A Proposal of Instrumental Seismic Intensity Scale Compatible with MMI Evaluated from Three-Component Acceleration Records

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Seismic intensity provides useful information on the regional distribution of earthquake effects and has been used to assess seismic hazards and damages. The concept of intensity has been considered as a method to classify severity of the ground motion on the basis of observed effects in the stricken area. In 1996, the Japan Meteorological Agency (JMA) developed a new seismic intensity measurement scale using three-component strong ground motion records in order to provide a measure of the strength of the seismic motion, which is compatible with the existing JMA intensity scale. By applying a band-pass filter to the frequency domain and a vectoral composition of the three components in the time domain, the JMA seismic intensity scale (I_{JMA}) can be calculated without subjective judgement. In this study, we apply the I_{JMA} method to the acceleration records of three recent significant earthquakes in California. For a Modified Mercalli Intensity (MMI) between IV and VIII, a new relation between MMI and $\log a_0$, obtained in the process of calculating the new I_{JMA}, is given by the equation $MMI = 3.93 \log a_0 - 1.17$. We propose this relation as a new instrumental seismic intensity (I_{MM}) compatible with the California region MMI. [DOI: 10.1193/1.1425814]

INTRODUCTION

The Medvedev-Sponheuer-Karnik (MSK) scale, the Modified Mercalli Intensity (MMI) scale, and the Japan Meteorological Agency (JMA) intensity scale are the most common intensity scales used since the middle of last century. Recently, many new intensity scales denoting the correlation between earthquake ground motion parameters and MMI have been proposed, especially for the California region. Sokolov and Chernov (1998) introduced the concept of representative frequencies to designate the correlation between seismic intensity (in terms of the MMI or the MSK scales) and Fourier amplitude spectra, after examination of earthquake recordings for several seismic regions. Following the 1994 Northridge earthquake, Dengler and Dewey (1998) proposed a community decimal intensity (CDI) scale, where the community is defined as the geographical boundaries of zip codes. Their concept is based on the Humboldt Earthquake Education Center (HEEC) telephone survey, studying individual household responses and observations of earthquake effects as a function of the independently assigned U.S. Geological Survey (USGS) MM intensities for those communities.

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Thywissen and Boatwright (1998), using municipal safety inspection data, developed a shaking intensity map for the 1994 Northridge earthquake. They derived a quantitative estimation of shaking intensity from the number of buildings categorized as red, yellow, or green by age, number of housing units, and construction type. Wald, Dengler, and Dewey (1999) introduced an automatic rapid generation method of intensity mapping using the responses of the intensity surveys of Internet users who felt the earthquake in southern California by converting the individual answers of each community into numerical values of the Community Internet Intensity (CII) using a modified version of the CDI (Dengler and Dewey 1998) algorithm. Wald et al. (1999b) also generated rapid instrumental ground motion and shaking intensity maps in real-time, designated TriNet "ShakeMaps." To generate ShakeMaps they use the new relationships between recorded ground motion parameters and shaking intensity values, taking into consideration spatially variable effects due to local site conditions in the southern California. TriNet "ShakeMaps" are available to the public as well as emergency response agencies within a few minutes of an earthquake on the World Wide Web.

Although many of these methods are useful in the evaluation of earthquake regions, each has its limitations, necessitating the development of an accurate, objective measurement system. Although the Sokolov and Chernov (1998) method has been used for hazard assessment in the former USSR, it considers only a single "representative frequency" for each intensity value and it does not include the effect of the vertical component in the calculation of frequency. The CDI intensity values proposed by Dengler and Dewey (1998) are influenced by the human response to intermediate to large earthquakes, different seismotectonic regions, and the time needed to construct a distribution map of CDI intensity values. The proposed tagging intensity method (Thywissen and Boatwright 1998) depends on the municipal tagging and population density information created for a census tract. In contrast, the CII mapping method of Wald, Dengler, and Dewey (1999) provides an actual intensity based on shaking and damage, while there is no recorded instrumental intensity. Although the CII method can be obtained more quickly than the CDI map of Dengler and Dewey (1998), in the case of large magnitude earthquake it may be impossible to receive quick responses from a highly damaged region. This delay limits the ability to draw a rapid CII map for early damage assessment and a rescue operation. During the Hector Mine earthquake (Mw 7.1, 16 October 1999), however, more than 25,000 responses were received from the people who felt the earthquake.

In October 1996, the JMA adopted a new instrumental seismic intensity scale (I_{JMA}), derived from three-component strong ground motion records. The new instrumental seismic intensity values, as real numbers, are promptly obtained just after an earthquake, as well as additional earthquake ground motion parameters, including peak ground acceleration (PGA), peak ground velocity (PGV), and spectrum intensity (SI). Recently, Yamaguchi and Yamazaki (2001) introduced a method to estimate the distribution of earthquake ground motion parameters such as I_{JMA}, PGA, PGV, and SI, based on building damage data due to the 1995 Hyogoken-Nanbu (Kobe) earthquake. However, the use of such methods is limited to devastating events and a long time is required to obtain building damage data.

We utilized the new instrumental JMA seismic intensity (I_{JMA}) as an earthquake ground motion index to apply the I_{JMA} methodology to three damaging California earthquakes. Collecting the reported Modified Mercalli Intensities for selected recording stations during the 1994 Northridge, the 1989 Loma Prieta, and the 1987 Whittier Narrows earthquakes, we calculated the new JMA seismic intensities. We then derived a linear regression for reported MMI and the geometric mean of the a_0 obtained during the computation of I_{JMA}. Using this relationship, we propose a new instrumental seismic intensity (I_{MM}) scale, compatible with MMI, which was obtained from a three-component record. The linear regression of MM intensity with respect to the I_{MM} is performed on the data set. These results were then compared to the Wald, Dengler, and Dewey (1999) relation between MMI and CII.

MODIFIED MERCALLI INTENSITY SCALE

In 1902, Mercalli introduced the basis for the Modified Mercalli Intensity scale of ten levels. In 1904, Cancani, expressing these grades in terms of acceleration, increased the scale to contain twelve grades. Sieberg published an elaboration of the Mercalli scale, including Cancani's scheme, in 1923. The scale was later improved by Wood and Neumann in 1931 and by Richter in 1958. The United States uses the MMI scale (Wood and Neumann 1931): the USGS is responsible for collecting earthquake intensity data using a questionnaire survey, as well as for undertaking the field investigation of destructive earthquakes in order to analyze the regional damage distribution.

Linear relationships between MMI and peak ground acceleration (PGA) have been proposed by several researchers (Gutenberg and Richter 1942, Kawasumi 1951, Neumann 1954, Hershberger 1956, Trifunac and Brady 1975, Murphy and O'Brien 1977, and Wald et al. 1999a). The correlation of PGA or PGV values from recording stations with the actual reported MMI values, which are based on the observations of a community with an area of many square kilometers, must be obtained to derive such relationships (Wald et al. 1999a). In this study, we determine the new JMA seismic intensity (I_{JMA}) for the Northridge earthquake (Shabestari and Yamazaki 1998), the Loma Prieta earthquake, and the Whittier Narrows earthquake, using the three-component acceleration records, allowing accurate and objective determination of the correlation.

JMA INSTRUMENTAL SEISMIC INTENSITY

After a revision of the JMA instrumental intensity scale in October of 1996, a large number of seismometers measuring JMA intensity were deployed throughout Japan (JMA 1996, Yamazaki et al. 1998). To calculate JMA intensity, Fourier transform is applied to each of three-component acceleration time history. Then a band-pass filter, consisting of three sub-filters (Figure 1), is applied to the frequency domain.

$$F(f)=F_1(f)F_2(f)F_3(f) \tag{1}$$

in which

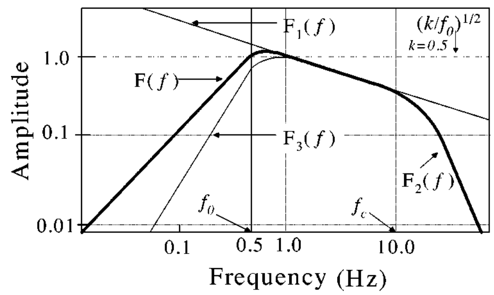

Figure 1. A band pass filter in the frequency domain.

Period-effect Filter: $F_1(f)=(1/f)^{1/2}$ (2)

High-cut Filter: $F_2(f)=(1+0.694x^2+0.24x^4+0.0557x^6+0.009664x^8+0.00134x^{10}+0.000155x^{12})^{-1/2}\ (x=f/f_c)$ (3)

Low-cut Filter: $F_3(f)=(1-\exp(-f/f_0)^3)^{1/2}$ (4)

After taking the inverse Fourier transform, the effect of the duration (τ) was calculated into the square root of the vectoral composition of the three components in the time domain (Figure 2a). Using a reference acceleration value of a_0, having a total duration, τ, satisfying the relation $\tau(a_0)\geqslant 0.3$ s (Figure 2b), and then substituting a_0 into Equation 5, the JMA seismic intensity, I_{JMA}, is obtained as a real (continuous) number

$$I_{JMA}=2.0\,log\,a_0+0.94 \quad (5)$$

STRONG GROUND MOTION AND USGS MM INTENSITY DATA

We applied the new JMA instrumental seismic intensity model to three damaging earthquakes in California: the October 1, 1987, Whittier Narrows earthquake (M_S

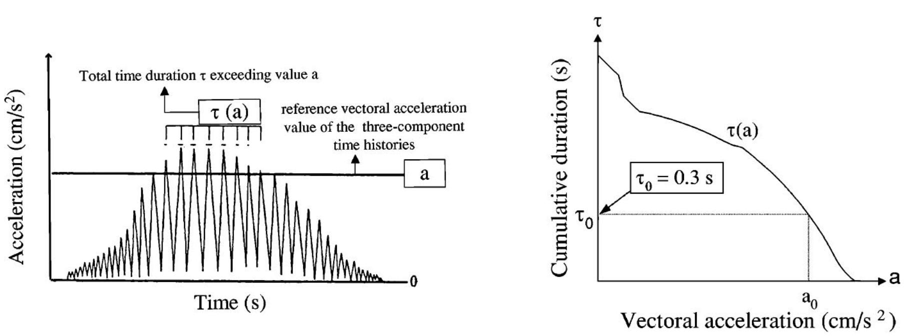

Figure 2. (a) The vectoral composition of the three filtered acceleration components and (b) the total duration $\tau(a)$ of the vectoral acceleration, obtained by summing the time segments exceeding value a.

Table 1. Summary of the USGS/CSMIP station data used in the calculation of new seismic intensities

Earthquake name	No. of free-field records	Velocity range (cm/s)	Acceleration range (cm/s^2)
1994 Northridge	20	5.60 – 128.90	67.00 – 865.97
1989 Loma Prieta	52	3.39 – 62.78	45.17 – 618.00
1987 Whittier Narrows	33	1.27 – 28.94	33.90 – 420.00

$=5.9$), the October 17, 1989, Loma Prieta earthquake ($M_S=7.1$), and the January 17, 1994, Northridge earthquake ($M_S=6.8$). All data were recorded by the USGS or by the California Strong Motion Instrumentation Program (CSMIP). The USGS data were obtained from the National Oceanic and Atmospheric Administration (NOAA), the National Geophysical Data Center (NGDC). To avoid instrumental response effects from the records, corrected time histories were selected from the data sources. All the corrected records meet the conditions necessary to apply the band-pass filtering in Equation 1. To avoid structural response effects, free-field records were used. The record of the 1994 Northridge earthquake from the Tarzana station was excluded from the analysis due to an extremely high peak acceleration (1,744 cm/s^2) value (Spudich et al. 1996), which does not correlate well with the average MMI reported for this community. The summary of the data used in this study is given in Table 1.

To develop a relation between the MMI and the $\log a_0$ values, we utilized the average reported USGS MM intensity for the Northridge earthquake from EQE (1995) report, containing the digital MMI values for the communities. For the Loma Prieta and Whittier Narrows earthquakes, we examined the reported USGS MMI values corresponding to the nearest postal zip codes, according to the criteria used by Wald et al. (1999a). Table 2 lists the USGS MMI values recorded closest to the selected stations for each of the three California earthquakes.

PROPOSAL OF INSTRUMENTAL SEISMIC INTENSITY SCALE (I_{MM})

The location of all stations and reported USGS MMI values were plotted for the three earthquakes before beginning the regression analysis of the data. The MMI value nearest to each recording station was utilized as the MMI value for that station. The primary linear regression of MMI versus $\log a_0$ for a limited range of MMI (IV $\leqslant$ MMI $\leqslant$ VIII) (Figure 3) demonstrates a standard deviation of 0.769 and an r-square value of 0.709. Due to the wide range of a_0 values for each given MMI level, we derived the linear relation between the USGS MMI and the geometric mean of the a_0 values for a given MMI unit (Figure 4). With a standard deviation of 0.274, the r-square (0.989) is very high after applying regression to the relation between MMI and the geometric mean of a_0.

To distinguish the estimated MMI, which is derived from a_0, from reported MMI, we will use I_{MM} instead of MMI. The proposed instrumental seismic intensity (I_{MM}) scale compatible with MMI is determined for the three significant California earthquakes (Figure 4) as:

Table 2. Summary of the records and reported MMIs for the three California significant earthquakes (PGA [cm/s^2] and PGV [cm/s] are the larger of two horizontal components, a_0 is measured in cm/s^2).

Northridge Earthquake

No	Station Name	Source	Lat.	Long.	PGA	PGV	MMI	a_0	I_{JMA}	I_{MM}
1	LA., Sepulveda Canyon	USGS	34.050	-118.480	462.1	26.5	8	213.8	5.6	8.0
2	Huntington Beach, Hun. B.	USGS	33.662	-117.997	118.1	11.1	5	67.6	4.6	6.0
3	LA, Bell Postal Facil.	USGS	33.929	-118.260	260.4	17.0	6	75.9	4.7	6.2
4	Malibu Canyon, Monte Nido Fire	USGS	34.080	-118.690	173.1	8.5	6	53.7	4.4	5.6
5	Littlerock, Lit. Post Off.	USGS	34.520	-117.990	165.0	7.9	5	60.3	4.5	5.8
6	Topanga, Top. Fire Station	USGS	34.080	-118.600	326.5	15.0	7	107.2	5.0	6.8
7	Long Beach, L. b. VA. Hos.	USGS	33.780	-118.120	67.0	5.7	5	33.9	4.0	4.8
8	LA, Griffith Obs.	USGS	34.120	-118.300	291.1	25.7	7	169.8	5.4	7.6
9	LA, Wadsworth VA Hos.	USGS	34.050	-118.450	382.9	32.9	8	151.4	5.3	7.4
10	Irvine, 2603 Main, Ground	USGS	33.656	-117.859	102.6	6.8	5	42.7	4.2	5.2
11	Hawthorne, Haw. F. A. A. B.	USGS	33.746	-118.396	183.6	13.3	5	60.3	4.5	5.8
12	Prado Dam, Downstream	USGS	33.890	-117.640	190.3	9.9	5	85.1	4.8	6.4
13	Fullerton, Brea Dam, Downstream	USGS	33.890	-117.930	191.0	11.2	5	67.6	4.6	6.0
14	Norwalk, 12400 Imperial Highway	USGS	33.920	-118.070	79.1	5.6	5	38.0	4.1	5.0
15	Pasadena, 535 South Wilson Ave.	USGS	34.136	-118.127	161.4	9.9	6	75.9	4.7	6.2
16	Arleta Nordhoff Ave. Fire St.	CSMIP	34.236	-118.439	541.4	40.4	7	190.5	5.5	7.8
17	Castaico Oldridge Route	CSMIP	34.564	-118.642	557.1	52.6	7	302.0	5.9	8.6
18	Newhall LA, County Fire St.	CSMIP	34.387	-118.530	578.2	94.7	8	478.6	6.3	9.4
19	Santa Monica City Hall Ground	CSMIP	34.011	-118.490	866.0	41.8	8	169.8	5.4	7.6
20	Sylmar County Hos.	CSMIP	34.326	-118.444	826.8	128.9	8	478.6	6.3	9.4

Loma Prieta Earthquake

No	Station Name	Source	Lat.	Long.	PGA	PGV	MMI	a_0	I_{JMA}	I_{MM}
1	Hollister Airport Differential	USGS	36.888	-121.413	281.4	44.4	8	213.8	5.6	8.0
2	Calaveras Array, Fremont, Emer.	USGS	37.535	-121.929	190.7	10.8	7	75.9	4.7	6.2
3	Apeel Array #2, Redwood City	USGS	37.520	-122.250	272.3	53.1	7	239.9	5.7	8.2
4	Anderson Dam, Downstream	USGS	37.166	-121.628	245.4	22.3	7	120.2	5.1	7.0
5	Emeryville, 6363 Christie Ave.	USGS	37.844	-122.295	254.7	41.1	7	190.5	5.5	7.8
6	Hayward City Hall, Ground Site	USGS	37.679	-122.082	50.6	5.7	6	24.0	3.7	4.3
7	Apeel Array St.# 9, Crystal Spr.	USGS	37.470	-122.320	115.1	18.7	7	75.9	4.7	6.2
8	Bear Valley Array Station 7, P	USGS	36.483	-121.180	45.2	3.4	6	21.4	3.6	4.1
9	Berkeley, U.C., Strawberry Can.	USGS	37.870	-122.240	74.6	10.5	7	38.0	4.1	5.0
10	Calaveras Array, Cherry Flat R	USGS	37.396	-121.756	78.2	8.7	6	38.0	4.1	5.0
11	Hollister, Sago Vault	USGS	36.765	-121.446	60.1	8.8	6	33.9	4.0	4.8
12	Larkspur Ferry Terminal	USGS	37.946	-122.508	134.7	20.3	6	107.2	5.0	6.8
13	SF, Fire Station #17	USGS	37.728	-122.385	104.4	10.6	7	47.9	4.3	5.4
14	Berkeley, Lawrence Berkeley Lab.	CSMIP	37.876	-122.249	114.0	22.0	7	85.1	4.8	6.4
15	Capitola Fire Station	CSMIP	36.974	-121.952	463.0	36.2	7	269.2	5.8	8.4
16	Coyote Lake Dam Downstream	CSMIP	37.124	-121.551	175.0	21.0	7	107.2	5.0	6.8
17	Corralitos, Eureka Canyon Rd.	CSMIP	37.046	-121.803	618.0	55.2	8	302.0	5.9	8.6
18	Upper Crystal Springs Res., Pulgas	CSMIP	37.490	-122.310	154.0	17.6	7	75.9	4.7	6.2
19	Upper Crystal Springs Res. Skyline	CSMIP	37.465	-122.343	101.0	21.8	7	85.1	4.8	6.4
20	Foster City - Redwood Shores	CSMIP	37.550	-122.230	278.0	45.4	6	213.8	5.6	8.0
21	Fremont, Mission San Jose	CSMIP	37.530	-121.919	118.0	10.2	7	60.3	4.5	5.8
22	Gilroy #1, Gavilan Coll., Water Tank	CSMIP	36.973	-121.572	434.0	33.8	7	239.9	5.7	8.2
23	Gilroy #2, Hwy 101/Bolsa Rd. Motel	CSMIP	36.982	-121.556	344.0	39.2	7	239.9	5.7	8.2
24	Gilroy #3, Gilroy Sewage Plant	CSMIP	36.987	-121.536	532.0	43.8	7	190.5	5.5	7.8
25	Gilroy #4, San Ysidro School	CSMIP	37.005	-121.522	408.0	39.1	7	169.8	5.4	7.6

Table 2 (cont.). Summary of the records and reported MMIs for the three California significant earthquakes (PGA [cm/s^2] and PGV [cm/s] are the larger of two horizontal components, a_0 is measured in cm/s^2).

No	Station Name	Source	Lat.	Long.	PGA	PGV	MMI	a_0	I_{JMA}	I_{MM}
26	Gilroy #6, San Ysidro	CSMIP	37.026	-121.484	167.0	13.9	7	95.5	4.9	6.6
27	Gilroy, Gavilan Coll., Phys. Sci. Bldg.	CSMIP	36.973	-121.568	349.0	28.9	7	151.4	5.3	7.4
28	Halls Valley, Grant Park	CSMIP	37.338	-121.714	128.0	13.7	6	75.9	4.7	6.2
29	Hollister, South Street and Pine Drive	CSMIP	36.848	-121.397	362.0	62.8	8	302.0	5.9	8.6
30	Hayward, Bart Station	CSMIP	37.670	-122.086	155.0	14.4	6	85.1	4.8	6.4
31	Hayward, Csuh Stadium Grounds	CSMIP	37.657	-122.061	82.6	7.4	6	42.7	4.2	5.2
32	Hayward, Muir School	CSMIP	37.657	-122.082	166.0	13.6	6	85.1	4.8	6.4
33	Monterey, City Hall	CSMIP	36.597	-121.897	68.5	4.7	6	30.2	3.9	4.6
34	Piedmont, Piedmont Jr. High Grounds	CSMIP	37.823	-122.233	81.2	9.7	7	47.9	4.3	5.4
35	Point Bonita	CSMIP	37.820	-122.520	71.4	13.6	7	67.6	4.6	6.0
36	Richmond, City Hall Parking Lot	CSMIP	37.935	-122.342	123.0	17.1	6	95.5	4.9	6.6
37	Sago South, Hollister, Cienega Rd.	CSMIP	36.753	-121.396	70.7	10.3	6	60.3	4.5	5.8
38	Salinas, John and Work St.	CSMIP	36.671	-121.642	110.0	15.8	7	53.7	4.4	5.6
39	Santa Cruz, UCSC/Lick Lab.	CSMIP	37.001	-122.060	433.0	21.2	7	169.8	5.4	7.6
40	Saratoga, Aloha Ave.	CSMIP	37.255	-122.031	494.0	43.6	6	213.8	5.6	8.0
41	SF, Cliff House	CSMIP	37.780	-122.510	106.0	21.0	7	85.1	4.8	6.4
42	SF, Diamond Heights	CSMIP	37.740	-122.430	111.0	14.3	7	67.6	4.6	6.0
43	SF, Int. Airport	CSMIP	37.622	-122.398	326.0	29.3	6	169.8	5.4	7.6
44	SF, Pacific Heights	CSMIP	37.790	-122.430	60.2	14.3	7	47.9	4.3	5.4
45	SF, Presidio	CSMIP	37.792	-122.457	195.0	33.6	7	95.5	4.9	6.6
46	SF, Rincon Hill	CSMIP	37.790	-122.390	88.5	11.6	7	47.9	4.3	5.4
47	SF, Telegraph Hill	CSMIP	37.800	-122.410	90.5	9.6	7	42.7	4.2	5.2
48	SO. SF, Sierra Pt.	CSMIP	37.674	-122.388	103.0	8.2	7	47.9	4.3	5.4
49	Treasure Island	CSMIP	37.825	-122.373	156.0	33.4	7	134.9	5.2	7.2
50	Woodside, Fire Station	CSMIP	37.429	-122.258	79.7	15.6	7	60.3	4.5	5.8
51	Yerba Buena Island	CSMIP	37.810	-122.360	65.8	14.7	7	38.0	4.1	5.0
52	Agnews State Hospital	CSMIP	37.397	-121.952	163.0	30.9	6	85.1	4.8	6.4

Whittier Narrows Earthquake

No	Station Name	Source	Lat.	Long.	PGA	PGV	MMI	a_0	I_{JMA}	I_{MM}
1	12400 Imperial Highway, Norwalk	USGS	33.920	-118.070	234.9	21.6	7	107.2	5.0	6.8
2	Alhambra Fremont School	CSMIP	34.070	-118.150	374.0	21.7	8	134.9	5.2	7.2
3	Altadena Eaton Canyon Park	CSMIP	34.177	-118.096	299.0	10.2	6	67.6	4.6	6.0
4	Arleta Nordhoff Ave Fire Station	CSMIP	34.240	-118.440	87.1	5.7	5	42.7	4.2	5.2
5	Castaic Hasley Canyon	CSMIP	34.459	-118.650	38.6	2.2	4	21.4	3.6	4.1
6	Castaic Old Ridge Route	CSMIP	34.564	-118.642	67.2	4.3	4	38.0	4.1	5.0
7	Downey County Maint. Bldg.	CSMIP	33.924	-118.167	193.0	28.9	7	151.4	5.3	7.4
8	Featherly Park Park Maint. Bldg.	CSMIP	33.869	-117.709	77.0	4.4	6	42.7	4.2	5.2
9	Hemet Stetson Ave Fire Station	CSMIP	33.729	-116.979	33.9	1.4	4	12.0	3.1	3.1
10	Huntington Beach Lake St. Fire St.	CSMIP	33.662	-117.997	43.0	1.9	5	17.0	3.4	3.7
11	Inglewood Union Oil Yard	CSMIP	33.905	-118.279	246.0	16.4	5	95.5	4.9	6.6
12	LA, 116th St, School	CSMIP	33.929	-118.260	384.0	18.6	6	120.2	5.1	7.0
13	LA, Baldwin Hills	CSMIP	34.009	-118.361	150.0	7.7	5	67.6	4.6	6.0
14	Century City La Country Club North	CSMIP	34.063	-118.418	97.5	6.6	5	38.0	4.1	5.0
15	LA, Hollywood Storage Bldg.	CSMIP	34.090	-118.339	201.0	9.2	6	53.7	4.4	5.6
16	Lancaster Medical Office Bldg.	CSMIP	34.688	-118.156	59.6	3.0	5	24.0	3.7	4.3
17	LA, Obregon Park	CSMIP	34.037	-118.178	420.0	21.8	6	134.9	5.2	7.2
18	Long Beach Harbor Admin. Bldg.	CSMIP	33.754	-118.200	68.9	7.9	6	38.0	4.1	5.0
19	Long Beach Rancho Los Cerritos	CSMIP	33.840	-118.194	233.0	18.5	6	107.2	5.0	6.8

Table 2 (cont.). Summary of the records and reported MMIs for the three California significant earthquakes (PGA [cm/s^2] and PGV [cm/s] are the larger of two horizontal components, a_0 is measured in cm/s^2).

No	Station Name	Source	Lat.	Long.	PGA	PGV	MMI	a_0	I_{JMA}	I_{MM}
20	Long Beach Recreation Park	CSMIP	33.778	-118.133	57.2	5.5	6	30.2	3.9	4.6
21	Leona Valley #5 Ritter Ranch	CSMIP	34.600	-118.241	51.2	2.6	5	19.1	3.5	3.9
22	Leona Valley #6	CSMIP	34.604	-118.244	47.3	1.9	5	15.1	3.3	3.5
23	Malibu Point Dume School	CSMIP	34.077	-118.800	46.3	2.4	4	19.1	3.5	3.9
24	Moorpark Ventura Co. Fire Dpt. Garage	CSMIP	34.288	-118.881	47.2	3.1	5	19.1	3.5	3.9
25	MT. Wilson Caltech Seismic Station	CSMIP	34.224	-118.057	171.0	4.2	5	42.7	4.2	5.2
26	Newhall La County Fire Station	CSMIP	34.390	-118.530	57.2	3.7	4	24.0	3.7	4.3
27	Pacoima Kagel Canyon	CSMIP	34.288	-118.375	155.0	7.8	5	53.7	4.4	5.6
28	Pomona 4th & Locust	CSMIP	34.056	-117.748	68.4	2.4	5	21.4	3.6	4.1
29	Rancho Cucamonga Law & Justice Cnt.	CSMIP	34.104	-117.574	55.4	1.4	5	13.5	3.2	3.3
30	Riverside Airport	CSMIP	33.951	-117.446	56.8	1.3	5	13.5	3.2	3.3
31	Rosamond Godde Ranch	CSMIP	34.827	-118.265	73.8	3.6	4	30.2	3.9	4.6
32	Sylmar Olive View Medical Center	CSMIP	34.326	-118.444	55.8	4.0	4	30.2	3.9	4.6
33	Vasquez Rocks Park	CSMIP	34.490	-118.320	61.7	2.2	5	19.1	3.5	3.9

$$I_{MM} = 3.93 \log a_0 - 1.17 \tag{6}$$

where a_0 is the reference vectoral acceleration value that is obtained during the computation of I_{JMA}.

In order to estimate the MMI from I_{JMA}, the linear relation between the USGS MMI and the I_{JMA} for a limited range of MMI (IV $\leqslant$ MMI $\leqslant$ VIII) is obtained (Figure 5) in Equation 7.

$$I_{MM} = 1.95 I_{JMA} - 2.91 \tag{7}$$

Table 2 lists the station name, data source, location of each station, and larger of the peak acceleration and peak velocity values of the two horizontal components (PGA_L, PGV_L). Also listed are the USGS MMI for the 1994 Northridge earthquake (EQE 1995), the 1989 Loma Prieta earthquake (Wald et al. 1999a), and the 1987 Whittier Narrows earthquake (Wald et al. 1999a). The value of a_0 calculated in the I_{JMA} procedure, the I_{JMA} intensity values, and the corresponding proposed instrumental seismic intensity (I_{MM}), obtained using Equation 6, are also given.

RESULTS AND DISCUSSIONS

As the accuracy of MM intensities are based on observations throughout a community with an area of several square kilometers and as there is no clear association with strong motion values, it is difficult to accurately determine the correlation of MMI with ground acceleration. Through the calculation of I_{JMA}, however, we are able to derive a relationship between MMI and geometric average value of the a_0. To derive such a relation, we utilized the MMI value reported closest to the corresponding station.

In the Northridge earthquake, the largest JMA seismic intensity (I_{JMA}) of 6.3 was recorded at the Sylmar County Hospital station having a PGA_L value of 826.8 cm/s^2, a

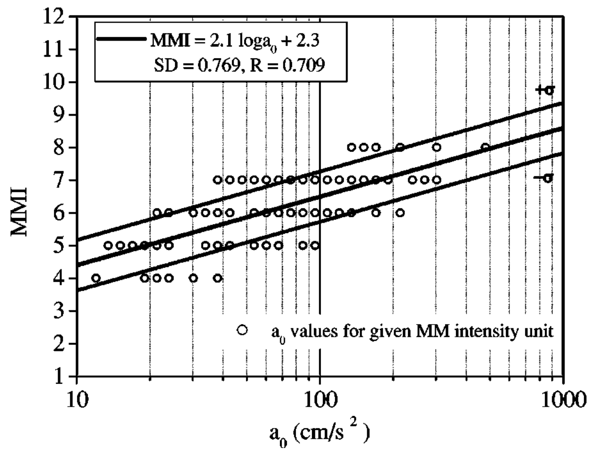

Figure 3. The linear relation between MMI and a_0 in cm/s^2 (thick line) for the three California earthquakes. Thin lines denote the boundaries of both plus and minus one standard deviations. Open circles are the calculated a_0 values.

PGV_L value of 128.9 cm/s, and an epicentral distance of 16 km (Table 2). The second largest value of the I_{JMA} of 6.3 was recorded during the same earthquake at the Newhall Los Angeles County Fire station, with a PGA_L value of 578.2 cm/s^2, a PGV_L value of 94.7 cm/s, and an epicentral distance of 20 km. Using the relation between the a_0 and the I_{MM} denoted by Equation 6, the I_{MM} value was determined to be 9.4 for both of the above stations.

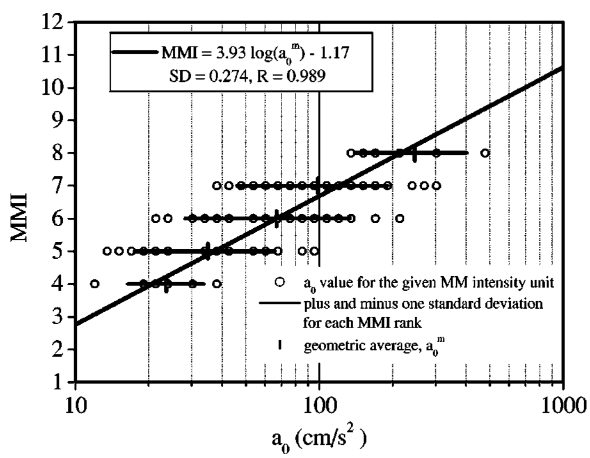

Figure 4. The linear relation between MMI and the geometric mean of a_0 in cm/s^2 for the three California earthquakes. The bars represent the geometric average of a_0 for a given MMI unit. Horizontal lines show the range of mean plus or minus one standard deviation for each MMI rank. Open circles denote the a_0 values.

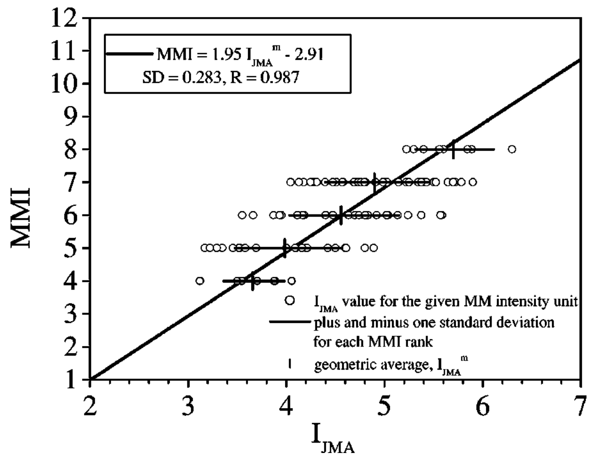

Figure 5. The linear relation between the MMI and the I_{JMA}. The bars represent the geometric average of I_{JMA} for a given MMI unit. Horizontal lines show the range of mean plus or minus one standard deviation for each MMI rank. Open circles denote the I_{JMA} values.

In the 1989 Loma Prieta earthquake, the largest JMA seismic intensity (I_{JMA}) of 5.9 was recorded at both the Corralitos-Eureka Canyon and Hollister-South Street/Pine Drive stations, with PGA_L values of 617.7 cm/s^2 and 362.0 cm/s^2, PGV_L values of 55.2 cm/s and 62.8 cm/s, and epicentral distances of 7 km and 48 km, respectively. We determined the proposed instrumental seismic intensity (I_{MM}) to be 8.6 for these two stations.

In the 1987 Whittier Narrows earthquake, the largest JMA seismic intensity (I_{JMA}) is 5.3, recorded at the Downey County Maintenance Building. This reading had a PGA_L value of 193.0 cm/s^2 and a PGV_L value of 28.9 cm/s. The next largest I_{JMA} value was

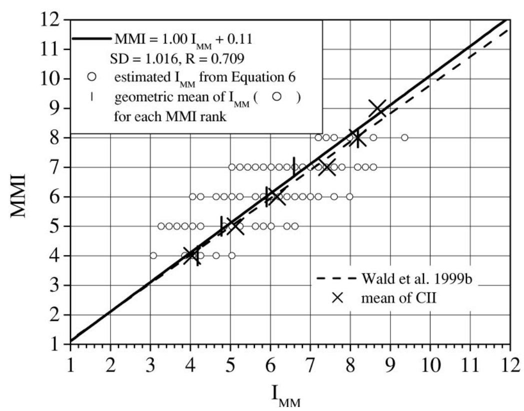

Figure 6. The linear relation between MMI and the proposed I_{MM} seismic intensity (solid line) for the three California earthquakes. The dashed and solid lines compare the USGS MMI and CII system (dash line) of Wald, Dengler, and Dewey (1999).

5.2, obtained at the Los Angeles, Obregon Park and Alhambra Fremont School stations, with PGA_L values of 420.0 cm/s^2 and 374.0 cm/s^2 and PGV_L values of 21.8 cm/s and 21.7 cm/s, respectively. The I_{MM} values determined were 7.4 for the Downey County Maintenance Building station and 7.2 for the other two stations.

Figure 6 details the relation between the estimated I_{MM} values (Table 2) and reported USGS MMI values. Equation 8 expresses the linear relation between the proposed intensity (I_{MM}), calculated from Equation 6, and the USGS MM intensity for the limited range of USGS MMI. The Wald, Dengler, and Dewey (1999) CII-mapping method recently correlated the CII of the Northridge, the Whittier Narrows, and the Sierra Madre earthquakes with the USGS MMI and corresponding MM intensity values for events in California of small to moderate magnitude using the TriNet ShakeMaps instrumental intensity method (Wald et al. 1999b). The results of our study (Figure 6, solid line) are in good agreement with the results of Wald, Dengler, and Dewey (1999) (Figure 6, dashed line). We find that the geometric mean of proposed I_{MM} values correlate well with the USGS MM intensities, especially within the given range of MMI (IV $\leqslant$ MMI $\leqslant$ VIII). As I_{MM}, obtained by Equation 6, corresponds to an instrumental seismic intensity at one point, a wide range variation in this value is observed (Figure 6). This variation might result from local site conditions and spatial radiation patterns from the source to the stations

$$MMI = 1.00 I_{MM} + 0.11 \ (\sigma = 1.016, R = 0.709) \tag{8}$$

CONCLUSIONS

Using the JMA instrumental seismic intensity algorithm as a foundation, we propose a method to estimate the MMI from a three-component acceleration record. We obtained the JMA seismic intensity I_{JMA} from the free-field records for the January 17, 1994, Northridge earthquake, the October 17, 1989, Loma Prieta earthquake, and the October 1, 1987, Whittier Narrows earthquake. Utilizing a linear regression, we determined a new relationship between the USGS MMI and the geometric average of a_0, obtained during the computation of I_{JMA}, for a given MM intensity unit. The new instrumental seismic (I_{MM}) scale is obtained directly, using the three-component acceleration records by applying the relation, $I_{MM} = 3.93 \log a_0 - 1.17$. The relationship between I_{JMA} and MMI is derived using the current data set.

The proposed instrumental I_{MM} represents the seismic intensity of a single recording site, whereas the USGS MMI represents the damage level of a community across several square kilometers. The geometric mean of the I_{MM} values correlate well with the reported USGS MMI values, especially for intermediate to high USGS MMI values. Considering the close correlation of our data with the MMI versus CII and correspondence MMI of TriNet (Wald, Dengler, and Dewey 1999 and 1999b), the proposed instrumental seismic intensity, I_{MM}, will be useful to estimate MM intensities from three-component acceleration records.

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