Final Technical Report

Analysis of "Did You Feel It?" Intensity Data to Determine Ground Motion Characteristics for the Central United States

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Gail M. Atkinson
280 McLean Ave.
Arnprior, ON K7S 3T2
613-623-3240 (phone/fax)
gmatkinson@aol.com

Non-technical Summary

This study uses earthquake ground-motion information that is being collected by the "Did You Feel It?" (DYFI) online citizen response program initiated by the U.S. Geological Survey to determine ground motion characteristics for earthquakes in the Central United States. The DYFI data offer the potential to resolve long-standing issues in earthquake ground motion science, due to their volume and widespread regional coverage. For example, DYFI data provide strong evidence that earthquake stress drops, which control the strength of high-frequency ground shaking, are higher in the central and eastern United States (CEUS) than in California. The DYFI data can be used to improved predictions of the shaking that is expected from future large earthquakes in the CEUS, particularly the New Madrid seismic zone.

Introduction

Uncertainty in the ground motion amplitudes that will be caused by future large earthquakes in the central and eastern United States (CEUS) is the largest source of uncertainty in evaluating seismic hazards in the region, and a significant impediment to mitigating future earthquake losses. It is also an impediment to public and engineering acceptance of seismic hazard results that suggest large ground motions are appropriate for engineering design in areas of the Central United States that will be affected by the next New Madrid-type earthquakes. The main reason why uncertainties are so high is that large earthquakes in the CEUS are rare and the distribution of strong motion and seismographic stations is sparse, leading to relatively few instrumental records for moderate CEUS events and essentially no instrumental records for large events. Thus empirical data to develop or test strong ground motion relations are lacking. Furthermore, there is considerable controversy regarding source characteristics for large CEUS events, and whether or not large California events can be used as 'analogs' in understanding CEUS source processes and the resulting ground motions. This issue heightens our uncertainty in CEUS ground motion relations.

This study utilizes a vast new database of ground motions for the CEUS that are directly relevant to earthquake hazards, with potential that has not yet been tapped. These are the intensity data collected by the U.S.G.S. "Did You Feel It?" (DYFI) program. The DYFI program compiles thousands of citizen responses submitted over the internet shortly after an earthquake occurs to map in detail the felt effects of moderate to large earthquakes. This program has been

remarkably successful, with over 3/4 million responses being collected within the last few years. Analyses of these data show that they are of surprisingly high quality, capable of distinguishing propagation and source effects, and of highlighting differences in source and propagation characteristics between the CEUS and California. These data are, practically by definition, directly applicable to seismic hazard estimation and mitigation. This research is aimed at improving regional seismic hazard maps for the CEUS, and providing tools that can be directly used in evaluating earthquake hazards and their uncertainties.

DYFI is a unique approach to collecting intensity data (Wald et al., 1999a), in which reports of felt and observed earthquake effects submitted by citizens via the internet (http://earthquake.usgs.gov/dyfi/) immediately after the shaking subsides are used by the USGS to rapidly map the extent and distribution of shaking and damage within each zip code in any area of the country. DYFI is also in use internationally; outside of the U.S. citizens submit their location by city or town name rather than zip code. DYFI has been an overwhelming success, with typically *thousands* of responses being registered for all magnitude 4 or greater earthquakes throughout the U.S. DYFI and its instrumental equivalent, ShakeMap (Wald et al., 1999b), are natural complements. The advantage of DYFI information is that it is plentiful even (and especially!) in regions with sparse instrumental coverage. By using ShakeMap data from well-instrumented regions in combination with DYFI, we can effectively calibrate the DYFI information to quantitative ground-motion measures and further enhance its utility.

To illustrate the MMI data quality relative to instrumental data, I compare DYFI data to instrumental ShakeMap data (http://earthquake.usgs.gov/shakemap/) for a single earthquake (2004 Parkfield). Figure 1 plots the mean and standard deviation of the DYFI ZIP code MMI values, in distance bins that are 0.1 log units in width, as we move away from the causative earthquake fault. The intensity values show a well-behaved progression of decreasing intensity with increasing distance. Overlaid on the intensity data are the instrumental ground-motion data for the same event, binned and plotted in the same way. The ground-motion measure plotted is based on the recorded peak ground velocity (PGV), which has been transformed via a linear function (determined by regression of the MMI versus PGV data), $fn(\mathrm{PGV}) = 3.94 + 1.22 \log_{10} \mathrm{PGV}$. The transformation is used so that the PGV data will plot on the same scale as the MMI data for ease of comparison. Notice that the MMI and PGV data track each other closely, suggesting that the MMI observations are actually providing reliable data on ground-motion amplitudes, albeit with somewhat larger variability (as noted by the larger error bars for MMI observations in comparison to those for PGV). This means that MMI observations, properly calibrated with instrumental observations, can be used to make inferences about earthquake ground motions. Even subtle features can be seen in the DYFI observations, such as a flattening of attenuation in the distance range from 70-150 km, where direct-arrival seismic phases are joined by post-critical reflections off the Moho (Burger et al., 1987). This is an important finding, because there are many regions, such as the eastern United States, where instrumental data are sparse, but human populations are dense; citizen responses provide "human seismometers", which can effectively fill gaps in earthquake ground-motion observations, and potentially shed light on unresolved questions in earthquake ground-motion science.

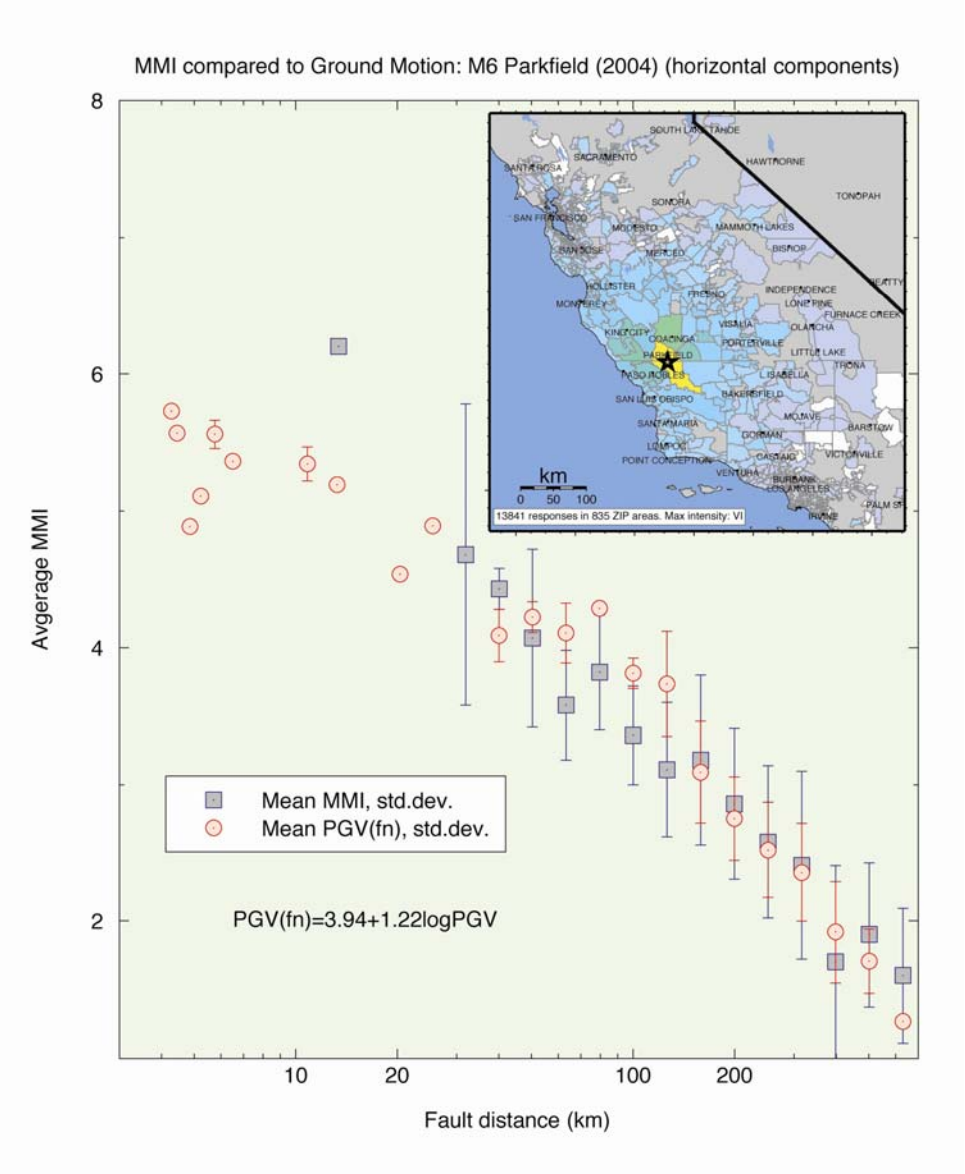

*Figure 1 – MMI amplitudes compared to instrumental ground motion amplitudes for the **M**6 Parkfield earthquake of 2004. Symbols show mean and standard deviation of observations, for data grouped in bins 0.1 log distance units in width. Inset shows DYFI map for the event.*

Results

Using the large DYFI database, MMI observations can be used to evaluate differences in earthquake source and propagation characteristics between the CEUS and CA. Figure 2 shows the intensity database that has been compiled for the CEUS and CA, where the data are again grouped in distance bins as in Figure 1. Binning the data is a process that sharpens the underlying image, similar to "stacking" multiple images in reflection seismology. All magnitudes are moment magnitude (**M**) or equivalent. Studies have shown that the DYFI information is equivalent to earlier postal questionnaire-based intensity observations (Dewey et

al., 2000), and thus I have augmented the data at larger magnitudes with historical MMI observations (NOAA catalogue at www.ngdc.noaa.gov/seg/hazard/int_srch.shtml). The equivalence of traditional and DYFI MMI values has been reconfirmed for several earthquakes having both types of MMI data. The MMI data for the two regions have been used in empirical regression analyses to determine the dependence of MMI on **M** and distance from the fault, D (which is equivalent to hypocentral distance for small to moderate events). The regression analysis is based on the maximum likelihood method of Joyner and Boore (1993). By analyzing the residuals (defined as observed-predicted MMI for the the given **M** and D) from various trial functional forms as a function of magnitude and distance, it was determined that the MMI data can be described, with an average error of 0.4 MMI units (standard deviation of residuals), by an equation of the following form:

$$\mathrm{MMI} = c_1 + c_2(\mathbf{M}-6) + c_3(\mathbf{M}-6)^2 + c_4 \log \mathrm{R} + c_5 \mathrm{R} + c_6 B + c_7 \mathbf{M} \log \mathrm{R}$$

where $\mathrm{R} = \sqrt{(\mathrm{D}^2 + h^2)}$

$B = 0 \qquad \mathrm{R} \leq R_t$

$B = \log(\mathrm{R}/R_t) \qquad \mathrm{R} > R_t$

The coefficients to be determined are c_1 through c_7, an effective depth term (h), and the transition distance in the attenuation shape (R_t). The form allows flexibility in modeling both magnitude and distance dependencies in the amplitude and attenuation of intensity, and follows a typical form used in empirical regressions of instrumental ground motion data (eg. Boore and Atkinson, 2006). Residuals for this functional form have no trends in magnitude or distance in either region. Coefficient values are as follows, where the coefficients listed are c_1 through c_7, h, and R_t, respectively: 1) for CA: 12.27(±0.24), 2.270, 0.1304, -1.30, -0.0007070, 1.95, -0.577, 14., 30. ; 2) for CEUS: 11.72(±0.36), 2.36, 0.1155, -0.44, -0.002044, 2.31, -0.479, 17., 80.

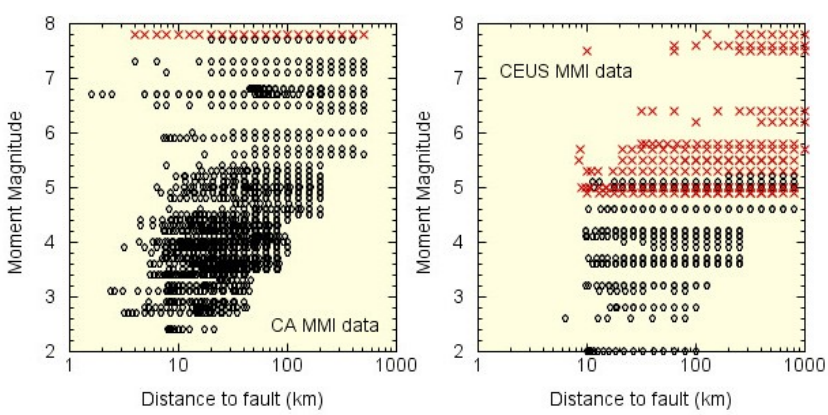

Figure 2 – Intensity data distribution for California (left) and the CEUS (right). Black circles are DYFI data, red x are historical MMI.

Figure 3 plots the determined relationship for MMI versus distance, for **M** 4, 6 and 8 in CA and the CEUS. MMI values for the CEUS are about one unit larger than those for CA at near-fault distances (<30 km), for all magnitudes. Due to the large volume of data, these average

amplitude levels are robustly determined (standard error 0.3 MMI units at close distances). This strongly implies that the source level of ground motions is higher in the CEUS than in CA. As distance increases, MMI attenuates more quickly in CA than in the CEUS, due to the well-known phenomenon of greater ground-motion attenuation in CA than in stable tectonic regions (Nuttli, 1973, and many others). Hence intensity values are typically 1 ½ to 2 units higher for CEUS earthquakes than for CA events of the same magnitude, at distances greater than 100-200 km.

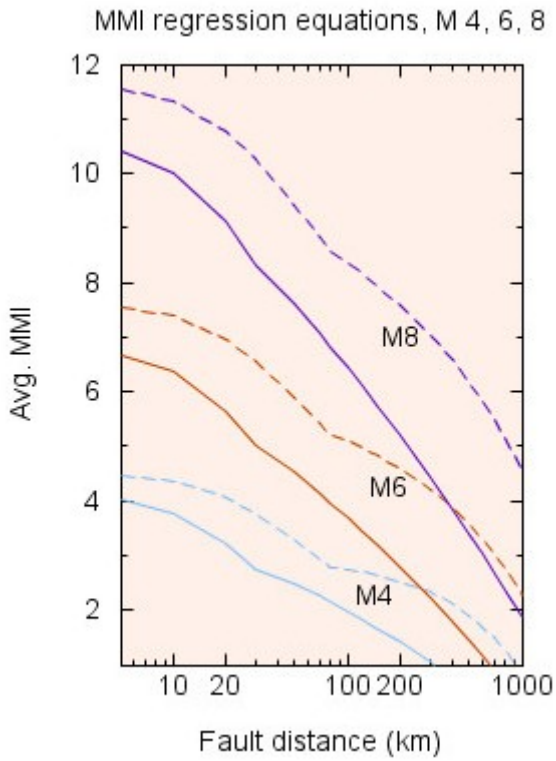

*Figure 3 – Predicted MMI values for events of **M** 4, 6 and 8 for CA (solid) and the CEUS (dashed), based on empirical regression. Note that at 300 km the MMI for a CEUS event of **M**=4 is similar to that of a CA event of **M**=6. At 400 km the MMI for a CEUS event of **M**=6 is similar to that of a CA event of **M**=8.*

The fact that ground motions at near-fault distances are larger in the CEUS than in CA suggests that the stress drop of CEUS events is greater, as the stress drop is the most important factor controlling ground-motion amplitudes at intermediate-to-high frequencies. (Alternative explanations are unlikely; these include (i) site amplification effects are systematically higher in the CEUS than in CA, or (ii) human and structural responses are systematically higher in the CEUS than in CA.) A rough estimate of the stress-drop difference between the regions can be made based on simple concepts of ground-motion scaling. According to the Brune (1970) source model, high-frequency ground motions, above the corner frequency of an earthquake, are closely related to stress drop, with peak ground acceleration (PGA) scaling as 5/6 log $\Delta\sigma$, where $\Delta\sigma$ is stress drop (Hanks and McGuire, 1981; Boore, 1983). Empirical correlations between PGA and

MMI (eg. Wald et al., 1999b, Atkinson and Sonley, 2000) generally show that the increase in the amplitude of log PGA, per unit increase in MMI, is about 0.38 (a factor of 2.4). It follows that a near-source difference of 1 MMI unit would correspond to a stress drop that is, on average, nearly 3 times larger in the CEUS than in CA ($10^{(0.38*6/5)} = 2.9$). This is a very rough calculation, illustrating the concept only. More detailed analyses as more data are collected will enable a better understanding of the differences in CEUS and CA ground-motion properties, based on analyses of correlated MMI and ground-motion databases.

Work in Progress

In the second year of this project, instrumental ground-motion data are being compiled for all of the MMI study events. This is based on ShakeMap parameters for CA. For the CEUS, processed seismographic data from current and past NEHRP studies will be used. Parameters to be compiled are PGA, PGV and response spectra (PSA) at 0.1s, 0.3s, 1s and 3s (the last is not very relevant for intensity, but will be compiled for completeness as it is provided for CA ShakeMaps; 0.1s values will be compiled only for the CEUS as they are not available from CA ShakeMaps). Correlations between MMI and ground motion will be checked individually for each significant event, then used as appropriate to develop event-specific attenuation curves of instrumental parameters versus distance from the MMI observations.

The combination of regional relations for intensity at moderate magnitude, with comparative information for CA that extends over a broader magnitude range, will be used to "translate" the intensity attenuation curves into equivalent ground-motion amplitude curves. In essence, the MMI data can be used to "fill in" the blanks in the instrumental ground-motion distribution, based on a calibration process. The details of this process will be fine-tuned as the study progresses, with the formulation depending on how good the correlation is between each of the index parameters and MMI.

Acknowledgements

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References

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

Boore, D. (1983). Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bull. Seism. Soc. Am., **73**, 1865-1894.

Boore, D. and G. Atkinson (2006). Boore-Atkinson NGA Empirical Ground Motion Model for the Average Horizontal Component of PGA, PGV and SA at Spectral Periods of 0.1, 0.2, 1, 2, and 3 Seconds, www.peer.berkelely.edu, June 2006.

Brune, J. (1970). Tectonic stress and the spectra of seismic shear waves from earthquakes. J. Geophys. Res., **75**, 4997-5009.

Burger, R., P. Somerville, J. Barker, R. Herrmann, and D. Helmberger (1987). The effect of crustal structure on strong ground motion attenuation relations in eastern North America. Bull. Seism. Soc. Am., **77**, 420-439.

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.

Hanks, T. and R. McGuire (1981). The character of high-frequency strong ground motion. Bull. Seism. Soc. Am., **71**, 2071-2095.

Joyner, W. and D. Boore (1993). Methods for regression analysis of strong motion data. Bull. Seism. Soc. Am., **83**, 469-487.

Nuttli, O. (1973). Seismic wave attenuation and magnitude relations for eastern North America. J. Geophys. Res., **78**, 876-885.

Wald, D., V. Quitoriano, L. Dengler and J. Dewey (1999a). Utilization of the Internet for rapid community intensity maps. Seism. Res. L., **70**, 680-697.

Wald, D., V. Quitoriano, T. Heaton, H. Kanamori (1999b). Relationships between peak ground acceleration, peak ground velocity and Modified Mercalli Intensity in California. Earthquake Spectra, **15**, 557-564.