6	Faenza and Michelini (2010)	$MMI=5.11+2.35*\log(PGV)$
7	Wald et al. (1999)	$MMI=3.66*\log(PGA)-1.66$

RELATIONSHIPS BETWEEN INSTRUMENTAL GROUND MOTION PARAMETERS, AND MODIFIED MERCALLI INTENSITY IN GUERRERO, MEXICO

Gama-García² and A. Gómez-Bernal¹

2. RELATIONS BETWEEN SEISMIC INTENSITY AND STRONG GROUND MOTIONS PARAMETERS

In Table 2.1 is presented a summary of several relations of the Intensities with PGA, with PGV, or with PGD. These relations were developed for different seismic regions of the world (see Trifunac and Brady (1975). Thus, in the decade of the 40s and 50s, Gutenberg and Richter in 1942, Kawasumi in 1951 (see Trifunac and Brady, 1975), Neumann in 1954 (see Trifunac and Brady, 1975), and Hershberger in 1956, they were first in developing functional of the form: $\log a = A + B \cdot I$, where a is the PGA, A and B are adjustment coefficients, and I is the seismic intensity. Each one of those expressions is applicable only to the region from which the data belong. Trifunac and Brady (1975), considered horizontal and vertical components separately, as can be observed in the functional of Table 2.1. Also, they grouped the records in such way that the effect of geology in each level of intensity could be identified. When their results are compared, they find that the values for acceleration, velocity and displacement are greater than those obtained in previous works.

More recently, Wald et al. (1999) obtained relations, that define the intensity from the acceleration or from the velocity, as $I_{mm} = A \log (PGA) + B$, and $I_{mm} = C \log (PGV) + D$, respectively. These relations are applicable for a range of MMI between V-VIII and V-IX, respectively. Their results determine values considerably greater than those obtained by Trifunac and Brady (1975). On the other hand, Boatwright et al. (2006), developed expressions for California, as much for the acceleration as for the velocity. They extended their study when considered relations between MMI and pseudo-acceleration spectra, with the purpose of considering maps based on spectral ordinates for the San Francisco earthquake of 1906. Atkinson and Kaka (2007) propose an equation that relates MMI with instrumental parameters. This relation is based on data of moderate earthquakes of the central region of the United States. These data correspond to acceleration records and seismograms. The data were calibrated and extrapolated from observations of California earthquakes in order to determine maps of strong movement.

Table 2.1 Data for relations from several studies.

Author	Relation	Interval	Region
Gutenberg-Richter (1942)	$\log a = -0.5 + 0.33I$	MM	
Kawasumi, (1951)*	$\log \bar{a} = -0.35 + 0.5I$	JMA	Japan
Neumann, (1954) *	$\log a = -0.041 + 0.308I$	Between 15 and 25 millas	
Hershberger, (1956)	$\log a = -0.9 + 0.43I$		
*Trifunac-Brady, (1975)	$\log a_v = -0.18 + 0.30I_{MM}$, $\log a_H = -0.014 + 0.30I_{MM}$ $\log v_v = -1.10 + 0.28I_{MM}$, $\log v_H = -0.63 + 0.25I_{MM}$ $\log d_v = -1.13 + 0.24I_{MM}$, $\log d_H = -0.53 + 0.19I_{MM}$	$IV < I_{MM} < X$ $IV \leq I_{MM} \leq X$ $V \leq I_{MM} \leq X$	West USA
Barrientos, (1980)	$I = 1.3844M - 3.7355 \log_{10}(r) - 0.0006r + 3.8461$ I-Intensity, r: Hip. Dist. (km), M: Magnitude Ms		Chile
Wald, et al., (1999)	$I_{mm} = 3.66 \log(PGA) - 1.66$; ($\sigma = 1.08$) $I_{mm} = 3.47 \log(PGV) + 2.35$; ($\sigma = 0.98$)	$V \leq IMM \leq VIII$ $V \leq IMM \leq IX$	California
Boatwright, et al., (2006)	$I_{intr} = 3.66 \log PGA + 1.99 \log PGA (\%g)$ $I_{intr} = 3.47 \log PGV + 2.35 \log PGV (cm/seg)$	$I_{intr} \leq 5$ $I_{intr} \geq 6$ MM	San Fco California
D. Benouar, (2007)	$Msc = A_1 + A_2(I_i) + A_3(R_i) + A_4 \log R_i + \sigma P$ $I = B_1 + B_2(M_s) + B_3(R) + B_4 \log R + \sigma P$		Algeria
Atkinson and Kaka (2007)	$MMI = 4.37 + 1.32(\log PGV) \log PGV \leq 0.483$ $MMI = 3.54 + 0.3(\log PGV) \log PGV \geq 0.48$	$MMI < 0.48$ $MMI \geq 0.48$	California