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ATTENUATION OF INTENSITIES IN THE UNITED STATES

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ABSTRACT

Isoseismal maps for a number of earthquakes were analyzed to study the attenuation of intensities with distance for different regions of the United States. A graphical method for the estimation of an initial set of epicentral intensities, I_0, from the intensity-distance plot for different earthquakes was used, thus avoiding the need to equate the maximum reported or mapped intensity with I_0. The attenuation relations were derived by using an iterative least-squares fit procedure, wherein an initial approximate estimate of I_0 for each earthquake is successively improved. As a by-product, the analysis yielded improved estimates of I_0 for each earthquake. These I_0 values were used to derive empirical relations between felt area and epicentral intensities for different regions.

INTRODUCTION

Attenuation of strong ground motion is one of the most important considerations in seismic risk evaluation for the design of critical facilities. Recently, a number of accelerographs have been installed in most seismic regions of the United States. However, the lack of strong-motion records at different stations from earthquakes in large parts of the country makes it essential to understand the attenuation of intensities for a meaningful seismic risk analysis.

Both the deterministic method for the evaluation of site acceleration (for example, *Appendix A to 10 CFR, Part 100,* U.S. Atomic Energy Commission, 1973) as well as probabilistic risk analysis procedures, such as those published by Algermissen and Perkins (1976) and McGuire (1976), make use of relations developed for the attenuation of intensities with distance.

Attenuation characteristics vary from region to region. Recently, several authors, such as Brazee (1972), Cornell and Merz (1974), Howell (1974), Howell and Schultz (1975), Gupta (1976), Gupta and Nuttli (1976), Bollinger (1977), and Anderson (1978) have developed attenuation relations for various regions of the United States.

DATA

In this paper we have followed the division of the United States and southern Canada into three attenuation provinces proposed by Howell and Schultz (1975) and have considered isoseismal maps for the same earthquakes. The hypocentral parameters and other pertinent information for different earthquakes, for the three attenuation provinces, San Andreas, Cordilleran, and Eastern, are summarized in Tables 1 to 3. The left-hand column contains an identification number for each earthquake. The location of epicenters and boundaries of the attenuation provinces are shown in Figure 1.

The intensity-distance data for the central United States, defined as the region bounded by the Rocky and the Appalachian mountains, published by Gupta and Nuttli (1976) were used in this analysis. The hypocentral parameters and other pertinent data for these earthquakes are presented in Table 4 and the earthquake locations are shown in Figure 1. The maximum intensity of the December 16, 1811 earthquake, which was accompanied by large land slumps and rifts, was revised upward on the MM scale to XI by Gupta and Nuttli (1976).

TABLE 1

EARTHQUAKES SELECTED FOR THE STUDY OF SAN ANDREAS PROVINCE ATTENUATION

No.	Date	Latitude (°N)	Longitude (°W)	Location	Magnitude*		Maximum I	Graphical I_o	Calculated† I_o	Calculated‡ I_o	Area (sq. km)	Isoseismal Reference
1	18 Apr. 1906	38.0	123.0	San Francisco, CA			XI	9.29	9.39		971,000	Lawson *et al.* (1908)
2	21 Jul. 1952	35.0	119.0	Kern Co., CA	7.7	M_L PAS	XI	9.85	9.97	9.92	632,000	Murphy and Cloud (1954)
3	22 Aug. 1952	35.3	118.9	Bakersfield, CA	5.8	M_L PAS	VIII	7.32	7.51	7.51	128,000	Murphy and Cloud (1954)
4	12 Jan. 1954	35.0	119.0	Wheeler Ridge, CA	5.9	M_L PAS	VIII	7.80	7.95	7.95	160,000	Murphy and Cloud (1956)
5	25 Apr. 1954	36.9	121.7	Watsonville, CA	$5\frac{1}{4}$	M_L BRK	VIII	7.05	7.24	7.24	50,000	Murphy and Cloud (1956)
6	4 Sept. 1955	37.4	121.8	San Jose, CA	5.8	M_L BRK	VII	7.45	7.61	7.61	69,000	Murphy and Cloud (1957)
7	23 Oct. 1955	38.0	122.1	Walnut Creek, CA	5.4	M_L BRK	VII	7.25	7.49	7.50	43,000	Murphy and Cloud (1957)
8	16 Dec. 1955	33.0	115.5	Brawley, CA	5.4	M_L PAS	VII	7.04	7.23	7.23	34,000	Murphy and Cloud (1957)
9	8 Apr. 1961	36.7	121.3	Hollister, CA	5.6	M_L BRK	VII	7.48	7.71	7.72	44,000	Lander and Cloud (1963)
10	27 Jun. 1966	35.9	120.9	Parkfield, CA	5.3	m_b	VII	7.45	7.68	7.68	78,000	Von Hake and Cloud (1968)

* In the magnitude column the references are abbreviated as, PAS—California Institute of Technology, Pasadena; BRK—Seismographic Station, University of California, Berkeley. M_L is local magnitude and m_b is body-wave magnitude determined by the USGS.

† Obtained as a by-product in the derivation of equation (3).

‡ Obtained as a by-product in the derivation of equation (4).

TABLE 2

EARTHQUAKES SELECTED FOR THE STUDY OF CORDILLERAN PROVINCE ATTENUATION

No	Date	Latitude (°N)	Longitude (°W)	Location	Magnitude*		Maximum I	Graphical I_o	Calculated† I_o	Calculated‡ I_o	Area (sq. km)	Isoseismal Reference
1	18 Oct. 1935	46.6	112.0	Helena, MT	$6\frac{1}{4}$	PAS	VIII	7.28	7.44		569,000	Neumann (1935)
2	14 Feb. 1946	47.3	122.9	Puget Sound, WA	$5\frac{3}{4}$	PAS	VII	7.34	7.50	7.50	484,000	Barkdale and Coombs (1946)
3	14 Dec. 1950	40.1	120.1	Herlong, CA	5.6	PAS	VII	6.82	6.95	6.93	85,000	Murphy and Ulrich (1952)
4	15 May 1954	47.4	122.3	Puget Sound, WA			VI	6.61	6.76		62,000	Murphy and Cloud (1956)
5	6 Jul. 1954	39.4	118.5	Fallon, NV	6.8	M_L BRK	IX	8.06	8.24	8.27	370,000	Cloud (1956)
6	23 Aug. 1954	39.6	118.5	Fallon, NV	6.8	M_L BRK	IX	8.20	8.36	8.40	436,000	Cloud (1956)
7	16 Dec. 1954	39.3	118.2	Dixie Valley, NV	7.2	M_L BRK	X	8.73	8.88	8.97	612,000	Murphy and Cloud (1956)
8	21 Dec. 1954	40.8	124.1	Eureka, CA	6.6	PAS	VII	7.51	7.66	7.65	241,000	Murphy and Cloud (1956)
9	17 Aug. 1959	44.8	111.1	Hebgen Lake, MT	7.1	PAS	X	9.06	9.16		1,169,000	Eppley and Cloud (1961)
10	30 Aug. 1962	41.8	111.8	Logan, UT	5.7	PAS	VII	7.25	7.44	7.41	206,000	Lander and Cloud (1964)
11	29 Apr. 1965	47.4	122.3	Puget Sound, WA	6.5	m_b	VIII	8.01	8.18	8.18	410,000	Von Hake and Cloud (1967)
12	12 Sept. 1966	39.4	120.1	Boca Dam, CA	$6\frac{1}{4}$–$6\frac{1}{2}$	PAS	VII	7.40	7.55	7.52	180,000	Von Hake and Cloud (1967)
13	4 Oct. 1967	38.5	112.1	Marysvale, UT	5.2	m_b	VII	7.03	7.16	7.12	79,000	Von Hake and Cloud (1969)

* In the magnitude column the references are abbreviated as PAS—California Institute of Technology, Pasadena; BRK—Seismographic Station, University of California, Berkeley. M_L is local magnitude and m_b is body-wave magnitude determined by the USGS. When no magnitude type, M_L or m_b, is indicated, surface-wave magnitude is assumed.

† Obtained as a by-product in the derivation of equation (5).

‡ Obtained as a by-product in the derivation of equation (6).

TABLE 3

EARTHQUAKES SELECTED FOR THE STUDY OF EASTERN PROVINCE ATTENUATION

No.	Date	Latitude (°N)	Longitude (°W)	Location	Magnitude*	Maximum I	Graphical I_o	Calculated† I_o	Calculated‡ I_o	Area (sq. km)	Isoseismal Reference
1	16 Dec. 1811	36.6	89.6	New Madrid, MO		X–XI (10.5)	11.40	11.81			Nuttli (1973)
2	22 Dec. 1875	37.6	78.5	Chesterfield Co., VA		VII	6.46	6.93		129,000	Hopper and Bollinger (1971)
3	31 Aug. 1886	32.9	80.0	Charleston, SC		X	10.04	10.22		5,180,000	Bollinger (1977)
4	1 Mar. 1925	47.6	70.1	St. Lawrence, Que.	7.0 PAS	IX	8.37	8.73	8.72		Smith (1966)
5	1 Nov. 1935	46.8	79.1	Timiskaming, Ont.	6¼ PAS	VII	7.69	8.00	8.01	2,590,000	Smith (1966)
6	19 Oct. 1939	47.8	70.0	St. Lawrence, Que.	5.6 PAS	VI	6.69	7.13	7.06		Smith (1966)
7	4 Sept. 1944	44.8	74.8	Massena, NY	5.6 PAS	VIII	7.69	8.06	8.02		Smith (1966)
8	9 Apr. 1952	35.4	97.8	El Reno, OK	5.5 PAS	VII	7.54	7.92	7.87	363,000	Murphy and Cloud (1954)

* PAS refers to surface-wave magnitude determined by the California Institute of Technology, Pasadena.

† Obtained as a by-product in the derivation of equation (7).

‡ Obtained as a by-product in the derivation of equation (8).

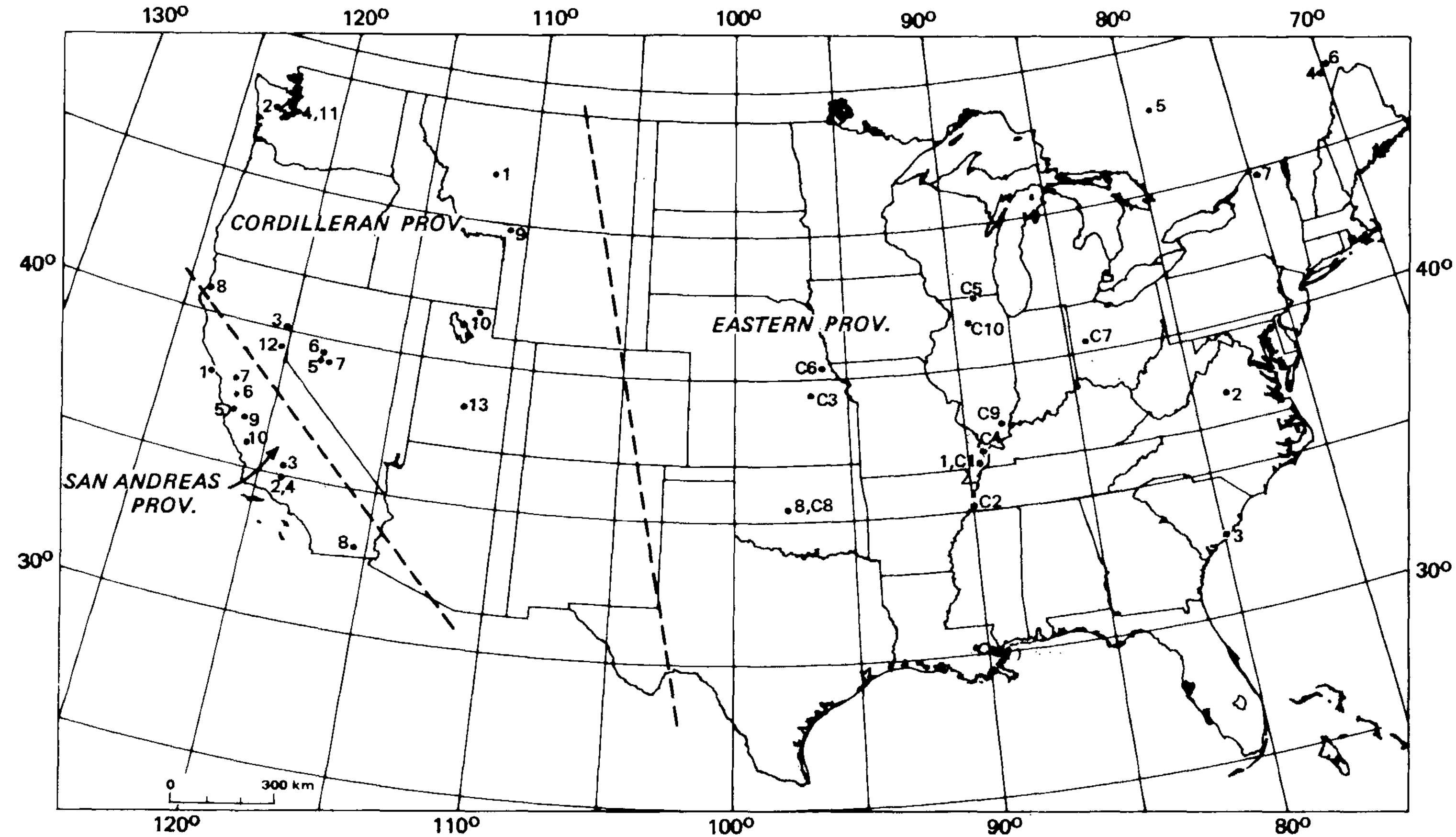


FIG. 1. Index map showing the location of earthquakes selected for the study of attenuation of intensities with distance. The country is broadly divided into three attenuation provinces, viz., San Andreas, Cordilleran, and Eastern. Earthquakes in each province are identified by numbers corresponding to those given in Tables 1 to 3. Earthquakes in the central United States (Table 4), defined as the region between the Rocky and Appalachian mountains, are identified as C1 through C10.

TABLE 4

EARTHQUAKES SELECTED FOR THE STUDY OF CENTRAL UNITED STATES ATTENUATION

No.	Date	Latitude (°N)	Longitude (°W)	Location	Magnitude*	Maximum I	Graphical I_o	Calculated† I_o	Area (sq. km)	Isoseismal References
1	16 Dec. 1811	36.6	89.6	New Madrid, MO		XI	11.20	11.34		Gupta and Nuttli (1976)
2	4 Jan. 1843	35.2	90.0	Memphis, TN		VIII	8.32	8.50	1,036,000	Nuttli (1974)
3	24 Apr. 1867	39.5	96.7	Manhattan, KS		VII	6.50	6.75	777,000	Docekal (1971)
4	31 Oct. 1895	37.0	89.4	Charleston, MO		IX	8.59	8.72	2,590,000	Nuttli (1974)
5	26 May 1909	42.5	89.0	Aurora, IL		VII	7.69	7.91	1,295,000	Docekal (1971)
6	1 Mar. 1935	40.3	96.2	Tecumseh, NE		VII	5.85	6.10	129,000	Docekal (1971)
7	8 Mar. 1937	40.4	84.2	Anna, OH	5.5 PAS	VII–VIII (7.5)	6.63	6.84	388,000	Docekal (1971)
8	9 Apr. 1952	35.4	97.8	El Reno, OK	5.5 PAS	VII	7.53	7.74	363,000	Murphy and Cloud (1954)
9	9 Nov. 1968	38.0	88.5	Southern Illinois	5.3 m_b	VII	6.99	7.26	1,502,000	Gordon *et al.* (1970)
10	15 Sept. 1972	41.6	89.4	Northern Illinois	3.7 m_b	VI	5.88	6.21	650,000	Heigold (1972)

* PAS refers to surface-wave magnitude determined by the California Institute of Technology, Pasadena; m_b is body-wave magnitude determined by the USGS.
† Obtained as a by-product in the derivation of equation (9).

Most of the central United States region, defined by Gupta and Nuttli (1976), is part of the Eastern province defined by Howell and Schultz (1975).

ANALYSIS

Recently, several authors have published empirical attenuation relations of the form

$$I(R) - I_0 = a + bR + c \log R \tag{1}$$

where $I(R)$ is the intensity at a distance R from the epicenter of an earthquake of epicentral intensity I_0, and a, b, and c are constants appropriate to the region under consideration.

Because of the constant term a in this equation, the level of the attenuation curve is quite sensitive to the initial I_0 set selected for the analysis. The empirical relation will show a high rate of attenuation if the initial I_0 set contains systematically high values of I_0 for different earthquakes, and a low rate of attenuation if the initial I_0 set contains systematically low values of I_0. The problem arises when one is limited to using maximum reported intensities in integral values (or bi-integral values, e.g., VII to VIII) for I_0. Systematically low value is obtained when maximum isoseismal intensity is equated to the epicentral intensity. In this paper, we overcome the problem by using a graphical method, described below, for the estimation of the I_0 set from an intensity-distance plot for different earthquakes.

Also, the above equation is valid only in the far field. It becomes singular at the epicenter and shows attenuation only at some distance away from the epicenter. For seismic risk analysis at smaller distances, an assumption of no attenuation is ordinarily made. This problem may be avoided by replacing R by $R + D$, where D is a suitably chosen constant, and then applying the constraint $I(R) = I_0$ at $R = 0$. With this constraint, equation (1) may be written as

$$I(R) - I_0 = bR + c \log (1 + R/D). \tag{2}$$

The above change removes the singularity at $R = 0$ in recognition of the fact that the earthquake focus is always at some depth below the surface. The constant D was intuitively chosen to be equal to an approximate average focal depth for the region under consideration. The value selected for the San Andreas province was 10 km. For all other regions, the value of D was assumed equal to 25 km.

Estimation of I_0 set. Our approach for the estimation of a graphical I_0 set from an intensity-distance plot was presented in a recent paper (Chandra *et al.*, 1979). The intensity-distance plots for different regions of the United States are shown in Figures 2 through 5. Following the general parallelism of the intensity lines for different earthquakes, a smooth curve, shown by a dashed line in Figures 2 to 5, was drawn for each region. The intensities at zero distance for the dashed curves for the San Andreas province, Cordilleran province, Eastern province, and central United States are 7.6, 8.0, 7.5, and 7.3, respectively. Using the dashed curve as a reference for the region under consideration, for a particular earthquake, I_0 at each isoseismal intensity point was estimated and then averaged. For example, the three points for event 7 in Figure 2, in order of increasing distance, occur at 0.20, 0.28, and 0.57 intensity units below the intensity 7.6 (dashed) curve. Therefore, from these three points, I_0 for event 7 will be inferred as 7.40, 7.32, and 7.03, respectively, and the average I_0 will be estimated at 7.25.

For the Eastern province, the general parallelism of the different intensity curves could be followed, and a dashed curve drawn, for a distance of about 520 km (Figure 4). Accordingly, the average I_0 for event 3 was estimated by considering the four largest intensity points. The epicentral intensity of event 1 was estimated at 11.4 by reference to the first point, which occurs at 3.9 intensity units above the dashed curve, plotted in Figure 4.

For the central United States, two dashed curves were drawn (Figure 5). The first curve, from 0 to 200 km distance, was drawn by reference to the intensity curves for event 3, and events 5 through 10. The second curve, between 100 and 600 km distance, was drawn by reference to the intensity curves for events 2 and 4. The

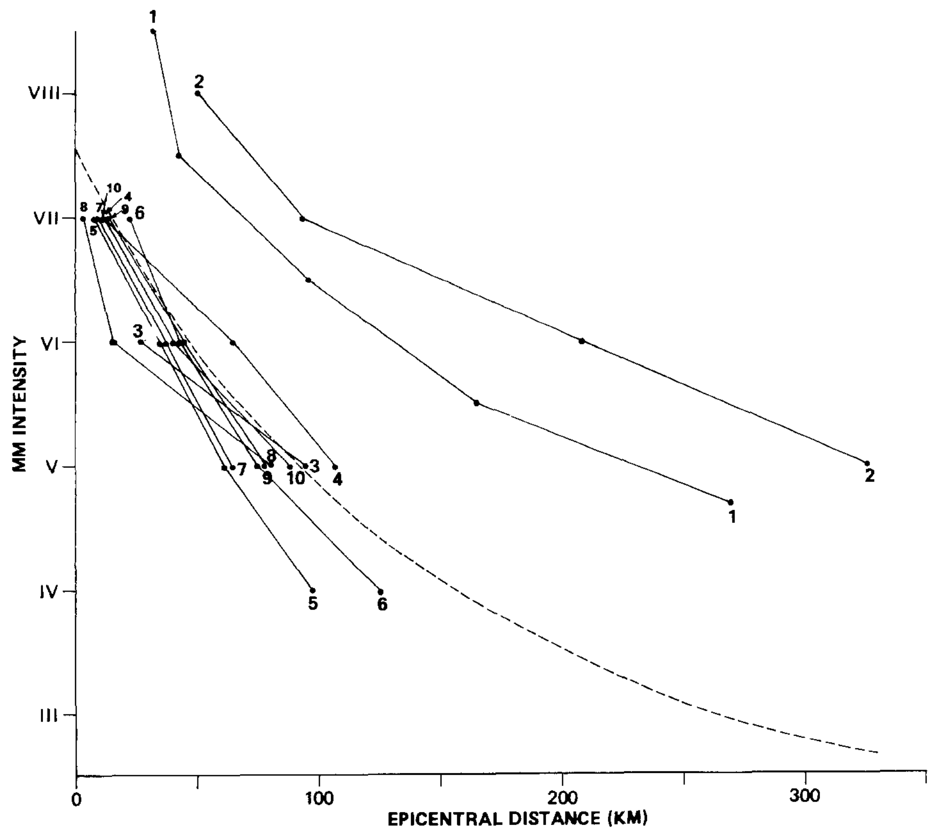


FIG. 2. Intensity-distance plot for earthquakes in the San Andreas province. The earthquake identification numbers correspond to those given in Table 1. The dashed curve is drawn by following the general parallelism of the intensity-distance curves for different earthquakes.

second curve occurs at 1.1 and 1.3 intensity units above the first dashed curve at distances 100 and 200 km, respectively. Therefore, the average epicentral intensity level for this curve was estimated at 8.5. In the estimation of epicentral intensities for events 2 through 10, the first curve was used as a reference for distances less than 200 km and the second curve was used as a reference for larger distances. The epicentral intensity of event 1 was estimated at 11.2 by reference to the first point, which occurs at 2.7 intensity units above the second dashed curve, plotted in Figure 5.

Attenuation relation. To derive an attenuation relation from the intensity-distance data for a number of earthquakes, the parameters b and c in equation (2) were

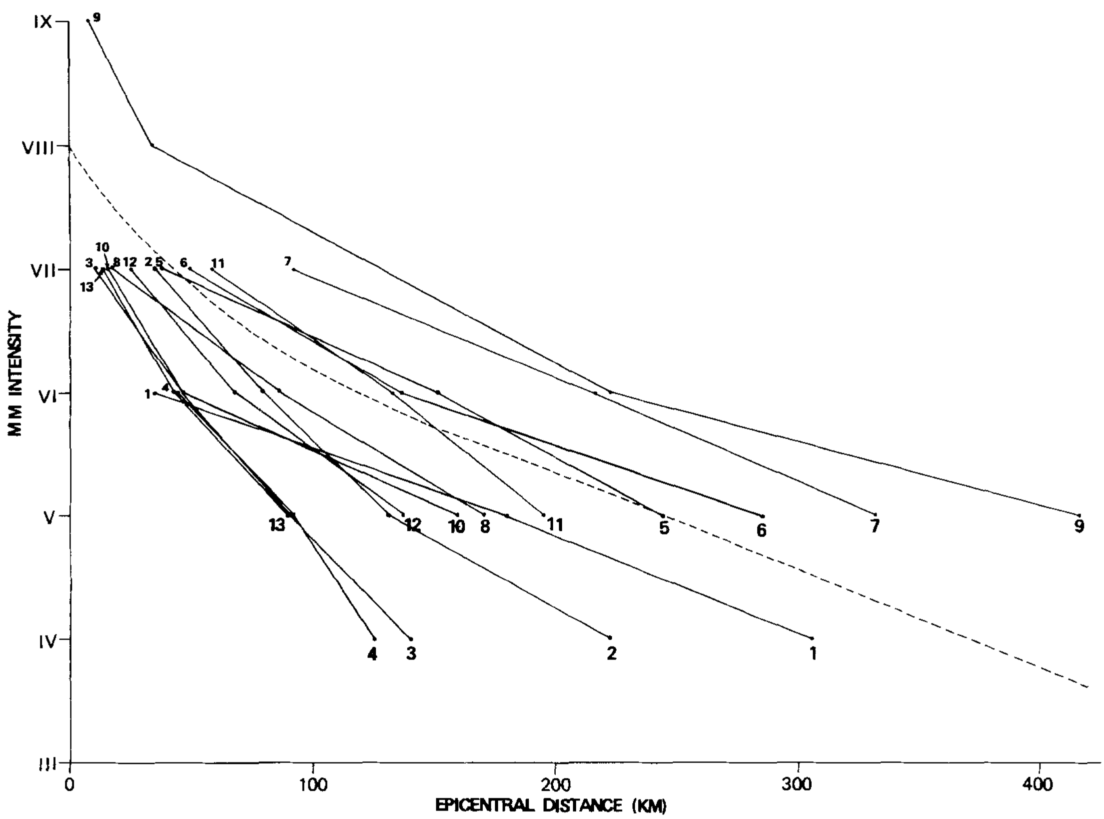


FIG. 3. Intensity-distance plot for earthquakes in the Cordilleran province. The earthquake identification numbers correspond to those given in Table 2. The dashed curve is drawn by following the general parallelism of the intensity-distance curves for different earthquakes.

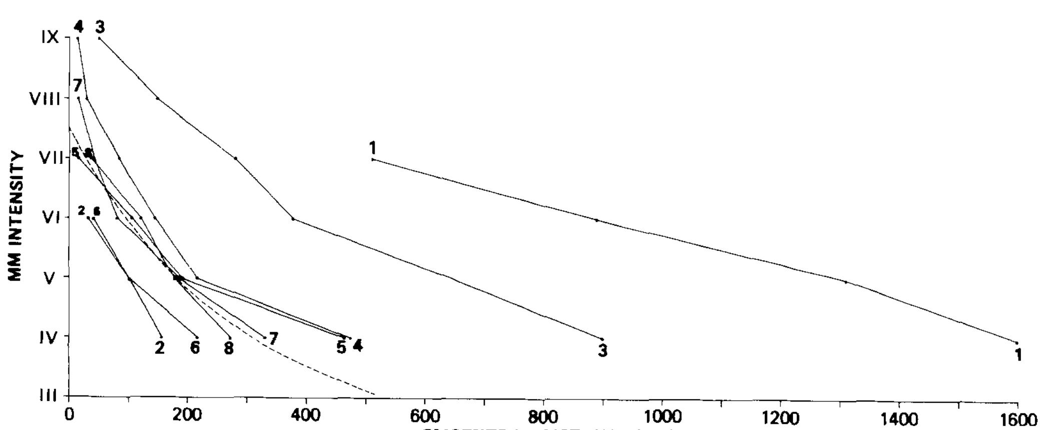


FIG. 4. Intensity-distance plot for earthquakes in the Eastern province. The earthquake identification numbers correspond to those given in Table 3. The dashed curve is drawn by following the general parallelism of the intensity-distance curves for different earthquakes.

determined by a least-squares fit between $I - I_0$ and R. The graphically estimated I_0 set was used as a first approximation. Using these values of b and c in equation (2), new average epicentral intensities for each earthquake were estimated by calculating I_0 from various isoseismal intensities and corresponding R. Using these values of I_0 for different earthquakes, revised values of b and c were derived by a least-squares fit between $I - I_0$ and R. The procedure was repeated until no significant improvement in the standard error of $I - I_0$ in the least-squares analysis could be made.

The isoseismal map of the San Francisco earthquake of 1906 was published in the Rossi-Forel scale. The isoseismal intensities were converted to Modified Mercalli Scale by using the equivalence given by Richter (1958). Contrary to the commonly held belief that the 1906 earthquake was the largest earthquake of this century in California, its graphically estimated epicentral intensity is about $\frac{1}{2}$ unit smaller than the Kern County earthquake of 1952. It is possible that the Rossi-Forel intensities VIII and below, which led to a low estimate of I_0 for the 1906 earthquake, were felt over a much larger area than depicted on the isoseismal map published by Lawson *et al.* (1908). Therefore, in order to examine the difference and its significance, we have considered in this study the San Andreas province attenuation both with and without the data for the 1906 earthquake.

In deriving the attenuation relations, Howell and Schultz (1975) did not use data

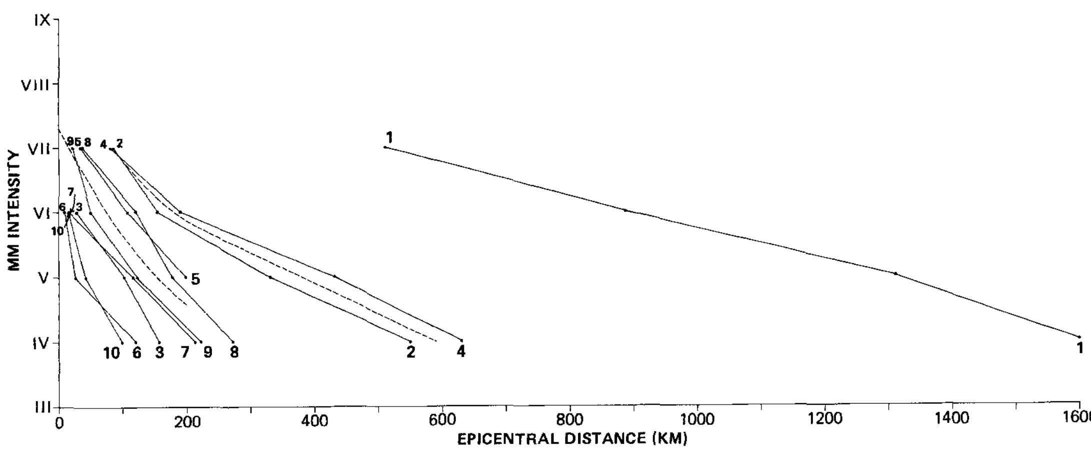


FIG. 5. Intensity-distance plot for earthquakes in the central United States. The earthquake identification numbers correspond to those given in Table 4. The general parallelism of the intensity curves for event 3 and events 5 through 10 could be followed, and the bottom dashed curve drawn, up to 200 km. The top dashed curve was drawn by reference to the intensity curves for events 2 and 4.

for three of the earthquakes in the Cordilleran province (events 1, 4, and 9) and three of the earthquakes in the Eastern province (events 1, 2, and 3). In this study, we have derived attenuation relations for both cases, with and without the data for these earthquakes.

The following attenuation relations and corresponding standard errors, σ of $I - I_0$, were obtained.

San Andreas province

$$I(R) - I_0 = 2.014 - 0.00659\,R - 2.014 \log (R + 10)$$

$$\sigma = 0.274 \quad R < 330 \text{ km} \tag{3}$$

all earthquakes considered

$$I(R) - I_0 = 2.065 - 0.00594\,R - 2.065 \log (R + 10)$$

$$\sigma = 0.266 \quad R < 330 \text{ km} \tag{4}$$

event 1 (Table 1) not considered.

Cordilleran province

$$I(R) - I_0 = 3.203 - 0.00343\,R - 2.291 \log (R + 25)$$

$$\sigma = 0.264 \quad R < 420 \text{ km} \tag{5}$$

all earthquakes considered

$$I(R) - I_0 = 2.819 - 0.00503\,R - 2.017 \log (R + 25)$$

$$\sigma = 0.245 \quad R < 335 \text{ km} \tag{6}$$

events 1, 4, and 9 (Table 2) not considered.

Eastern province

$$I(R) - I_0 = 3.828 - 0.00177\,R - 2.739 \log (R + 25)$$

$$\sigma = 0.322 \quad R < 1600 \text{ km} \tag{7}$$

all earthquakes considered

$$I(R) - I_0 = 3.374 - 0.00312\,R - 2.414 \log (R + 25)$$

$$\sigma = 0.363 \quad R < 475 \text{ km} \tag{8}$$

events 1, 2, and 3 (Table 3) not considered.

Central United States

$$I(R) - I_0 = 3.534 - 0.00164\,R - 2.528 \log (R + 25)$$

$$\sigma = 0.243. \quad R < 1600 \text{ km} \tag{9}$$

The attenuation relations corresponding to equations (3), (5), (7), and (9) are plotted in Figure 6.

As a by-product of the analysis, this procedure yielded improved estimates of I_0 (presented in Tables 1 to 4) for each earthquake. The epicentral intensities thus derived are based on an analysis of all isoseismal contours and are, therefore, independent of the subjective judgment of assigning intensity at one observation point.

A comparison of the observed isoseismals with the attenuated intensities corresponding to equations (3), (5), (7), and (9) is made in Figures 7 through 10 by using two isoseismal maps for each attenuation province. For each earthquake, the calculated I_0 value given in Tables 1 to 4 was used to derive the radii for different intensities. The intensity contours for the San Francisco earthquake of April 18, 1906 show a strong elongation in the northwest direction. Therefore, the isoseismal map of this earthquake was not considered suitable for a comparison of the observed and calculated intensity contours derived under an assumption of azimuthal symmetry. The isoseismal lines for other earthquakes do not show such a pronounced directional effect. However, some of these isoseismals show a considerable departure from a circular shape. Also, in some cases the geometric centers of high-intensity isoseismals are different from the centers for low-intensity isoseismals. This is probably due to differences in local geological and soil conditions. Considering these problems, the general agreement between the observed isoseismals and calculated isoseismals, shown by dashed circles in Figures 7 to 10, is quite good.

Relationship between felt area and epicentral intensity. Several authors, e.g., Bollinger (1973), have proposed empirical relations of the form

$$\log A = a + bI_0 \tag{10}$$

where A is the area (in square kilometers) over which the effect of an earthquake of epicentral intensity, I_0, was felt. From an improved estimate of epicentral intensities

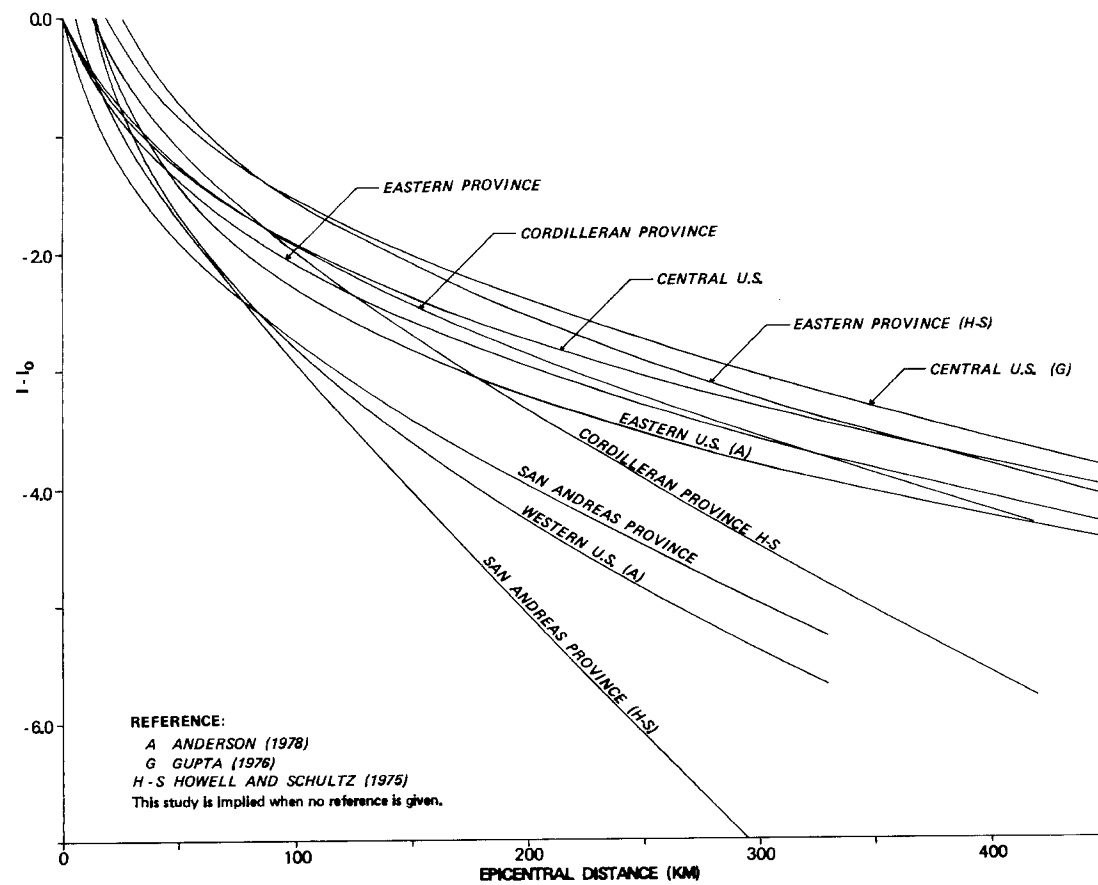
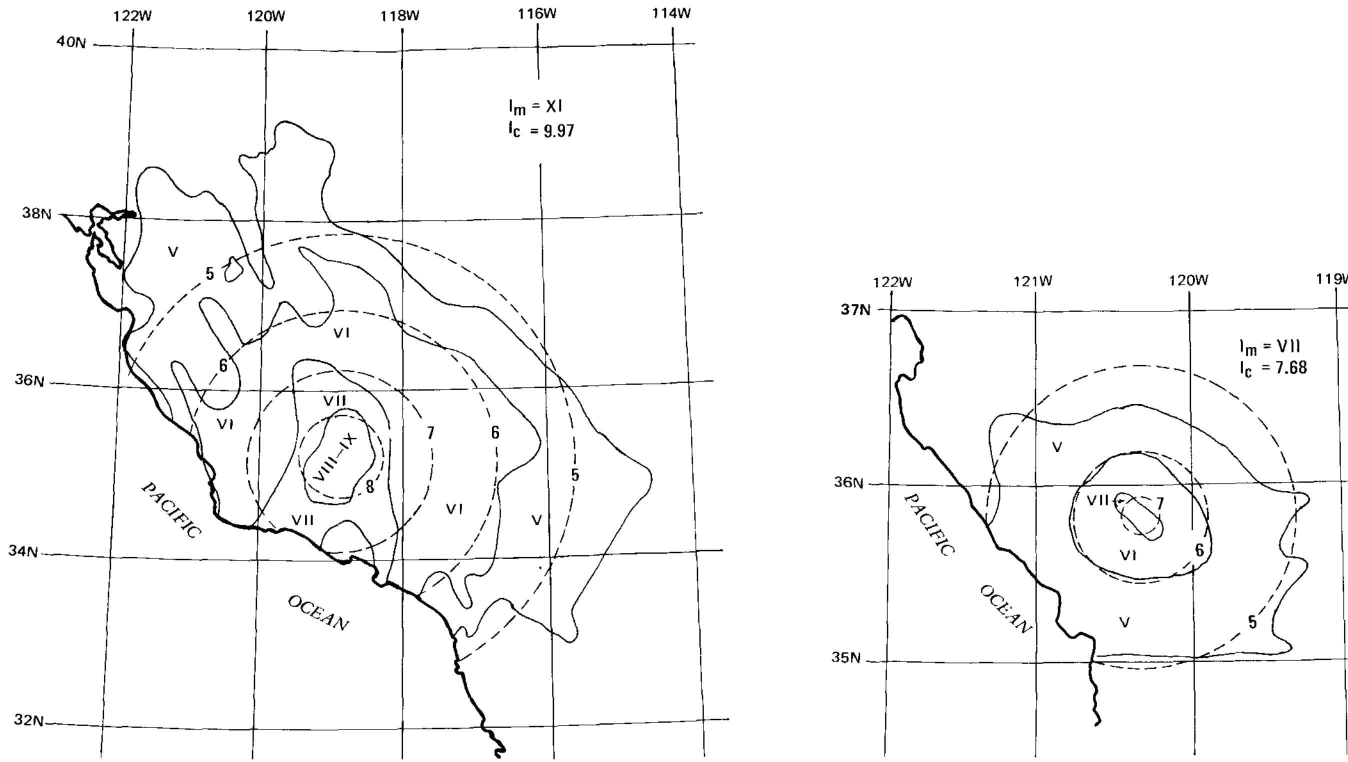


FIG. 6. Attenuation of intensities for different regions of the United States. For a comparison of the results, attenuation relations derived by some other authors are also shown.

derived in this study, it is now possible to develop correspondingly improved relations between felt area and epicentral intensity for different regions of the United States.

For the San Andreas and Cordilleran regions, the total felt area for different earthquakes was taken to be the area enclosed by the isoseismal contour defining the outer boundary of the region felt with intensity I to III or I to IV, as labeled on the isoseismal map. For the San Francisco earthquake of 1906 and for different earthquakes in the Eastern Province and central United States, the felt area information was taken from Coffman and Von Hake (1973) or from the yearly



21 JULY 1952 KERN COUNTY, CALIFORNIA — 27 JUNE 1966 PARKFIELD, CALIFORNIA

FIG. 7. Comparison of observed and calculated isoseismals (shown by dashed circles) for two earthquakes in the San Andreas province. In this figure, and in Figures 8 to 10, I_m corresponds to the maximum mapped or reported intensity and I_c corresponds to the calculated epicentral intensity.

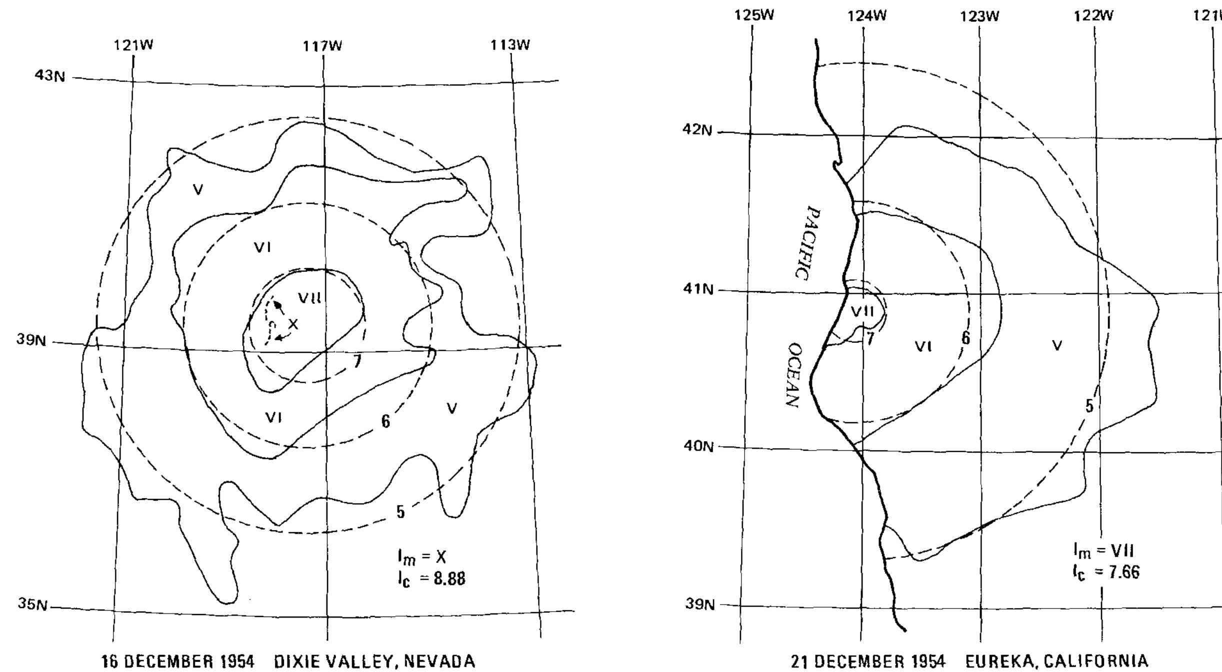


FIG. 8. Comparison of observed and calculated isoseismals (shown by dashed circles) for two earthquakes in the Cordilleran province.

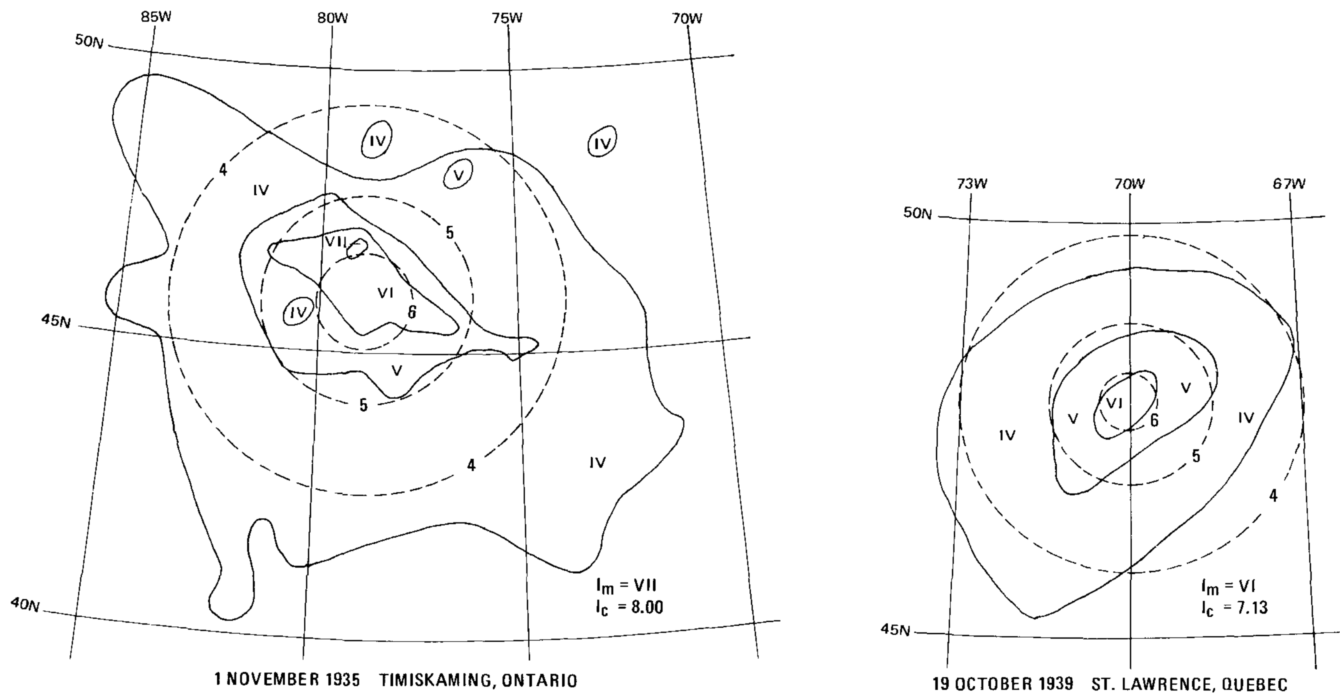


FIG. 9. Comparison of observed and calculated isoseismals (shown by dashed circles) for two earthquakes in the Eastern province.

publication of *U.S. Earthquakes* by the National Oceanic and Atmospheric Administration (NOAA).

It is observed that even though the computed epicentral intensity for the San Francisco earthquake of 1906 is smaller than that for the Kern County earthquake of 1952 (Table 1), it has a larger reported felt area. Therefore, for the San Andreas province two empirical relations were derived by a least-squares straight line fit between log A and I_0. Also, because of the presence of Atlantic Ocean toward the east and sparse population in northern Canada, a reasonably reliable estimate of the total area over which the New Madrid earthquake of 1811, St. Lawrence earthquakes of 1925 and 1935, and the Cornwall-Massena earthquake of 1944 could be felt is not available. Therefore, these earthquakes were not considered in the derivation of felt area versus epicentral intensity relationships.

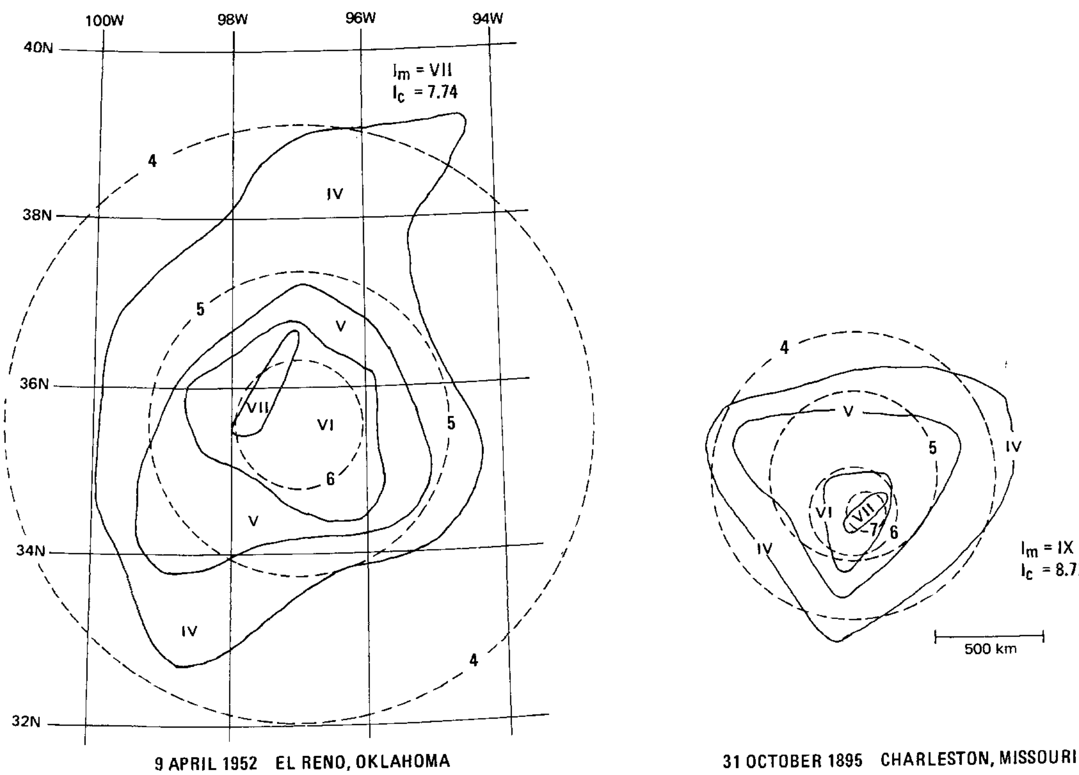


FIG. 10. Comparison of observed and calculated isoseismals (shown by dashed circles) for two earthquakes in the central United States.

The relations for different regions, along with the standard error (σ_A) of log A, are given below.

San Andreas province

$$\log A = 1.08 + 0.495\, I_0 \qquad 7.2 \leqq I_0 \leqq 10.0$$

all earthquakes considered

$$\sigma_A = 0.21 \tag{11}$$

$$\log A = 1.61 + 0.424\, I_0 \qquad 7.2 \leqq I_0 \leqq 10.0$$

$$\sigma_A = 0.19 \tag{12}$$

San Francisco earthquake of 1906 not considered.

Cordilleran province

$$\log A = 1.94 + 0.448\, I_0 \qquad 6.8 \leqq I_0 \leqq 9.2$$

$$\sigma_A = 0.22. \tag{13}$$

Eastern province

$$\log A = 2.20 + 0.453\, I_0 \qquad 6.9 \leqq I_0 \leqq 10.2$$

$$\sigma_A = 0.48. \tag{14}$$

Central United States

$$\log A = 3.76 + 0.285\, I_0 \qquad 6.1 \leqq I_0 \leqq 8.7$$

$$\sigma_A = 0.30. \tag{15}$$

A plot of log A versus I_0, for different regions, and the corresponding least-squares fitting straight lines is shown in Figure 11.

The largest standard error, $\sigma_A = 0.48$, is obtained for the Eastern province. In deriving the log A versus I_0 relationship for the Eastern province, if we ignore the point corresponding to the Timiskaming, 1935 earthquake (Figure 11), the resulting straight line will be very close to the line for the Cordilleran province. In this case, the corresponding relation is derived as

$$\log A = 1.70 + 0.490\, I_0 \qquad 6.9 \leqq I_0 \leqq 10.2$$

$$\sigma_A = 0.03. \tag{14a}$$

The straight line corresponding to the central United States region intersects the lines for other provinces at higher intensities. This is apparently due to a scatter of data points rather than due to any regional effect. The distribution of data points is such that a straight line parallel to the lines corresponding to other regions may be drawn with only a very small change in the standard error σ_A. By constraining the coefficient of I_0 to be the same as that for the Cordilleran province, the following relation is derived

$$\log A = 2.57 + 0.448\, I_0 \qquad 6.1 \leqq I_0 \leqq 8.7$$

$$\sigma_A = 0.32. \tag{15a}$$

From Figure 11, it may be concluded that for an earthquake of a given epicentral intensity, VI $\leqq I_0 \leqq X$, felt area will be maximum (and attenuation minimum) for the central United States and minimum (attenuation maximum) for the San Andreas province. The difference in felt area and attenuation between the Cordilleran and Eastern provinces is small.

Discussion

It is of some interest to compare the results derived in this study with the results presented by other investigators, who considered attenuation relations of the form given by equation (1). Some of these relations are summarized below.

$$I(R) = I_0 + 0.874 - 0.0186\,R - 0.422\ln R \tag{16}$$

San Andreas province (Howell and Schultz, 1975)

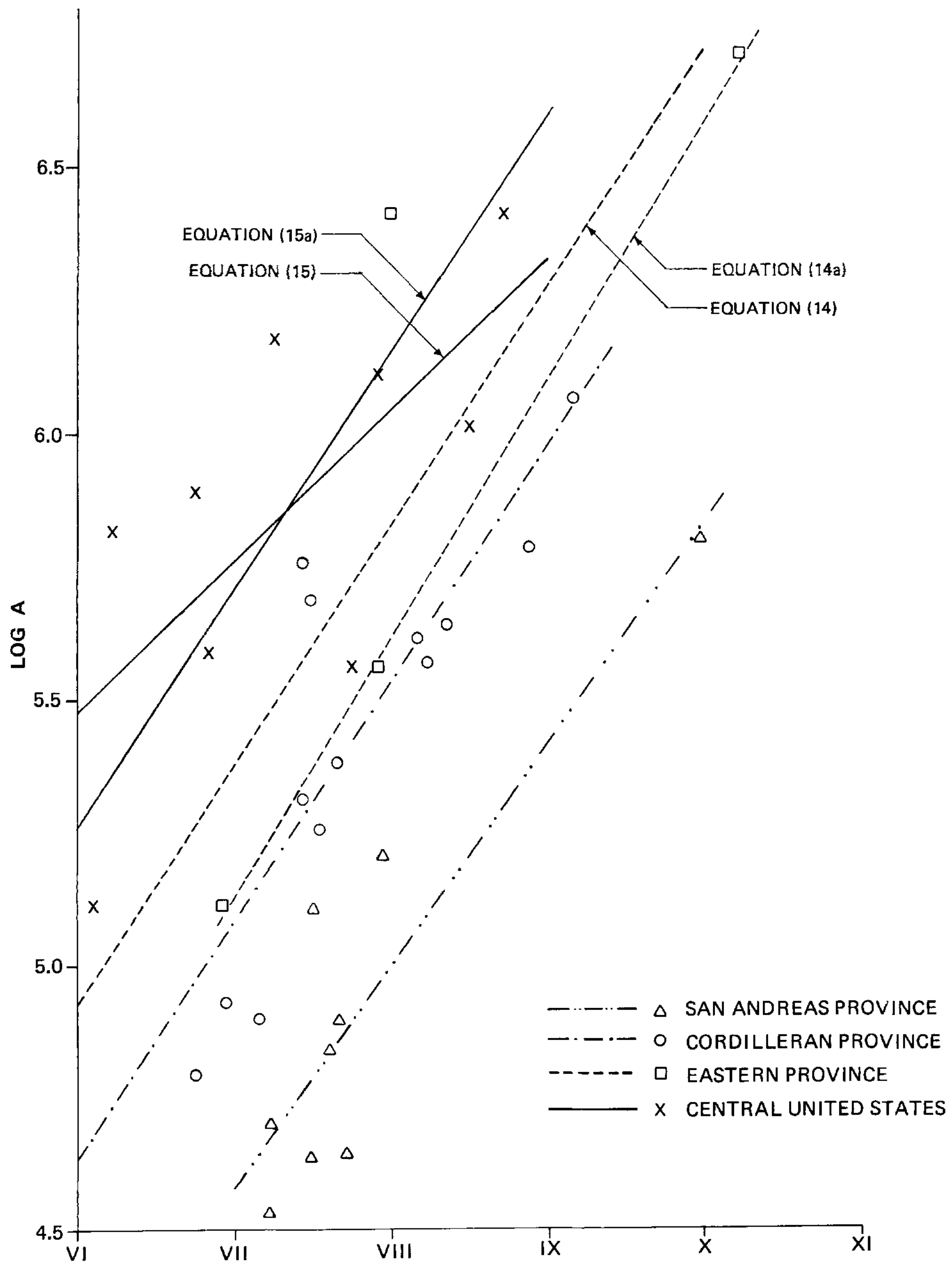


FIG. 11. Felt area-epicentral intensity relations for different regions of the United States. For each region, a least-squares straight line fit through the data points is shown.

$$I(R) = I_0 + 1.802 - 0.0090\,R - 0.628\ln R \tag{17}$$

Cordilleran province (Howell and Schultz, 1975)

$$I(R) = I_0 + 3.278 - 0.0029\,R - 0.989 \ln R \tag{18}$$

Eastern province (Howell and Schultz, 1975)

$$I(R) = I_0 + 2.35 - 0.00316\,R - 1.79 \log R \tag{19}$$

Central United States (Gupta, 1976)

$$I(R) = I_0 + 3.2 - 0.00634\,R - 2.7 \log R \tag{20}$$

Western United States (Anderson, 1978)

$$I(R) = I_0 + 3.2 - 0.00106\,R - 2.7 \log R \tag{21}$$

Eastern United States (Anderson, 1978).

The attenuation relations corresponding to equations (16) through (21) are plotted in Figure 6.

The attenuation curves derived in this study show higher attenuation at small distances and in most cases crossover the curves, at some distance, for the corresponding region derived by other investigators. This is due to a difference in the form of empirical equations to which data were fit. The constraint, $I(R) = I_0$ at $R = 0$, used in this study was not applied by other investigators. Therefore, in the following discussion, unless otherwise stated, the comparison of attenuation refers to distances beyond the crossover point.

San Andreas province. The two attenuation relations, given by equations (5) and (6), for the San Andreas province are quite close to each other. The difference between the two relations is 0.12 intensity unit at 300 km and decreases at smaller distances. For distances less than 100 km, the curves corresponding to the two equations are practically indistinguishable.

The San Andreas province attenuation derived by Howell and Schultz (1975) is much more rapid than the attenuation derived in this study. Anderson (1978) obtained a somewhat more rapid attenuation for the western United States than this study. The high rate of attenuation obtained by Howell and Schultz (1975) is obviously an outcome of the use of large I_0 values for the San Francisco, 1906 and Kern County, 1952 earthquakes. Although the data set considered was different, probably a similar reason also applies for the attenuation relation obtained by Anderson (1978).

Cordilleran province. The Cordilleran province attenuation relations (5) and (6) are fairly close to each other. The curves corresponding to the two equations crossover at a distance of about 150 km, beyond which equation (6) shows a slightly more rapid attenuation. At distances less than 150 km, the maximum difference in attenuation represented by the two equations is 0.05 intensity units and occurs at about 50 km. At a distance of 300 km, the difference in attenuation is 0.18 intensity units.

Howell and Schultz (1975) obtained a more rapid attenuation than derived in this study. This difference appears to be due to large reported maximum (or epicentral) intensities for the Dixie Valley, December 16, 1954; Fallon, July 6, 1954; and Fallon, August 23, 1954 earthquakes. For each of these earthquakes, the assignment of maximum intensities was based on the observation of ground rupture. It seems that the intensities based mainly on geological effects, such as surface faulting, may be overrated on the Modified Mercalli Scale.

Eastern province. The attenuations indicated by equations (7) and (8) are quite close to each other. The curves corresponding to the two equations crossover at a distance of about 250 km, below which the difference remains less than 0.1 intensity unit. At larger distances, equation (8) shows slightly higher attenuation. The difference at 500 km is 0.24. Four of the five earthquakes, for which data were considered in the derivation of equation (8), occurred in the northeast, close to the St. Lawrence River Valley. It seems that the attenuation near the border region of northeast United States and southern Canada is somewhat larger than the attenuation for the central United States. This inference is reinforced when a comparison is made with the attenuation represented by equation (9), which is derived only from the central United States earthquake data.

The Eastern province attenuation curve, corresponding to equation (18), derived by Howell and Schultz (1975) is nearly parallel to the curve corresponding to equation (8), and shows about 0.4 unit smaller attenuation. The computed epicentral intensities (Table 1) for the Timiskaming, 1935; St. Lawrence, 1939; and El Reno, 1952 earthquakes are almost one unit higher than the maximum reported intensities. This explains the smaller rate of attenuation obtained by Howell and Schultz (1975), who treated the maximum reported intensities, I_m, as I_0.

Central United States. Equation (9) shows a slightly higher attenuation than the attenuation derived by Gupta (1976) at distances less than about 600 km, and lower attenuation at larger distances. The computed epicentral intensities (Table 4) have higher values than maximum reported intensities for seven earthquakes and lower values for three earthquakes. The epicentral intensity of the New Madrid earthquake of December 16, 1811 is estimated at 11.34.

Equation (21), derived by Anderson (1978) for the Eastern United States, shows a somewhat larger attenuation than those obtained by Howell and Schultz (1975), Gupta (1976), or this study. Equation (21) is the same as the attenuation relation presented by Gupta and Nuttli (1976), except that the value of the constant term obtained by Gupta and Nuttli (1976) was 3.7 instead of 3.2.

Conclusions

The attenuation of intensities in the United States is maximum for the San Andreas province and minimum for the central United States. The difference in attenuation for the Cordilleran province and St. Lawrence Valley region is small, although the attenuation for these two regions is slightly more rapid than it is for the central United States.

A significant reduction in the scatter of data is accomplished by using a graphical method for the estimation of epicentral intensities. Improved estimates of epicentral intensities for different earthquakes are obtained as a by- product of the iterative least-squares analysis for the derivation of attenuation relation.

Several examples indicate that intensities based on surface faulting and other geological effects may be overestimated.

The felt area versus epicentral intensity relations, derived in this study, provide a means of estimating the epicentral intensities of historical earthquakes from the extent of area over which they were reported felt.

The attenuation relations are sensitive to the values of I_0 used in their derivation. In practical application of the relations developed in this paper, a reevaluation of epicentral intensities for earthquakes of significance to the seismic design of critical facilities is recommended.

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