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

David J. Wald, M.EERI, Vincent Quitoriano, Thomas H. Heaton, M.EERI, and Hiroo Kanamori, M.EERI

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.

INTRODUCTION

Seismic intensity has traditionally been used worldwide as a method for quantifying the shaking pattern and the extent of damage for earthquakes. Though derived prior to the advent of today's modern seismometric instrumentation, it nonetheless provides a useful means of describing, in a simplified fashion, the complexity of ground motion variations found on instrument recordings. Seismic intensity is still often the only observed parameter from which to quantify the level of ground shaking following damaging earthquakes in much of the world. In the United States, it has been used historically, and will very likely be used after future earthquakes. While advances in loss estimation in recent years now allow for the direct use of recorded ground motion parameters (e.g., Kircher et al., 1997; NIBS, 1997), seismic intensities will continue to be of value for post-earthquake analyses. As an example, seismic intensity maps for the 1994 Northridge, California earthquake have provided perhaps the most detailed descriptions of the variations of shaking and damage available (e.g., Dewey et al., 1995; Thywissen and Boatwright, 1998; Hales and Dengler, 1998).

(DJW) U.S. Geological Survey, 535 S. Wilson Ave., Pasadena, CA 91106
(VQ, THH, HK) Seismological Laboratory, Caltech, Pasadena, CA 91125

©*Earthquake Spectra,* Volume 15, No. 3, August 1999

We have developed regression relationships between Modified Mercalli intensity (I_{mm}, Wood and Neumann, 1931, later revised by Richter, 1958) and PGA or PGV by comparing the recorded peak ground motions to observed intensities for eight significant California earthquakes. The eight events, the 1971 (M6.7) San Fernando, the 1979 (M6.6) Imperial Valley, the 1986 (M5.9) North Palm Springs, the 1987 (M5.9) Whittier Narrows, the 1989 (M6.9) Loma Prieta, the 1991 (M5.8) Sierra Madre, the 1992 (M7.3) Landers, and the 1994 (M6.7) Northridge earthquakes, were chosen because they were well recorded by regional strong motion networks in addition to having numerous intensity observations (Dewey, written communication, 1997).

Since the earlier studies (e.g., Trifunac and Brady, 1975), there is now substantially more strong motion data available, particularly at larger ground motion amplitudes, for such a comparison. Also, in earlier studies, these relations were derived based on taking the intensity value from a map at the location of the strong motion station when no observation was available near the strong motion site. Yet I_{mm} maps are typically simplified representations of a spatially variable field, and the true I_{mm} value at the strong motion recording site is not usually known, so there is no guarantee that the I_{mm} at the strong motion station location corresponds with the I_{mm} value on the contour map. Here, we chose to correlate only those values where the strong motion station is near (within 3 km) an I_{mm} observation. For each station, the nearest intensity observation is chosen; if it is not within 3 km, however, then the strong motion data at that site is not used for correlation purposes. Although ground motions can vary significantly over this distance, futher reducing the correlation distance significantly reduces the available pairing of data.

Earlier comparisons of peak ground motions and intensities were also based primarily on regressions of intensity against peak acceleration, or in a few cases, against peak velocity and displacement. Part of our goal is to derive a relationship that can be used to estimate seismic intensity rapidly given instrumental recordings of ground motions (see Wald et al., 1999a). For this reason, one significant difference from previous studies is that here we chose to use both peak acceleration and velocity jointly, recognizing the saturation of PGA at high intensities, and the frequency and amplitude-dependent nature of the intensity scale as manifested by both felt shaking descriptions and actual damage.

REVISED PEAK GROUND MOTION VERSUS INTENSITY RELATIONS

We summarize the correlation of I_{mm} values and PGA for each of the individual earthquakes analyzed in Figure 1; Figure 2 shows a similar plot for PGV. The correlation and regressions of I_{mm} versus PGA and PGV for the data from all eight earthquakes combined are shown in Figures 3 and 4, respectively.

While there is no fundamental reason to expect a simple relationship between Modified Mercalli intensity (I_{mm}) and recorded ground motion parameters, over a range of accelerations and velocities a simple power-law representation is adequate and convenient. We find that for PGA in the limited range of $\mathrm{V} \leq I_{mm} \leq \mathrm{VIII}$,

$$I_{mm} = 3.66\ log(PGA) - 1.66 \quad (\sigma = 1.08) \tag{1}$$

and for peak velocity (PGV) within the range $\mathrm{V} \leq I_{mm} \leq \mathrm{IX}$,

$$I_{mm} = 3.47\ log(PGV) + 2.35 \quad (\sigma = 0.98) \tag{2}$$

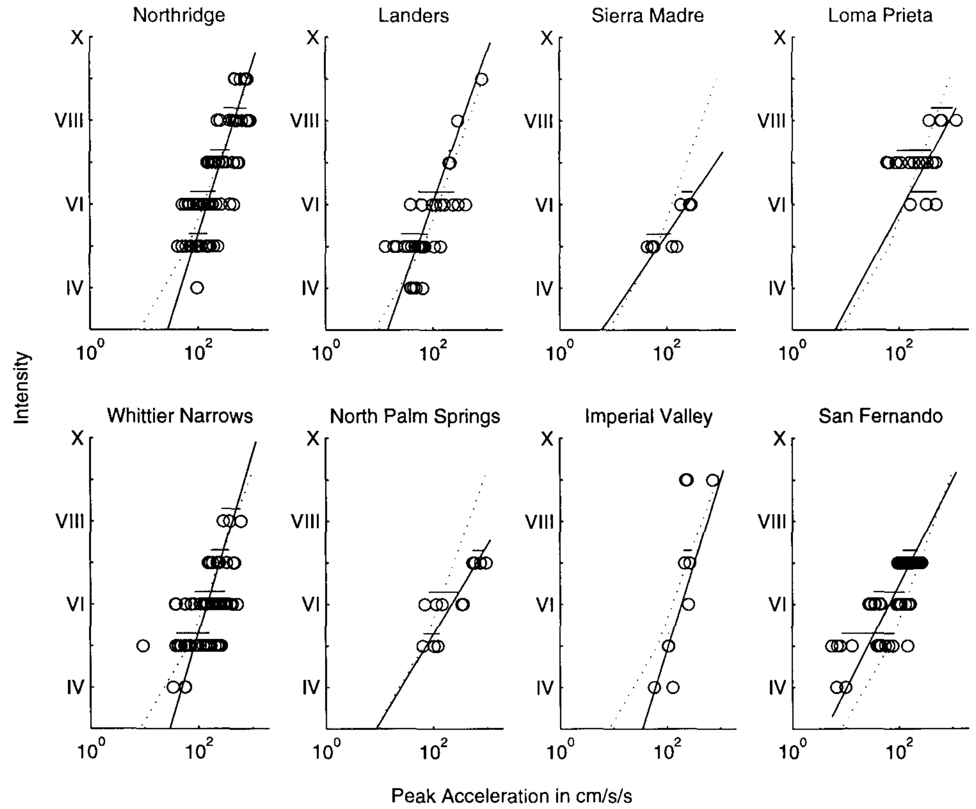

Figure 1. Modified Mercalli intensity plotted against peak ground acceleration for individual earthquakes. Circles denote data, horizontal lines above data depict the range of the geometric mean, plus and minus one standard deviation. Solid line is the regression for individual events; dotted line is regression for events combined.

The correlation coefficients (r) for Equations 1 and 2 are 0.597 and 0.686, respectively. Here the regressions are made on the geometric mean of the peak horizontal ground motion values for a given intensity unit. For acceleration, I_{mm} IX is not used in the regression since the peak acceleration values appear to saturate, and hence a simple power-law relation will not suffice. Likewise at I_{mm} IV, PGA and PGV are biased high due to lack of digitization of data from stations with lower values and hence they are not used in the regression. For I_{mm} IV, peak velocities do not continue decreasing, suggesting perhaps not only the above-mentioned bias, but also that a higher noise level (likely introduced in the integration of digitized recordings) may be controlling the peak values.

Requiring that the ground motion recording sites and I_{mm} observation points have similar surface geology, in addition to the maximum distance requirement, did not significantly reduce the scatter shown in Figures 3 and 4. However, this may be a limitation of the map scale used in the geology classification (1:750,000; Park and Ellrick, 1998), and a more detailed association of the geology at the strong motion sites and intensity

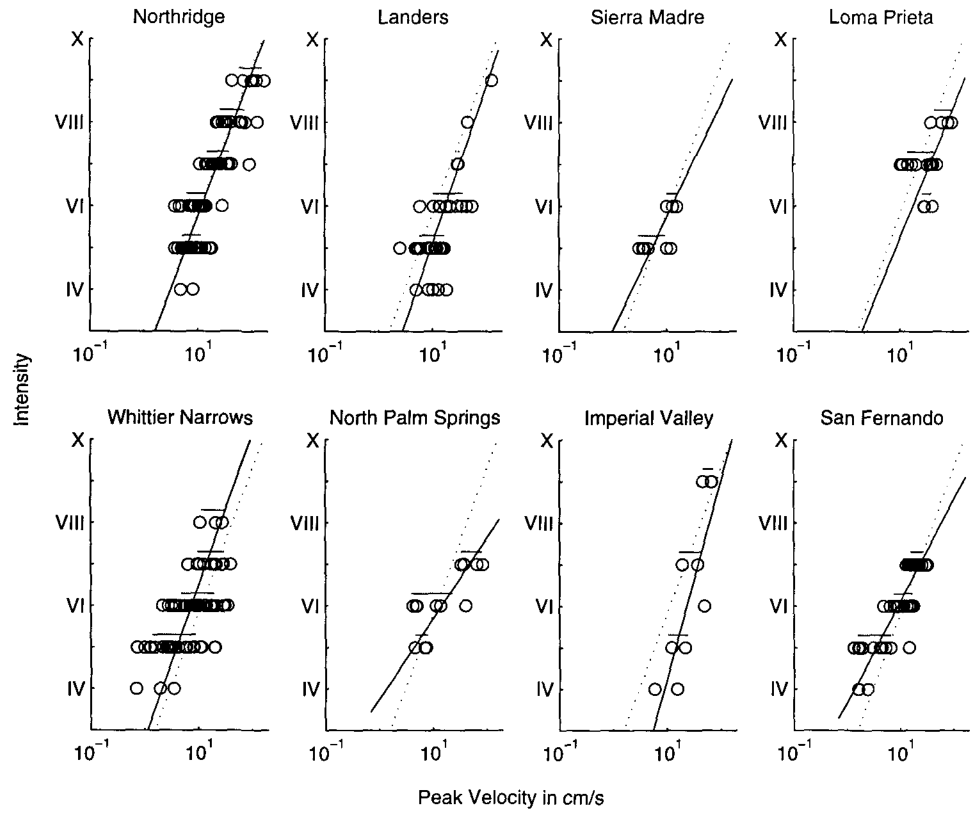

Figure 2. Modified Mercalli intensity plotted against peak ground velocity for individual earthquakes. Circles denote data, horizontal lines above data depict the range of the geometric mean, plus and minus one standard deviation. Solid line is the regression for individual events; dotted line is regression for events combined.

observations may be useful. Naturally, though, the association of an instrumental, point measurement of ground motion with an intensity observation defined as the maximum or average over a designated areal extent would be expected to show substantial scatter, particularly if the area does not contain the point measurement. This is a fundamental limitation originating from the definition of seismic intensity which requires an (unspecified) area be assigned a given intensity value based on the representative or average level of damage in the region; any single point observation in that area is not sufficient to satisfy such a definition.

As seen in Figures 3 and 4, low levels of shaking intensity correlate fairly well with both PGA and PGV, while high intensities correlate best with peak velocity. Basically, peak acceleration levels off at high intensity while peak velocity continues to grow. In contrast, the ground velocities, derived by integration of digitized analog accelerograms, are noisier at low levels of motion and the scatter is somewhat larger. By comparing maps of instrumental intensities with I_{mm} for the eight above-mentioned earthquakes, we have found that a relationship that follows acceleration for I_{mm}<VII and follows velocity

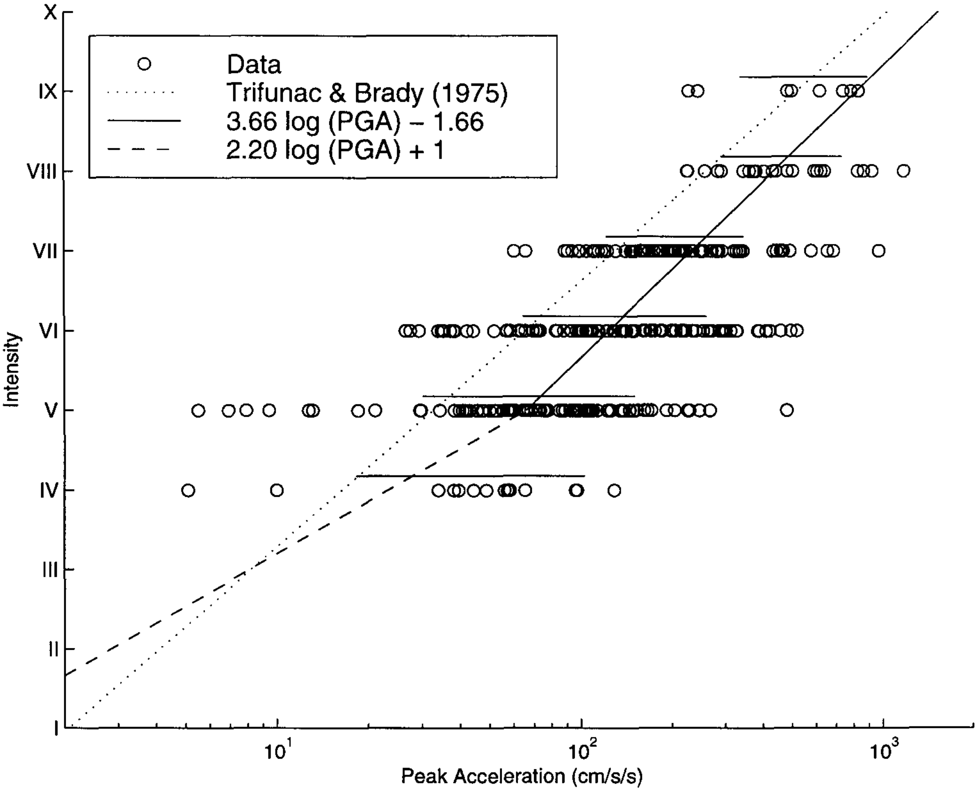

Figure 3. Modified Mercalli intensity plotted against peak ground acceleration for all events combined. Circles denote data; horizontal lines above data depict the range of the geometric mean, plus and minus one standard deviation. The solid line is regression from this study, the dashed line is assigned (see text for details). The dotted line is that of Trifunac and Brady (1975).

for I_{mm}>VII works fairly well in reproducing the observed I_{mm}.

Using peak acceleration to estimate low intensities is intuitively consistent with the notion that lower (<VI) intensities are assigned based on felt accounts, and people are more sensitive to ground acceleration than velocity. Higher intensities are defined by the level of damage; the onset of damage at the intensity VI to VII range is usually characterized by brittle-type failures (masonry walls, chimneys, unreinforced masonry, etc.) which are sensitive to higher-frequency accelerations. With more substantial damage (VII and greater), failure begins in more flexible structures, for which peak velocity is more indicative of failure (e.g., Hall et al., 1995). Our assumption is consistent with the recent analysis of Sokolov and Chernov (1998) which showed that seismic intensities correlate well for rather narrow ranges of Fourier amplitude spectra of ground acceleration, with 0.7-1.0 Hz being most representative of I_{mm} > VIII, while the 3-6 Hz range best represents I_{mm} V to VII; the 7-8 Hz range best correlates with the lowest I_{mm} range. In addition, Boatwright et al. (1999) have found that for the Northridge earthquake, PGV and the 3-0.3 Hz averaged spectral velocity are better correlated with intensity (VI and greater) than peak acceleration, and their correlation with intensity and peak spectral

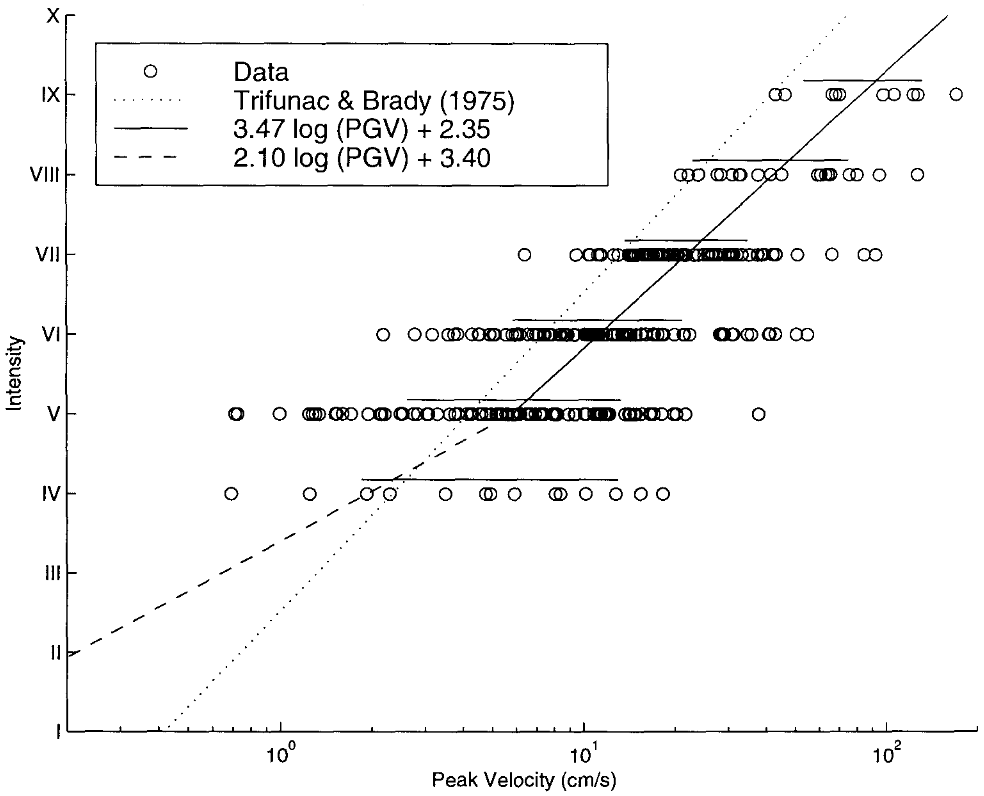

Figure 4. Modified Mercalli intensity plotted against peak ground velocity for all events combined. Circles denote data; horizontal lines above data depict the range of the geometric mean, plus and minus one standard deviation. The solid line is regression from this study, the dashed line is assigned (see text for details). The dotted line is that of Trifunac and Brady (1975).

velocity is strongest at 0.67 Hz.

While the range of $I_{mm}>$ V is well fit by a power law relation, this trend does not hold for lower intensities. Since we are also interested in estimating intensity at lower values with the peak ground motions, and our current collection of data from historical earthquakes does not provide constraints for lower intensity, we have imposed the following relationship (shown as a dashed line in Figure 3) between PGA and I_{mm}:

$$I_{mm} = 2.20\, log(PGA) + 1.00 \qquad (3)$$

The basis for the above relationship comes from correlation of TriNet peak ground motions recordings for recent magnitude 3.5 to 5.0 earthquakes with intensities derived from voluntary response from Internet users (Wald et al., 1999b) for the same events. We determined that the boundary between "not felt" and "felt" (I_{mm} I and II, respectively) regions corresponds to approximately one-to-two cm/sec/sec, at least for this range of magnitudes. We then assigned the slope such that the curve would intersect the relationship in Equation (1) at I_{mm} equal to V. We plan to refine this relationship as more digital data become available. The corresponding equation for PGV and I_{mm} (shown as a dashed line in Figure 4) is:

$$I_{mm} = 2.10\ log(PGV) + 3.40 \qquad (4)$$

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} verses 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} verses 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.

ACKNOWLEDGMENTS

Conversations with J. Boatwright, L. Dengler, J. Dewey, K. Campbell, R. Nigbor, and M. Petersen were very helpful. Jim Dewey provided the intensity data in digital form. Reviews by K. Campbell, M. Trifunac, R. Graves, and N. Field greatly improved this manuscript, as did recommendations of Editorial Board Member P. Somerville.

REFERENCES CITED

Boatwright, J., Thywissen, K., and Seekins, L., 1999, Correlation of ground motion and intensity for the January 17, 1994, Northridge, California earthquake, submitted to *Bull. Seism. Soc. Am.*

Dewey, J. W., Reagor, B. G., Dengler, L., and Moley, K., 1995, Intensity distribution and isoseismal maps for the Northridge, California, earthquake of January 17, 1994, *U. S. Geological Survey Open-File Report* **95-92**, 35 pp.

Hales, K. and Dengler, L. A., 1998, Detailed intensity map of the Jan. 17, 1994 Northridge earthquake, *Eos Trans. AGU*, **77**, p. F493.

Hall, J. F., Heaton, T. H., Halling, M. W. and Wald, D. J., 1995, Near-source ground motion and its effects on flexible buildings, *Earthquake Spectra*, **11**, 569-606.

Kircher, C. A., Reitherman, R. K., Whitman, R. V., and Arnold, C., 1997, Estimation of earthquake losses to buildings, *Earthquake Spectra*, **13**, 703-720.

National Institute of Building Sciences (NIBS), 1997, *Earthquake Loss Estimation Methodology: HAZUS97 Technical Manual*, Report prepared for the Federal Emergency Management Agency, Washington, D.C.

Park, S. and Ellrick, S., 1998, Predictions of shear wave velocities in southern California using surface geology, *Bull. Seism. Soc. Am.*, **88**, 677-685.

Richter, C. F., 1958, *Elementary Seismology*. W. H. Freeman and Co., San Francisco, pp. 135-149, 650-653.

Sokolov, V. Y. and Chernov, Y. K., 1998, On the correlation of Seismic Intensity with Fourier amplitude spectra, *Earthquake Spectra*, **14**, 679-694.

Thywissen, K. and Boatwright, J., 1998, Using safety inspection data to estimate intensity for the 1994 Northidge earthquake, *Bull. Seism. Soc. Am.*, **88**, 1243-1253.

Trifunac, M. D. and Brady, A. G., 1975, On the correlation of seismic intensity scales with the peaks of recorded ground motion, *Bull. Seism. Soc. Am.*, **65**, 139-162.

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

Wald, D. J., Quitoriano, V., Dengler, L., and Dewey, J. W., 1999b, Utilization of the Internet for rapid community seismic intensity maps, *Seism. Res. Lett.*, in press.

Wood, H. O. and Neumann, F., 1931, Modified Mercalli Intensity scale of 1931, *Bull. Seism. Soc. Am.*, **21**, 277-283.