RELATIONSHIPS BETWEEN FELT INTENSITY AND INSTRUMENTAL GROUND MOTION

FOR NEW MADRID SHAKEMAPS

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Abstract

ShakeMaps are computer-generated maps that indicate an earthquake occurrence, identify the area affected and estimate the severity of ground shaking, providing a tool to rapidly assess and mitigate damage. A reliable relationship between ground motion and felt intensity is required in generating ShakeMaps that are applicable to earthquakes in the Central United States (CUS). In this study, we develop empirical relationships between peak ground velocity (PGV) and observed MMI by using data from felt moderate earthquakes in the CUS that were also recorded on broadband seismographic networks and strong-motion recorders in the New Madrid region. The data are calibrated and supplemented at higher intensities based on observations in California. Similar predictive relationships for MMI are also developed for other instrumental parameters (acceleration and response spectra). MMI for ShakeMap applications in the New Madrid region (and in California) can be predicted from recorded PGV (in cm/s), with a standard deviation of 0.78 MMI units, using the following equation:

$$MMI = 4.40 + 1.92 (\log PGV) + 0.280 (\log PGV)^2$$

Introduction

ShakeMaps are computer-generated maps that indicate an earthquake occurrence, identify the area affected and estimate the severity of ground shaking, providing a tool to rapidly assess and mitigate damage. The ShakeMap concept originated in California as part of the research and development efforts of the “TriNet” (California Institute of Technology, the California Division of Mines and Geology, and the U.S Geological Survey). In the California ShakeMaps, the intensity of ground shaking is inferred through an empirical relation between recorded peak ground acceleration (PGA), peak ground velocity (PGV) and Modified Mercalli Intensity (MMI) that was developed from observations in California (Wald et al., 1999). Recent studies have shown that these relationships do not apply to the northeastern U.S. and southeastern Canada (Kaka and Atkinson, 2004). Specifically, the California relations underpredict MMI for earthquakes in these regions, often by several MMI units. Therefore, separate relationships have been developed for the northeastern U.S. and southeastern Canada (Kaka and Atkinson, 2004). In the CUS, the environment is quite different from either California or the northeastern states. The CUS is characterized by efficient propagation of high-frequency radiation, like the northeastern U.S., but is also strongly affected by the thick basin of unconsolidated sediments that overlies the New Madrid region. These sediments have a profound effect on recorded ground motions (Langston, 2003). The relationship between felt effects and instrumental ground motion in the CUS could be similar to California, similar to the northeastern U.S., or it may be unique.

A reliable relationship between ground motion and felt intensity is required in generating ShakeMaps that are applicable to earthquakes in the Central United States (CUS). In contrast to California, events that generate strong shaking are rare in the CUS. For CUS applications, it is important to create reliable intensity ShakeMaps for the more frequent small-to-moderate events that may be widely felt, but cause little to no damage (in addition to our interest in the larger events). Such maps are useful to operators of critical facilities that must provide timely information on all felt events. ShakeMaps are also accessed by thousands of members of the public and by the media following an earthquake. Having reliable maps for the frequent small events is critical to building credibility, so that ShakeMaps for larger events, when they occur, will be effectively utilized. If reliable maps cannot be generated for small events, there will be no confidence or 'buy-in' to the ShakeMap concept from the user community. The relations that are used in current ShakeMap applications throughout the United States were developed by Wald et al. (1999) from California data. Earthquakes recorded in California have a lower frequency content than those recorded in the CUS, and thus PGV and PGA have a different meaning in the two regions. Moreover, the Wald et al. (1999) relationship is not suitable to estimate intensity based on PGV at low-to-moderate intensity level (see Wald et al., 1999), which is of interest in CUS applications.

Peak ground velocity (PGV) is the ideal choice among the ground motion parameters for ShakeMap applications, as it is the simplest and most rapidly available parameter from seismographic monitoring networks in the CUS. It is also a parameter most directly related to kinetic energy, which in turns relates to damage. Wald et al. (1999) showed that low levels of shaking intensity correlate fairly well with both peak ground acceleration (PGA) and PGV, while high intensities correlate best with PGV. Boatwright et al. (2001) demonstrated that PGV is significantly better correlated with intensity than PGA based on the correlation of the tagging intensity with observations of PGA and PGV in the 1994 Northridge earthquake.

In this study, we develop empirical relationships between PGV (also PGA) and observed MMI by using data from felt moderate earthquakes in the CUS that were also recorded on broadband seismographic networks and strong-motion recorders in the New Madrid region. There are data for dozens of such events within the last few years. These recent data address the low-intensity end of the MMI-ground motion relationship, and also provide calibration/validation for approaches that can be used to predict ground motions from larger earthquakes. We supplement these data with inferred PGA/PGV values from larger events, using a calibration approach based on the small-magnitude data. The same data are also be used to derive relationships between 5% damped pseudo-acceleration (PSA) and MMI. These relationships are useful for engineering analyses keyed to a specific frequency.

Database and Data Processing

The instrumental database for the study is derived primarily from readily-available broadband seismographic data that have been recorded for felt earthquakes in the New Madrid region. Figure 1 shows the locations of broadband stations along with felt events for which internet intensity surveys have been compiled and posted by the U.S. Geological Survey (USGS, "Did You Feel It" program). Table 1 lists these study earthquakes, for which both instrumental ground-motion and DYFI data are available.

Table 2 lists locations of ground-motion recorders used in the study; in addition to traditional instruments, the information from velocity sensors, provided by Street et al. (2005), is also used. For each earthquake with reported felt effects (on DYFI), we obtain all available instrumental ground-motion data in the region. The seismographic data are processed to remove instrument effects; the instrument-corrected records are then used to calculate the peak ground acceleration, velocity and response spectra, using standard data processing procedures as described in Atkinson (2004).

The community intensity maps on the DYFI website (http://pasadena.wr.usgs.gov/shake/cus/archives.html) allow us to download data showing the average felt intensity reported by locality; localities are characterized by zip code, with a single latitude-longitude pair representing each zip code. We emphasize that these are observations from small to moderate events, and thus the felt effects in these data cover only the low-intensity end of the scale.

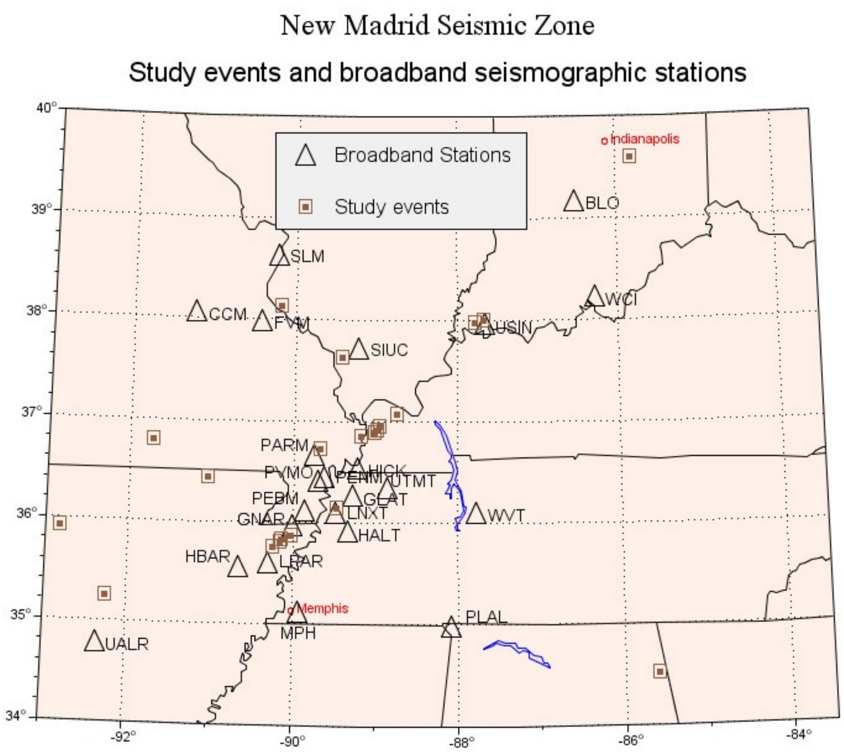


Figure 1 – Locations of recent felt earthquakes with on-line MMI reports, along with broadband seismograph stations.

Table 1. Study Earthquakes in New Madrid Region

Date (yy/mm/dd)	Magnitude	Event lat./lon.	Number of instrumental recording stations	Number of stations (MMI assigned)	Distance range (km)	Seismic zone
20000627	3.9	35.92/-92.82	5	1	134-441	NM
20000822	3.9	36.43/-91.05	4	1	106-500	NM
20001207	3.9	38.00/-87.68	2	4	139-307	NM
20010504	4.4	35.24/-92.25	5	3	50-386	NM
20020618	4.6	37.98/-87.78	5	2	228-372	NM
20020618∗	4.5	37.97/-87.78	46	30	40-184	NM
20030306	4.0	36.89/-89.01	11	10	64-382	NM
20030429	4.6	34.51/-85.6	11	5	359-640	NM
20030816	4.0	36.8/-91.72	15	4	146-526	NM
20030826	3.1	37.08/-88.74	12	9	83-413	NM
20030916	2.7	36.10/-89.76	5	4	32-255	NM
20031229	3.0	38.13/-90.19	11	9	59-420	NM
20040416	2.9	36.73/-89.69	11	7	65-389	NM
20040628	4.2	41.44/-88.93	12	4	325-799	NM
20040716	3.5	36.86/-89.18	9	3	68-367	NM
20040820	3.5	33.18/-86.95	6	4	418-666	NM
20040912	3.6	39.59/-85.80	5	2	77-788	NM
20041107	4.0	32.97 /-87.9	10	0	520-597	NM
20050210	4.1	35.76/-90.25	17	17	18-446	NM
20050430	1.8	36.25/-89.49	2	1	24-190	NM
20050501	4.1	35.83/-90.15	11	9	25-490	NM
20050502	2.5	35.83/-90.15	5	5	25-266	NM
20050518	3.3	38.41/-93.99	8	3	241-673	NM
20050602	4.0	36.15/-89.47	10	2	33-425	NM
20050615	3.7	36.73/-89.68	9	8	64-388	NM
20050620	2.7	36.92/-88.96	12	6	70-385	NM
20050627	3.0	37.63/-89.42	5	5	98-318	NM
20050713	2.7	35.81/-90.15	6	3	26-268	NM
20050815	3.0	35.87/-90.02	6	4	80-267	NM

∗ from Street et al, 2005

Table 2. Locations of ground-motion recorders in New Madrid Region

Station	latitude	longitude	comment
GLAT	36.269	-89.288	
BLO	39.172	-86.522	
CCM	38.056	-91.245	
FVM	37.98	-90.43	
GNAR	35.965	-90.018	

HALT	35.911	-89.34	
HBAR	35.555	-90.657	
HENM	36.716	89.472	
HICK	36.541	-89.229	
LNXT	36.101	-89.491	
LPAR	35.602	-90.3	
MPH	35.123	-89.932	
PARM	36.664	-89.752	
PEBM	36.113	-89.862	
PENM	36.45	-89.628	
PLAL	34.982	-88.076	
PVMO	36.413	-89.7	
SIUC	37.715	-89.217	
SLM	38.636	-90.236	
ULAR	34.775	-92.344	
USIN	37.965	-87.666	
UTMT	36.342	-88.864	
WCI	38.224	-86.29	
WVT	36.106	-87.775	
1	37.746	-88.337	Street05
2	37.75	-88.36	Street06
3	37.76	-88.368	Street07
4	37.756	-88.369	Street08
5	37.757	-88.374	Street09
6	37.758	-88.375	Street10
7	37.759	-88.377	Street11
8	37.639	-88.373	Street12
9	37.636	-88.374	Street13
10	37.789	-89.124	Street14
11	37.792	-89.129	Street15
12	38.128	-87.359	Street16
13	38.121	-87.358	Street17
14	38.227	-87.391	Street18
15	38.225	-87.393	Street19
16	38.089	-87.285	Street20
17	38.104	-87.274	Street21
18	38.101	-87.274	Street22
19	38.092	-87.275	Street23
20	38.101	-87.274	Street24
21	38.365	-87.365	Street25
22	38.337	-87.454	Street26
23	38.295	-87.377	Street27
24	38.296	87.377	Street28
25	38.285	-87.364	Street29
26	38.337	-87.446	Street30
27	38.353	-87.465	Street31
28	38.303	-87.376	Street32
29	38.363	-87.449	Street33
30	38.306	-87.349	Street34
31	38.339	87.341	Street35

32	38.354	-87.293	Street36
33	38.352	-87.283	Street37
34	38.352	-87.278	Street38
35	38.354	-87.279	Street39
36	38.354	-87.276	Street40
37	38.168	-86.946	Street41
38	37.925	-86.724	Street42
39	38.756	-87.434	Street43
40	38.804	-87.491	Street44
41	38.805	-87.474	Street45
42	38.605	-87.009	Street46
43	37.339	-87.086	Street47
44	37.335	-87.075	Street48
45	37.335	-87.073	Street49
46	38.032	-85.664	Street50

In general, MMI values are assigned based on a felt report from the Community Internet Intensity (CIMM), which is a description of the ground shaking experienced by the general public, or an assessment of damage level, as reported by the public on the DYFI site (http://pasadena.wr.usgs.gov/shake/cus/archives.html). The assigned CIMM is compiled from a number of online felt-report questionnaires submitted by the general public. All the submitted questionnaires within a zip code are averaged to obtain a single CIIM value for the latitude/longitude at the center of the zip code. Each CIMM value reflects the average description of the ground shaking experienced by the general public, or an assessment of damage level within the community. The online form of the questionnaire and methodology of felt-intensity assignments are developed and described by Dengler and Dewey (1998). Based on past calibration studies, such as those by Dewey et al. (2000), the CIIM value is equal to traditional Modified Mercalli Intensity (MMI).

For each instrumentally-recorded earthquake we assigned a CIMM value to every seismographic monitoring station. Since CIMM observations do not actually correspond to a single well defined location (i.e. they represent an average over a zip code area), our assignment is based on general proximity to one or more CIMM observations. We required reasonable confidence that the actual CIMM value at each station would be within one unit of the assigned value. Hence we assigned a CIMM value to the station only in cases for which we had reasonable confidence that actual CIMM value at the site would be within one unit of the assigned value (see Kaka and Atkinson, 2004 and Atkinson and Sonley, 2000). Visual inspection of maps showing station locations and MMI assignments in the surrounding area is the preferred method of assigning MMI values, in order to minimize errors.

Figure 2 shows a typical example (in which the decimal intensities reported on the CIMM scale have been rounded to the nearest integer for display purposes). For this event (M4.1 event of 050210), for example, the assigned intensity at ULAR, CCM and FVM is about 2. The compiled database of average intensity for each instrumental

ground-motion observation in the New Madrid region is available in an electronic appendix.

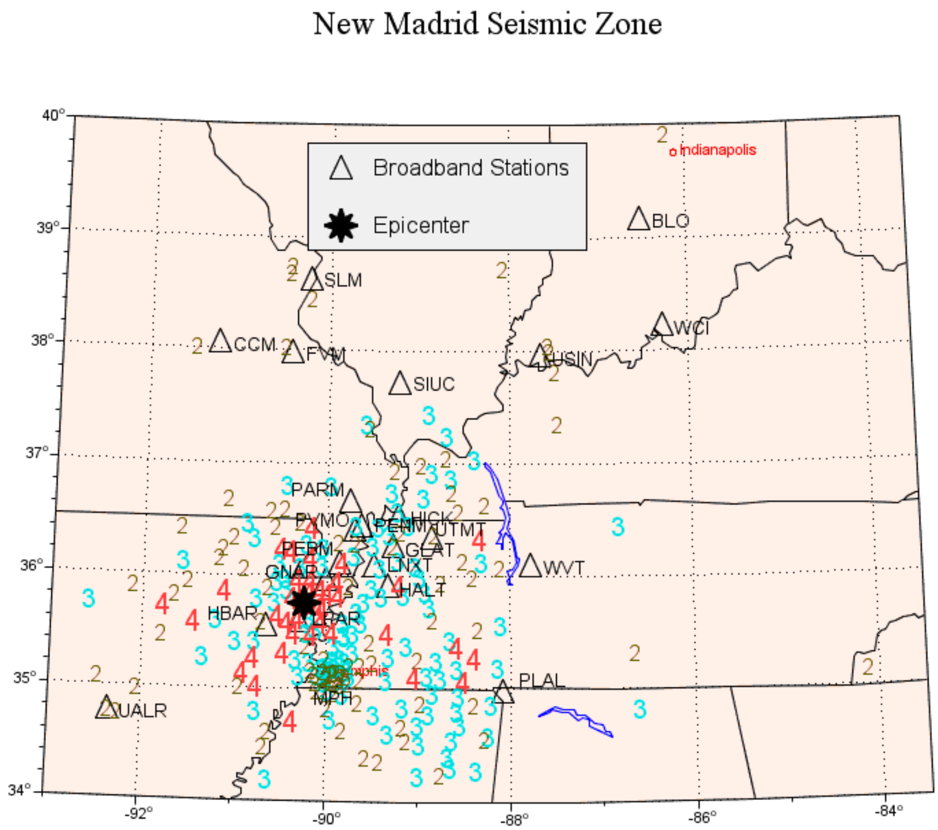


Figure 2 – Assignment of intensity to seismographic stations. MMI at UALR =2, for example.

Because the New Madrid data cover only the low-intensity end of the ground-motion scale, it is useful to compare the New Madrid observations with those in California, for which more plentiful data are available. This allows the calibration and extension of our approach to higher intensities, as described in the next section. A database of California strong-motions versus MMI observations has been collated by Atkinson and Sonley (2000). We supplement these data for California at the low intensity end of the scale using California ShakeMap and DYFI observations (correlating instrumental data from California ShakeMaps with MMI data from DYFI, using the same approach as described above for New Madrid). Table 3 lists the California events for which ShakeMap and DYFI data are compiled; these data supplement the high-intensity California data of Atkinson and Sonley (2000).

Table 3. Calibration earthquakes from California ShakeMap/DYFI Data

Date (yy/mm/dd)	Magnitude	Event lat./lon.	Number of instrumental recording stations	Number of stations (MMI assigned)	Distance range (km)	Seismic zone
20000221	4.5	34.05/-117.26	68	68	4-187	CA
20000307	4.0	33.81/-117.72	66	66	7-114	CA
20000409	3.6	34.13/-117.47	44	44	5-100	CA
20000409	4.3	32.69/-115.39	41	41	13-158	CA
20000614	4.2	32.89/-115.50	54	8	6-160	CA
20000614	4.5	32.88/-115.51	60	60	7-150	CA
20010114	4.0	34.29/-118.40	17	17	15-40	CA
20010210	5.1	34.29/-116.95	7	7	26-56	CA
20010413	3.5	33.87/-117.71	1	1	8.5	CA
20010514	3.8	34.23/-117.44	1	1	19.6	CA
20010517	4.0	35.80/-118.04	4	4	16-30	CA
20010517	4.1	35.80/-118.05	4	4	16-30	CA
20010523	3.8	34.02/-116.76	7	7	19-35	CA
20010717	4.9	36.01/-117.89	14	14	7-48	CA
20011031	5.1	33.51/-116.51	130	130	5-183	CA
20010719	3.8	34.27/-117.46	14	14	15-44	CA
20020222	5.7	32.32/-115.32	102	102	55-307	CA
20020316	4.6	33.67/-119.33	43	43	65-113	CA
19991016	7.1	34.63/-116.30	7	7	22-321	CA
20031222	6.5	35.71/-121.1	18	17	44-445	CA
20040928	6.0	35.81/-120.37	8	8	5-268	CA

Analysis

Observed Relationship between MMI and instrumental ground motions

Figure 3 plots and compares the correlation between MMI (=CIMM) and PGV obtained in this study for New Madrid events (Table 1), with that for California events as determined in this study (Table 3), and by Atkinson and Sonley (2000). Horizontal-

component ground motions are used in all cases. Predictive relationships according to Atkinson and Sonley (2000), Wald et al. (1999) and Kaka and Atkinson (2004) are also shown. The Atkinson and Sonley (2000) and Wald et al. (1999) relations are for California, whereas the Kaka and Atkinson (2004) relation is for southeastern Canada and the northeastern U.S. (ENA). Several important observations can be made from this figure. First, note that the California relations of Atkinson and Sonley and Wald et al. are highly biased to large PGV at low intensity levels; they do not adequately describe observed MMI according to ShakeMap observations from small-to-moderate earthquakes in either California or New Madrid. This is probably because they were based on strong-motion datasets, which contain an inherent bias to stronger ground motions (due to triggering issues and the tendency to compile only "significant" observations). The ShakeMap data on the MMI-PGV correlation are believed to be a more reliable indication of the actual relationship between PGV and MMI for low shaking levels. Thus an unexpected finding of this study is that the relationship between MMI and PGV for California events should be revised at low shaking levels, in accordance with the wealth of ShakeMap-MMI data.

A second important observation on Figure 3 is that the New Madrid and California relationship between MMI and PGV appears to be mutually consistent, in the region of overlap between datasets. This implies that California relationships, once corrected for the bias problem noted above, should be applicable to predict MMI from PGV in the New Madrid seismic zone.

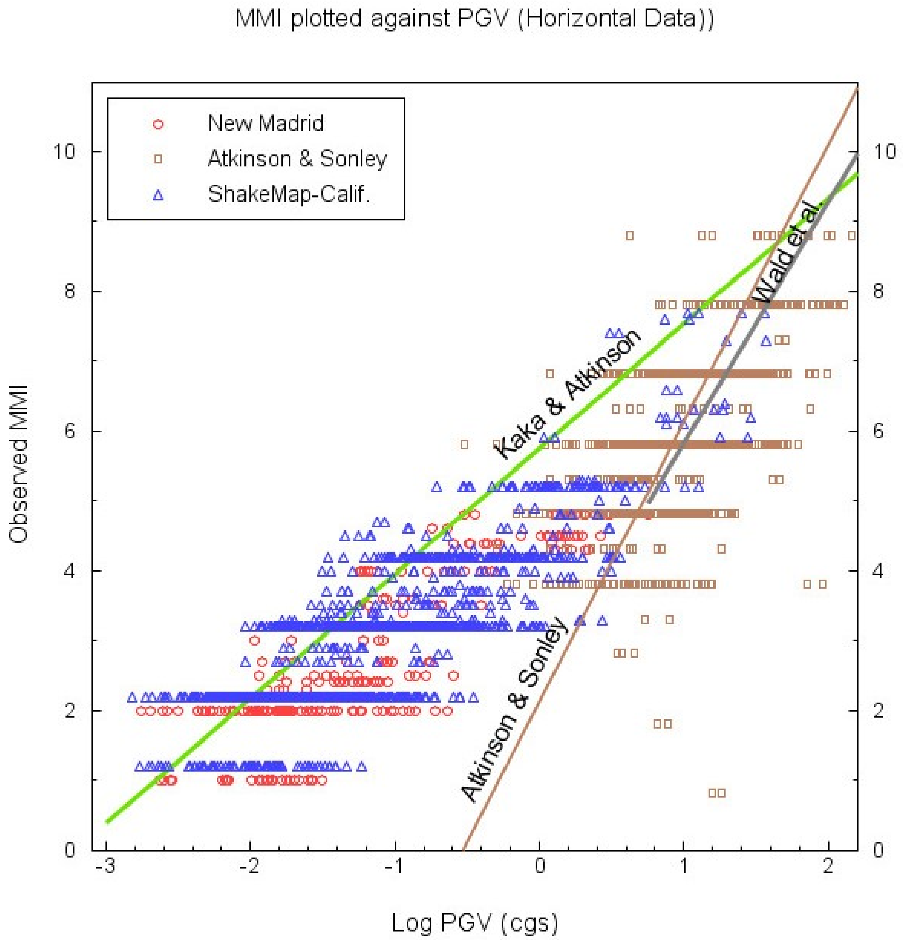


Figure 3 – Observed relationship between MMI and PGV in New Madrid (red) and California (blue for low-magnitude data, brown for strong-motion data)

Similar figures are presented in Figures 4 through 6 to show the relationship between MMI and PGA, and PSA (5% damped pseudo-acceleration) at frequencies of 1 and 3.3 sec, for both New Madrid and California. The observations from these figures parallel those made in Figure 3 for PGV. In essence, data on the relationship between MMI and instrumental ground motions are mutually consistent between the two regions, but the California relations require correction for biases at low shaking levels.

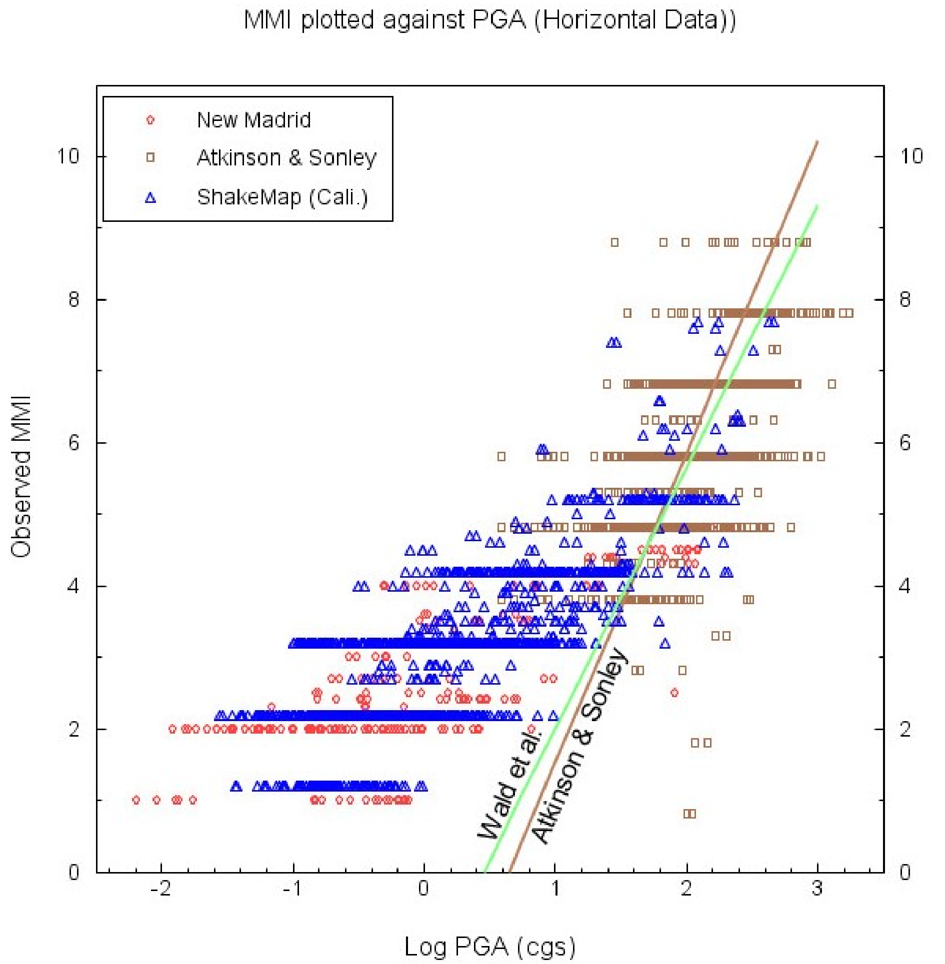


Figure 4 – Observed relationship between MMI and PGA in New Madrid (red) and California (blue for low-magnitude data, brown for strong-motion data)

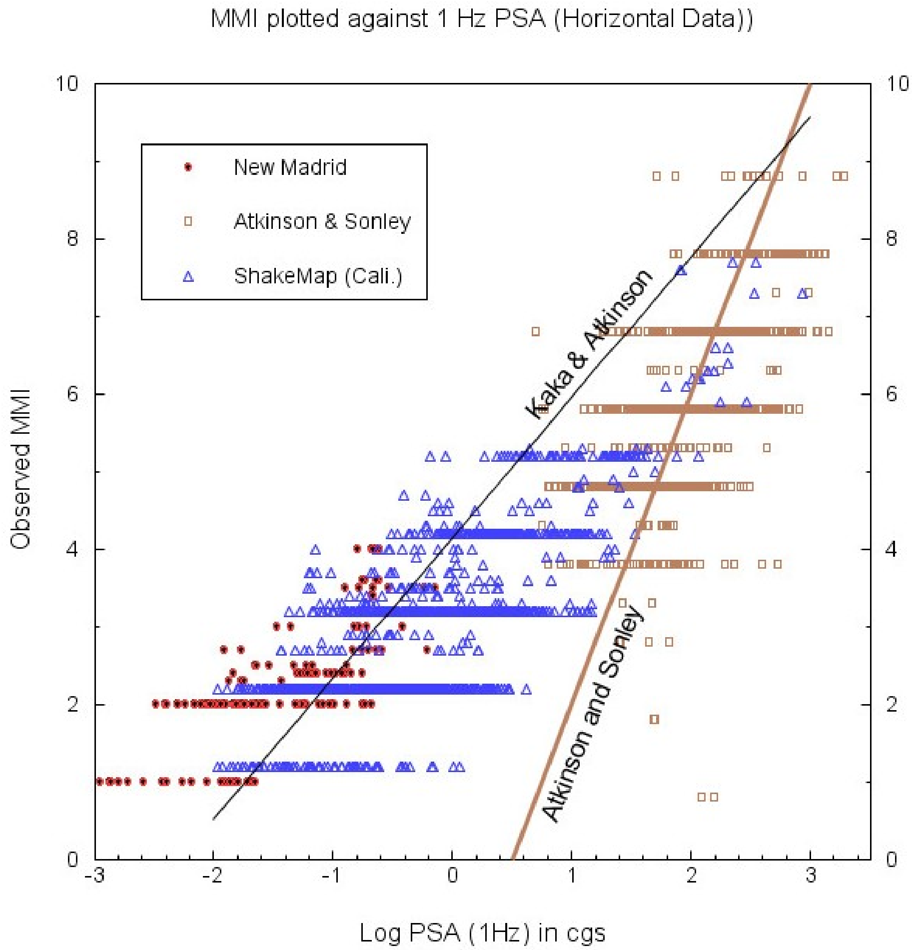


Figure 5 – Observed relationship between MMI and PSA at 1 Hz in New Madrid (red) and California (blue for low-magnitude data, brown for strong-motion data)

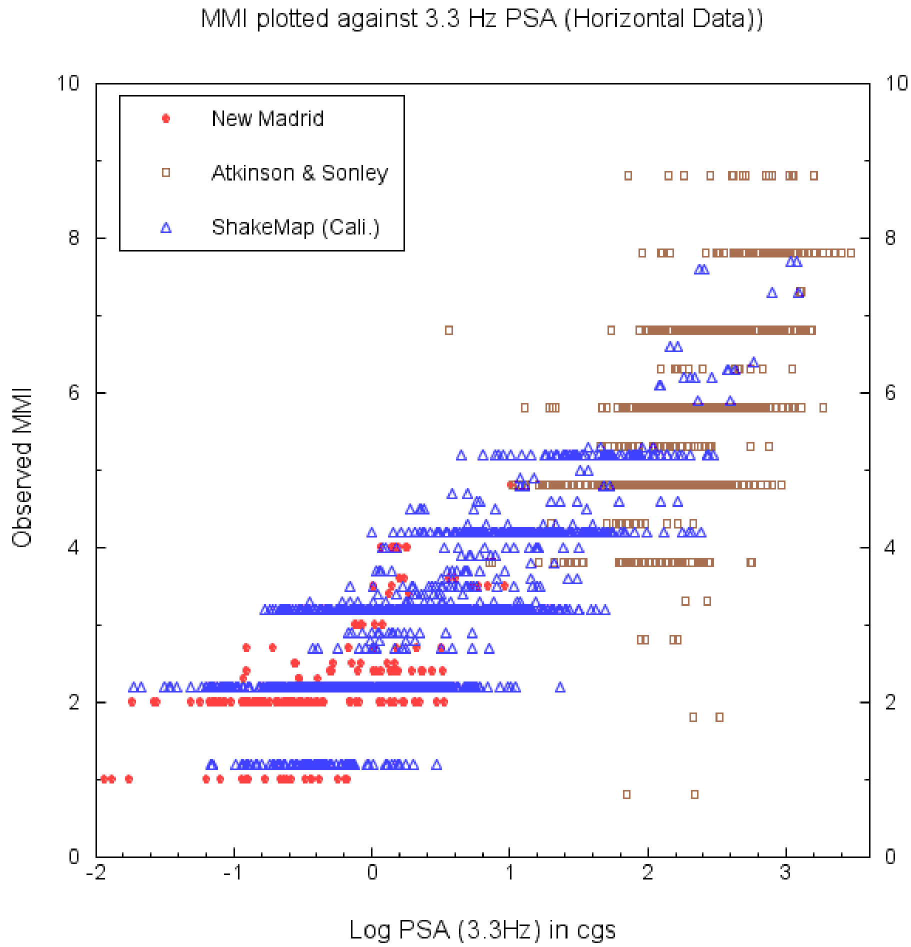


Figure 6 – Observed relationship between MMI and PSA at 3.3 Hz in New Madrid (red) and California (blue for low-magnitude data, brown for strong-motion data)

New Predictive relationships for MMI for California and New Madrid

The data on Figures 3 to 6 suggest that appropriate relationships between MMI and instrumental ground motion, for both California and New Madrid, at all intensity levels, can be derived by appropriate combination of the compiled datasets. We include the New Madrid data of this study and the California ShakeMap data, plus the Atkinson and Sonley California data for MMI≥5; the Atkinson and Sonley data for lower MMI (MMI<5) are excluded due to suspected bias as noted above. To obtain a regression result that is stable and well-constrained for each intensity level, we first find the mean logY (where Y is the selected ground-motion parameter) for each MMI level (=2,3,4,5,6,7,8,9), including in each average the data for MMI=1.5-2.49, 2.5-3.49, etc. A special case is made for MMI=5.5, for which we have a strong band of data; by contrast, all other bands of observations cluster near the integer MMI values. We include a special point for MMI=5.5, such that MMI=5 includes MMI=4.5-5.25, MMI=5.5 includes MMI 5.26-5.74, and MMI=6.0 includes MMI 5.75-6.49. These mean log Y levels for each intensity are given in Table 4.

Table 4 - PGV, PGA and PSA-values for each MMI level. SD=standard deviation.

MMI	Log PGV		Log PGA		Log PSA (0.5Hz)		Log PSA (1Hz)		Log PSA (3.3Hz)		No. Obs.
	cm/s	SD	cm/s/s	SD	cm/s/s	SD	cm/s/s	SD	cm/s/s	SD	
2	-1.656	0.43	-0.367	0.51	-1.149	0.66	-0.851	0.62	-0.180	0.53	576
3	-1.068	0.45	0.156	0.54	-0.513	0.49	-0.181	0.54	0.387	0.49	532
4	-0.506	0.43	0.903	0.51	-0.173	0.53	0.266	0.54	1.023	0.48	313
5	0.495	0.41	1.176	0.37	1.004	0.54	1.534	0.47	1.932	0.41	393
5.5	0.716	0.38	1.629	0.35	1.464	0.43	1.797	0.35	2.157	0.27	40
6	0.977	0.31	2.066	0.31	1.482	0.35	2.039	0.34	2.378	0.30	404
7	1.136	0.31	2.218	0.30	1.588	0.35	2.239	0.34	2.558	0.29	246
8	1.547	0.29	2.556	0.29	1.998	0.37	2.631	0.29	2.886	0.28	88
9	1.650	0.41	2.414	0.41	2.209	0.41	2.567	0.41	2.708	0.37	16

We regress the MMI averages of Table 4 versus logY to obtain the predictive equations. The purpose of using the average ground motion values for specified MMI levels is to force the curve to approximately follow the appropriate trend, rather than being overly influenced by the greater statistical volume of data at lower intensities.

Figures 7 through 11 plot the data used to derive the regressions, along with the regressed equations, which are quadratic in log Y versus MMI. Table 5 provides the coefficients of the equations for each parameter. Note that these equations, which apply to both New Madrid and California, are similar to those of Wald et al. (1999) and Atkinson and Sonley (2000) at high intensities, but significantly different at low intensities; the changes at low intensities are driven by the influence of the new data from this study.

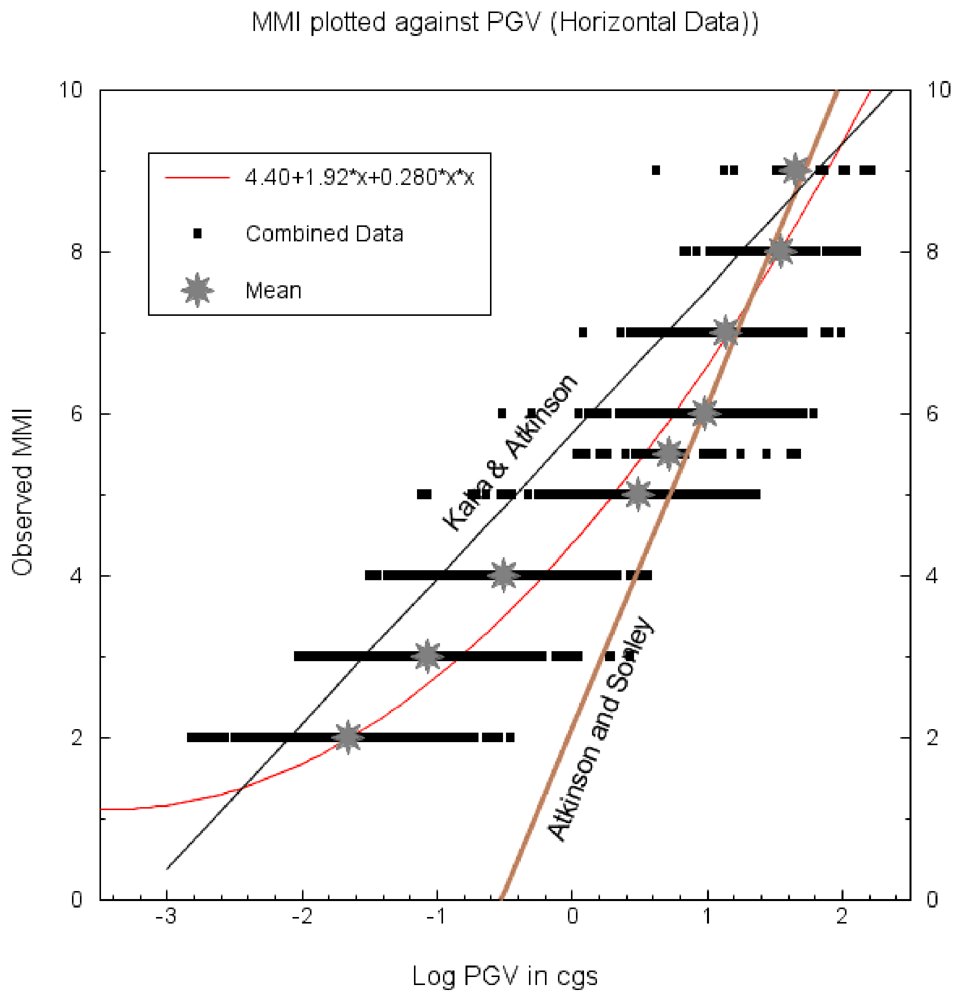


Figure 7 – Combined data points (black) used to derive average log PGV (grey stars) for each MMI level. Regressed line shown in red.

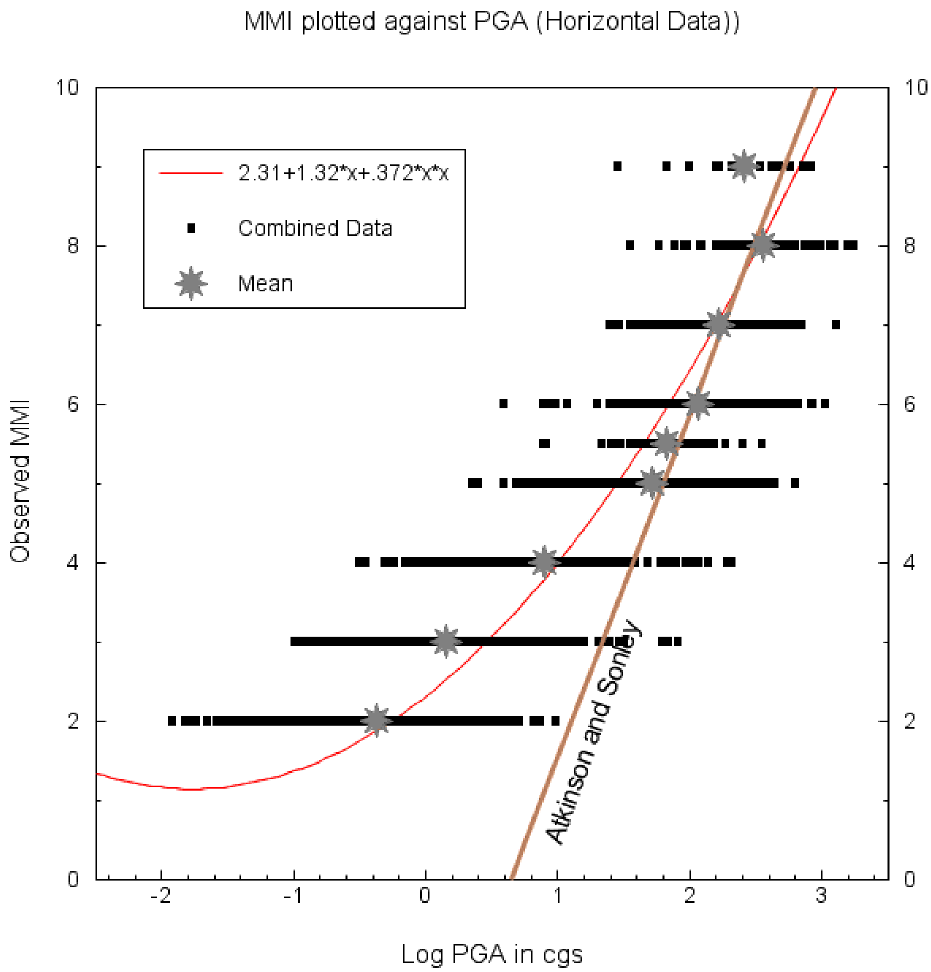


Figure8 – Combined data points (black) used to derive average log PGA (grey stars) for each MMI level. Regressed line shown in red.

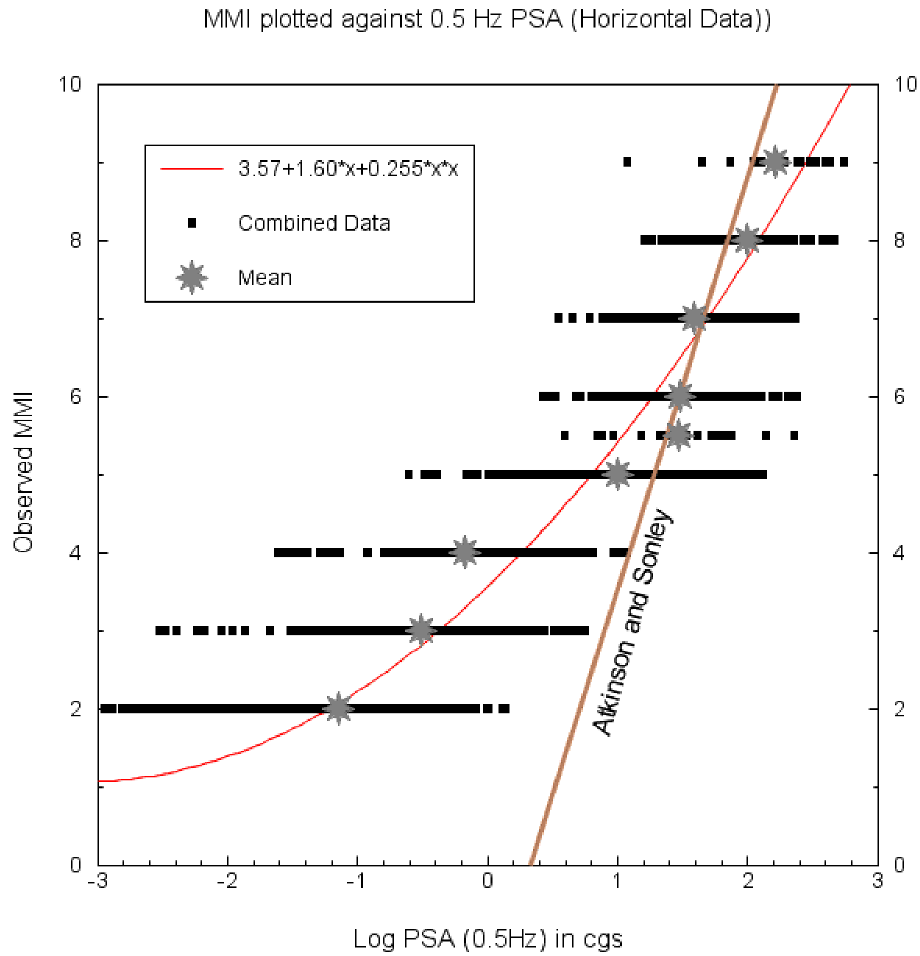


Figure 9 – Combined data points (black) used to derive average log PSA(0.5 Hz) (grey stars) for each MMI level. Regressed line shown in red.

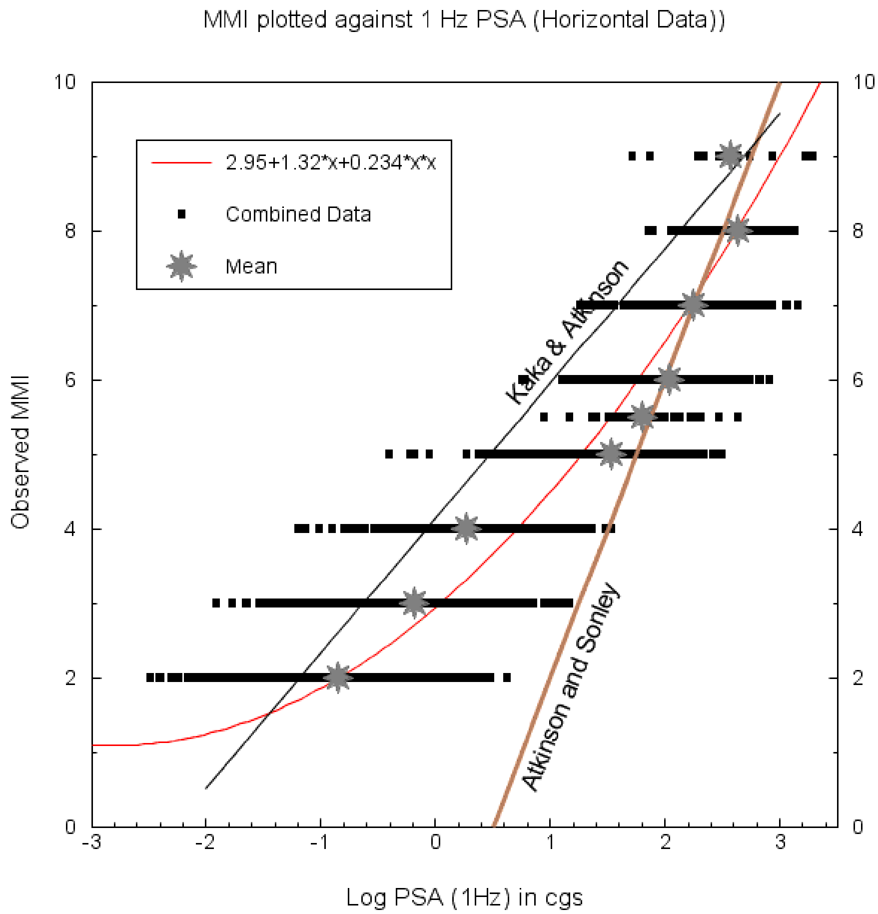


Figure 10 – Combined data points (black) used to derive average log PSA(1 Hz) (grey stars) for each MMI level. Regressed line shown in red.

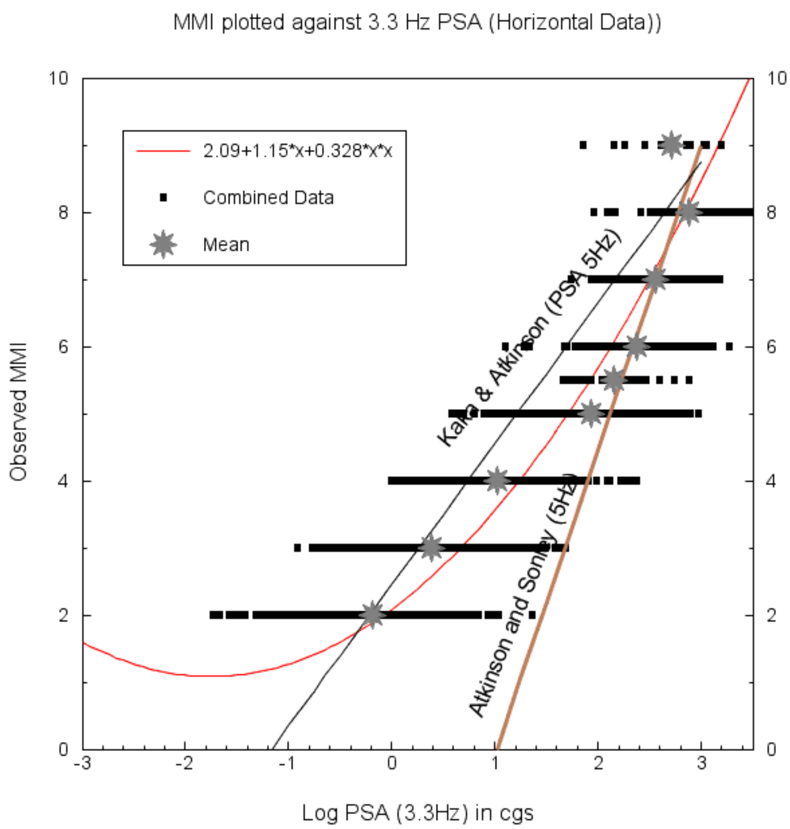


Figure 11 – Combined data points (black) used to derive average log PSA(3.3 Hz) (grey stars) for each MMI level. Regressed line shown in red.

Table 5 - Coefficients of Equations (and their standard errors) to predict MMI from Instrumental Ground Motion Parameters

$MMI = C_1 + C_2 \, LogY + C_3 \, (LogY)^2$, with standard deviation σ_{1MMI}

Y	**PGV**	**PGA**	**PSA (0.5Hz)**	**PSA (1Hz)**	**PSA (3.3 Hz)**
C_1	4.398	2.315	3.567	2.946	2.088
C_1 Error	0.21	0.38	0.29	0.34	0.36
C_2	1.916	1.319	1.596	1.324	1.146
C_2 Error	0.12	0.18	0.12	0.16	0.40
C_3	0.280	0.372	0.255	0.234	0.328
C_3 Error	0.07	0.11	0.06	0.10	0.17
σ_{1MMI}	0.78	0.93	0.86	0.84	0.87

Analysis of Residuals (Residual = Observed MMI – Predicted MMI)

Residuals, showing observed-predicted MMI, are plotted for each parameter as a function of magnitude and distance in Figures 12 through 16. These residuals show similar trends to those reported by Atkinson and Sonley (2000); for low frequencies (0.5, 1 Hz) and PGV, there is a magnitude trend in residuals, whereas for high frequencies (3.3 Hz) and PGA there is a distance trend in the residuals. It is likely that the existence of these trends, coupled with biases in previous MMI-log Y relationships at low intensities, may be the actual reason for the observed differences between ENA and California found by Kaka and Atkinson (2004). This possibility will be explored in more detail in future, to see if a single set of relationships for MMI-log Y is possible for all regions, if such trends are explicitly treated. These trends could be modeled by using an additional term in magnitude (for PGV) or distance (for PGA) in the predictive relationships, as described by Atkinson and Sonley (2000). For the present purposes (predicting MMI for New Madrid ShakeMaps), these trends are considered acceptable.

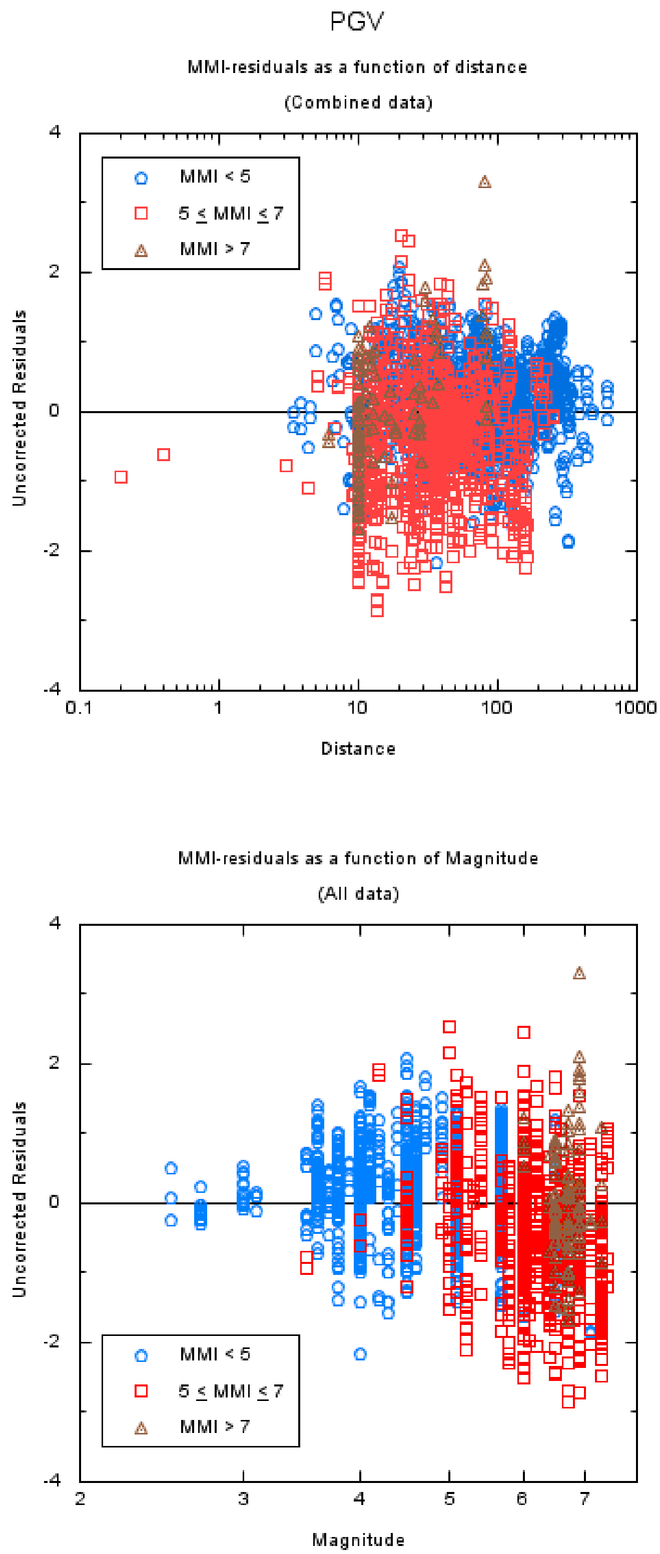


Figure 12 – MMI residuals (Observed MMI – Predicted MMI) for PGV-based predictions plotted versus distance (top) and magnitude (bottom).

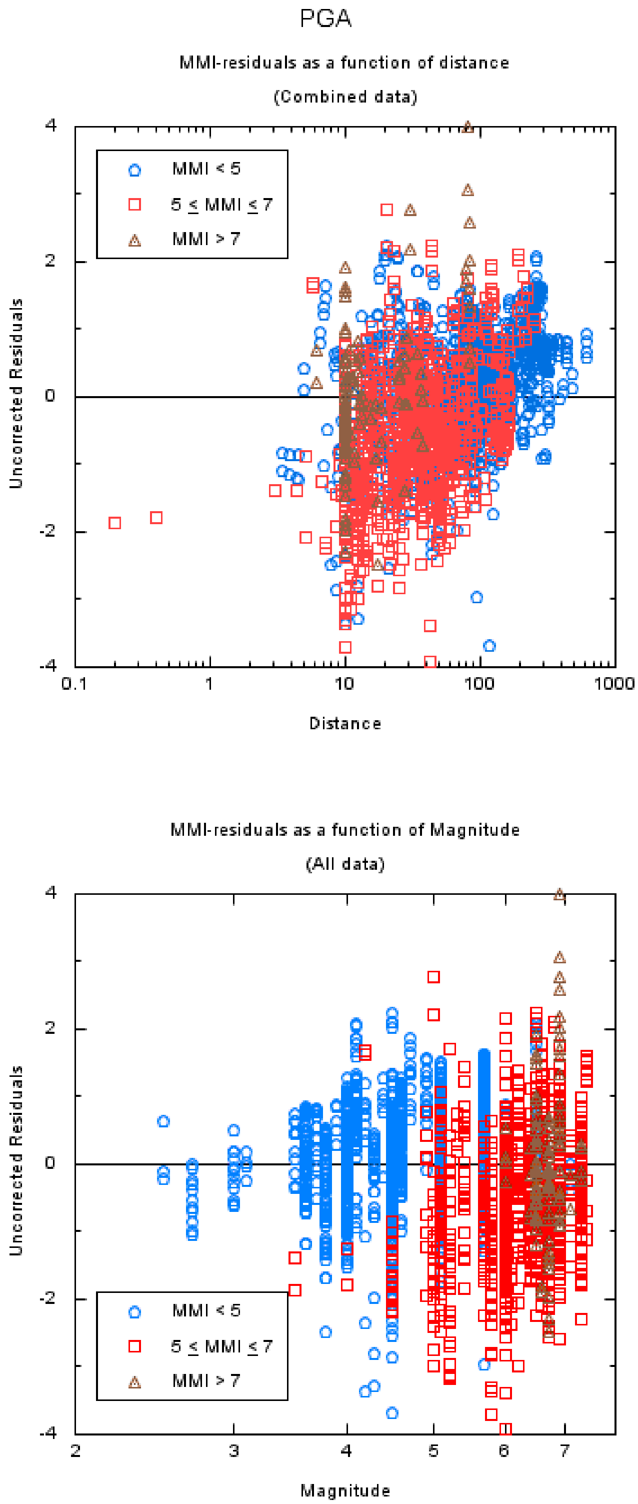
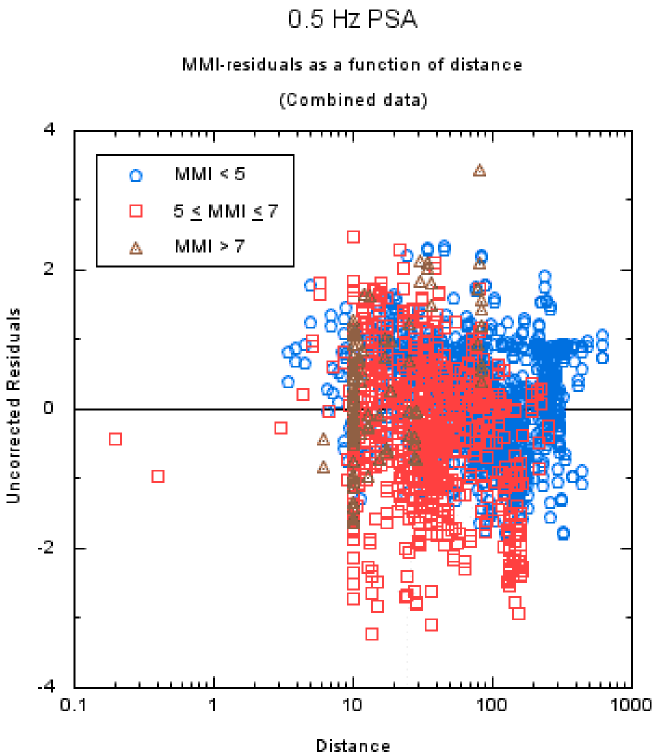


Figure 13 – MMI residuals (Observed MMI – Predicted MMI) for PGA-based predictions plotted versus distance (top) and magnitude (bottom).



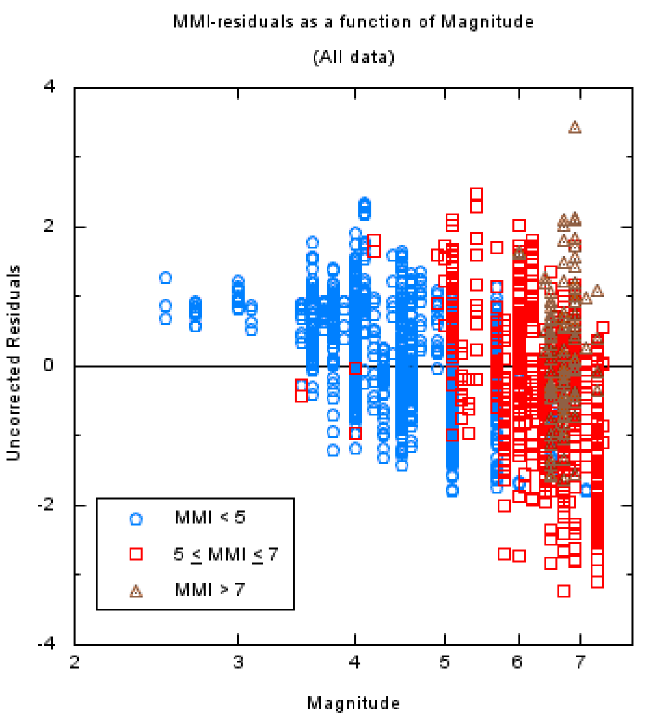


Figure 14 – MMI residuals (Observed MMI – Predicted MMI) for PSA (0.5 Hz)-based predictions plotted versus distance (top) and magnitude (bottom).

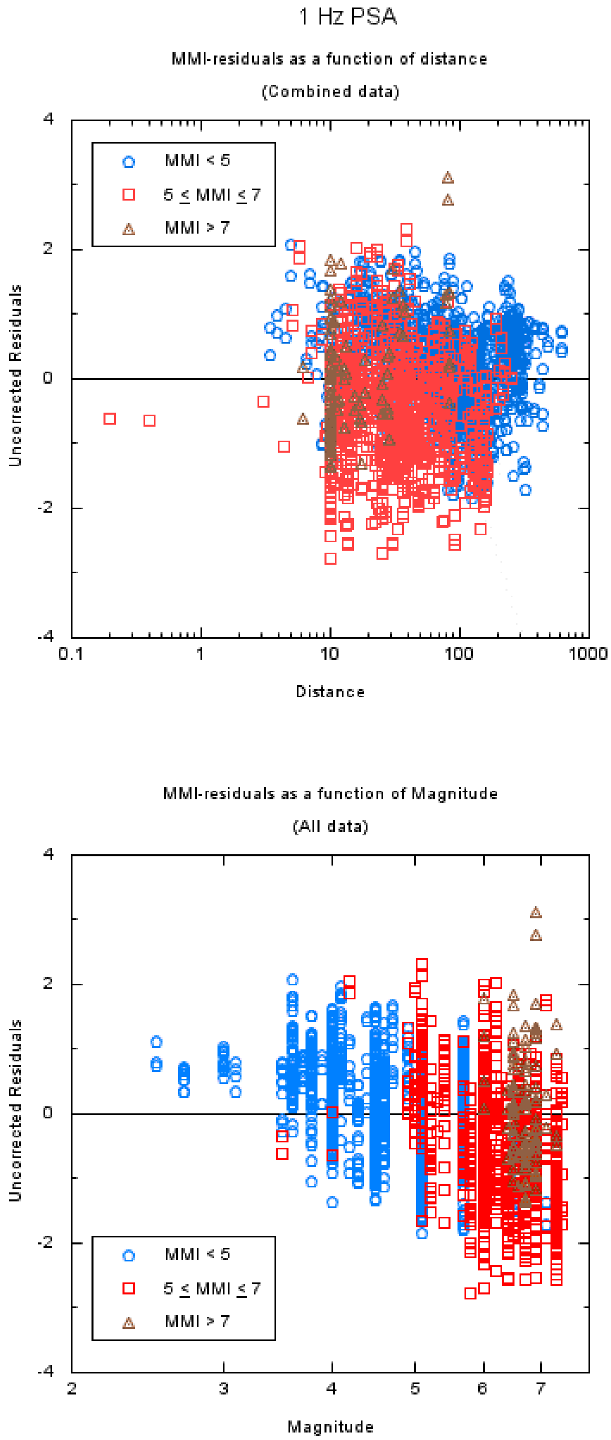


Figure 15 – MMI residuals (Observed MMI – Predicted MMI) for PSA (1 Hz)-based predictions plotted versus distance (top) and magnitude (bottom).

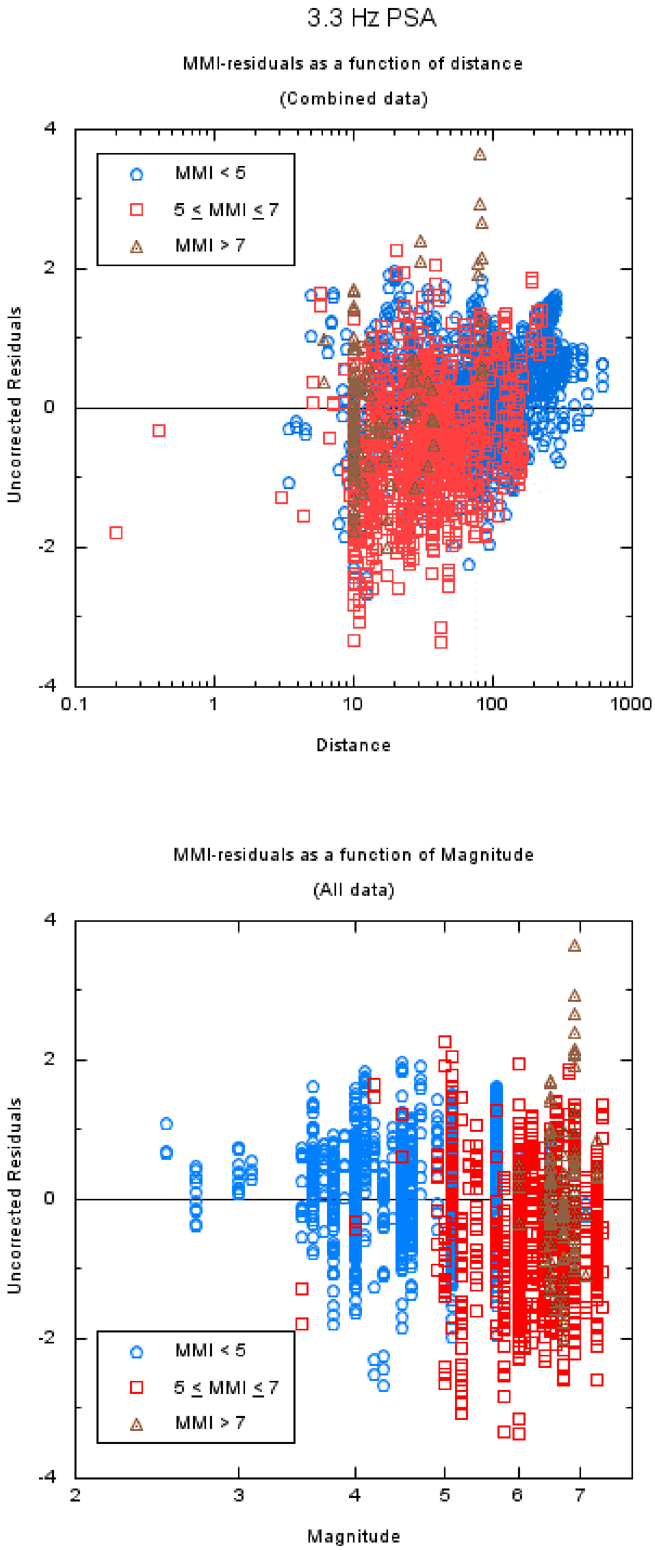


Figure 16 – MMI residuals (Observed MMI – Predicted MMI) for PSA (3.3 Hz)-based predictions plotted versus distance (top) and magnitude (bottom).

Conclusions

MMI for ShakeMap applications in the New Madrid region (and in California) can be predicted from recorded PGV (in cm/s), with a standard deviation of 0.78 MMI units, using the following equation:

$$MMI = 4.40 + 1.92 (\log PGV) + 0.280 (\log PGV)^2$$

Similar equations are available for PGA and response spectra, as shown in Table 5, with slightly larger standard deviations. There are magnitude-dependent trends in these relationships for PGV and PSA(0.5 Hz, 1 Hz), and distant-dependent trends for PGA and PSA(3.3 Hz). Refined relationships that include magnitude and distance as predictive variables could be used to slightly reduce the standard deviation by modeling these trends. However, the simple relationship proposed above is adequate for ShakeMap purposes.

References

Atkinson, G. (2004). Empirical attenuation of ground motion spectral amplitudes in southeastern Canada and the northeastern United States. Bull. Seism. Soc. Am.,**94**, 1079-1095.

Atkinson, G. and E. Sonley (2000). Empirical relationships between Modified Mercalli Intensity and response spectra. Bull. Seism. Soc. Am., **90**, 537-544.

Boatwright, J., K. Thywissen and L. Seekins (2001). Correlation of ground motion and intensity for the 17 January 1994 Northridge, California earthquake. Bull. Seism. Soc. Am., **91**, 739-752.

Dengler, L. A. and J. W. Dewey (1998).An intensity survey of housholds affected by the Northridge, California, earthquake of 17 January, 1994, Bull. Seism. Soc. Am., **88**, 441-462.

Dewey, J., D. Wald and L. Dengler (2000). Relating conventional USGS Modified-Mercalli Intensities to intensities assigned with data collected via the Internet. Seism. Res. L., **71**, 264.

Kaka, S. and G. Atkinson (2004). Relationships between instrumental intensity and ground motion parameters in eastern North America. Bull. Seism. Soc. Am., **94**, in press.

Langston, C. (2003). Local earthquake wave propagation through Mississippi Embayment sediments, Part II: Influence of local site velocity structure on Q_P-Q_S determinations. Bull Seism. Soc. Am., **93**, 2685-2703.

Street, R., J. Wiegand, E. Woolery and P. Hart (2005). Ground-motion parameters of the southwestern Indiana earthquake of 18 June 2002 and the disparity between the observed and predicted values. Seism. Res. L., **76**, 512-530.

Wald, D., V. Quitoriano, T. Heaton, H. Kanamori, C. Scrivner and C. Worden (1999). TriNet ShakeMaps: Rapid generation of peak ground motion and intensity maps for earthquakes in southern California. Earthquake Spectra, **15**, 537-555.