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ATTENUATION OF MODIFIED MERCALLI INTENSITY WITH DISTANCE IN MEXICO

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ABSTRACT

Two relations are proposed to predict the attenuation of Modified Mercalli Intensity (I) with distance (D) for Mexican earthquakes, i.e.

$$\ln I = B_0 + B_1 \ln (D/D') + B_2 (D-D') + B_3 \ln M_s$$

$$\ln I = B_0 + B_1 (D/D') + B_2 \ln (D-D') + B_3 \ln M_s$$

M_s is the earthquake surface-wave magnitude, D' is a distance related to the maximum I mapped for an earthquake, I' or to M_s. The coefficients B_i, $i = 0, 1, 2, 3$ were obtained by fitting in a least-square sense the information contained in the intensity maps of 32 events to the relations. Those events were classified in three groups according to their epicentral location, focal mechanism, and depth, i.e., events related to the subduction-zone intermediate-depth earthquakes in south-central Mexico and to shallow crustal events along the Trans-Mexican Volcanic Belt.

The I predicted by the proposed relations compare well with the I observed for historical earthquakes not included in the fitting. Results obtained from a parametrical study showed that the attenuation of I with D is different for each of the three types of earthquakes. For distances of less than about 200 km, the earthquakes associated with the subduction zone have a larger attenuation than the ones originating in the south-central region of Mexico; for greater distances ($D > 200$ km), the opposite behavior is observed. The events located in the Trans-Mexican Volcanic Belt have a larger attenuation with distance than that of events in the other two regions. From these results, it seems advisable in Mexico to use several attenuation relations to estimate the seismic hazard at a site, depending on the particular tectonic setting and the path of the events under consideration.

INTRODUCTION

To perform seismic hazard analysis it is necessary to use attenuation relations (Esteva and Chávez, 1982) which relate seismological data with parameters of engineering interest, such as peak ground accelerations, velocities, or response spectral ordinates. This practice implies that instrumental records of ground motions covering reasonable time spans are available for the region of interest. However, for many seismic regions of the world this information is scarce or nonexistent, and use has to be made of Modified Mercalli Intensity (I) maps of historical earthquakes in the region. With this information, attenuation relations of I with distance can be obtained (e.g., Howell and Schultz, 1975), and combining those with ground-motion-to-intensity (I) correlations from regions with abundant data, one can estimate the seismic ground motions parameters for the region of interest (e.g., McGuire, 1984). The situation just mentioned is typical of most of the Mexican territory, therefore the objective of this paper is to address the first part of the problem, i.e., to study the attenuation of I with epicentral distance (D) and surface-wave magnitude (M_s) for Mexican earthquakes. The second part of the problem will be presented elsewhere.

TABLE 1

Seismic Events Included in the Study

No.	Date	Latitude (°N)	Longitude (°W)	Depth (km)	I_o	I'	D' (km)	M_s	Group
1	4/7/1845	16.60	99.20		9 (+)	9	58.68	7.9	1
2	6/19/1858	19.60	101.60		8 (+)	9	41.72	7.5	2
3	10/3/1864	18.70	97.40		9 (+)	9	35.26	7.3	3
4	5/11/1870	15.80	96.70		9 (+)	9	49.87	7.9	1
5	2/11/1875	21.00	103.80		10 (+)	10	22.30	7.5	2
6	6/19/1882	17.70	98.20		7 (+)	9	41.72	7.5	2
7	5/3/1887	31.00	109.20		11 (+)	11	24.19	7.3	
8	6/5/1897	16.30	95.40		9 (+)	9	24.19	7.4	1
9	1/16/1902	17.62	99.72		7	8	24.19	7.0	2
10	9/23/1902	16.58	92.58	100	10	10	17.11	7.8	2
11	3/26/1908	17.00	101.00	S	7	10	34.21	7.2	1
12	7/30/1909	16.80	99.90	S	9	9	66.20	7.6	1
13	7/31/1909	16.62	99.95	S	9	9	45.23	6.4	1
14	9/5/1909	16.53	99.72		8	8	63.79	6.6	1
15	10/31/1909	17.00	101.20	S	9	9	80.08	6.9	1
16	5/31/1910	16.70	99.20	S	8	8	39.78	6.9	1
17	2/3/1911	18.20	96.36	80	7	10	27.53	7.25	2
18	6/7/1911	19.70	103.70	S	8	10	24.19	7.9	1
19	8/27/1911	16.77	95.90	80	8	8	47.31	6.7	2
20	12/16/1911	16.90	100.70	50	9	9	46.85	7.6	1
21	11/19/1912	19.93	99.83	5–15	10	10	11.62	7.0	3
22	1/3/1920	19.27	96.97	15	9	10	10.19	6.25	3
23	2/9/1928	17.98	97.88	84	6	9	17.40	7.7	2
24	3/21/1928	16.23	95.45	S	10	10	44.62	7.7	1
25	4/16/1928	17.29	96.55	115	9	10	24.61	6.7	2
26	6/17/1928	16.33	96.70	S	9	9	24.19	8.0	1
27	8/4/1928	16.83	97.61	20	8	9	34.21	7.4	1
28	4/15/1941	18.85	102.94	S	10	10	96.04	7.9	1
29	11/9/1956	16.97	94.48	150	8	8	101.46	6.5	2
30	7/28/1957	17.11	99.10	S	9	9	80.08	7.7	1
31	5/24/1959	17.35	97.26	80	8	9	24.61	6.8	2
32	8/26/1959	18.45	94.27	21	8	8	78.92	6.5	3
33	8/23/1965	16.30	95.80	16	9	9	47.25	7.8	1
34	3/11/1967	18.99	95.94	26	8	8	18.79	5.7	3
35	8/2/1968	16.59	97.70	16	8	8	28.93	7.4	1
36	9/25/1968	15.57	92.64	138	7 (+)	8	56.87	6.0	2
37	4/29/1970	14.45	92.71	22	5 (+)	7	8.29	7.2	2
38	1/31/1973	18.39	103.21	32	7	8	31.06	7.5	1
39	8/28/1973	18.00	96.55	80	8	8	74.45	6.8	2
40	11/29/1978	16.00	96.69	19	7	8	71.39	7.8	1
41	3/11/1979	17.46	101.46	15	8	8	134.08	7.6	1
42	10/24/1980	18.21	98.24	65	9	9	56.87	7.0	2

References and Notes for the List of Seismic Events

I_0, I', D', M_s as defined in Text

S Superficial depth

(+) Event not used in the regressions

References for isoseismic maps: Events 4, 8, 17, 19, 23, 24, 25, 26, 27, 29, 31, 33, 35 from Figueroa (1975); 2, 7, 9, 10, 11, 12, 13, 15, 20, 21, 30, 32 from Figueroa (1963); 1, 3, 6, 22, 34, 39 from Figueroa (1974b); 18, 28, 38 from Figueroa (1974a); 14, 16 from Figueroa (1971); 36, 37 from Figueroa (1973); 40, 41, 42 from Figueroa (1981, 1980a, 1980b)

References for location: Events 1, 2, 3, 4, 5, 6, 7, 8, 37, 38 from Singh *et al.* (1981); 9, 10, 12, 14, 17, 18, 19, 21, 29, 32 from Figueroa (1970); 13, 15, 16, 20, 22, 26, 40, 41 from Singh *et al.* (1984a); 24, 27, 28, 30 from Kelleher *et al.* (1973); 23, 25, 31 from Núñez (1983); 33, 35 from Chael *et al.* (1982); 11, 34, 36,

ATTENUATION RELATIONS

The attenuation relations which are analyzed in this paper take as a departure point those proposed by Howell and Schultz (1975). Those relations are based on the following assumptions: 1) the seismic energy generated during an earthquake is radiated from a point source through a space of simple geometry; 2) the Modified Mercalli Intensity, I, is proportional to the logarithm of the seismic energy density; 3) the seismic energy density diminishes exponentially with distance to the source. The expressions suggested by those authors are of the form

$$I = e^{B_0} D^{-B_1} e^{-B_2 D} I'^{B_3} \tag{1}$$

I' is the maximum intensity mapped for an earthquake, D is the epicentral distance and the B_i's, $i = 0, 1, 2, 3$ are coefficients related to the source, the geometric spreading, and the anelastic attenuation of the media, respectively. Howell and Schultz (1975) also proposed other equations which included a parameter D', related to the area of the I' isoseismal line, as well as the epicentral intensity I_0, and the magnitude M of the earthquake.

Based on equation (1) we analyzed 11 equations (Chávez and Castro, 1987) and adopted the expressions that showed better adjustment to the data. These equations are the following

$$\ln I = B_0 + B_1 \ln (D/D') + B_2 (D - D') + B_3 \ln M_s \tag{2}$$

$$\ln I = B_0 + B_1 (D/D') + B_2 \ln (D - D') + B_3 \ln M_s \tag{3}$$

As the surface-wave magnitude M_s is a measure of earthquake size, independent of the isoseismal information, it was considered adequate to use the distance D and M_s as independent variables in equations (2) and (3). In these equations, it was assumed that the intensity I attenuates with distance D and amplifies with M_s. In other words, the coefficients of the resulting equations should be as follows: B_1 and B_2 negatives and B_3 positive.

DATA

The data available for the study consist of isoseismal maps, the locations, and the values of M_s corresponding to 42 events occurring in Mexico from 1845 to 1980 (Table 1). Events 1 to 8 were not used in the fitting of the equations because their M_s were obtained based on the isoseismal information and not on instrumental

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39, 42 from Duda (1965), Lomnitz (1983), Dean *et al.* (1978), González-Ruíz (personal communication, 1986), Gongález-Ruíz *et al.* (1983).

References for depths: Events 11, 12, 13, 15, 16, 24, 26, 28, 30, 40, 41 from Singh *et al.* (1984a); 10, 17, 19, 29 from Figueroa (1970); 21, 22, 27 from Suárez (personal communication, 1985); 32, 34, 37 from Mota (1979); 25, 31 from Jiménez *et al.* (1978); 35, 36 from Dean *et al.* (1978); 39, 42 from Gonzalez-Ruiz *et al.* (1983); 18, 20, 23, 33, 38 from (5, 4, 8, 12, 1) Kelleher *et al.* (1973), Gutenberg *et al.* (1954), Nuñez (1983), Chael *et al.* (1982), Singh *et al.* (1981).

References for M_s: Events 12, 13, 15, 16, 18, 20, 24, 26, 27, 28, 30, 40, 41 from Singh *et al.* (1984a); 1, 2, 3, 4, 5, 6, 7, 8, 37, 38 from Singh *et al.* (1981); 9, 10, 14, 17, 19, 23, 36 from Figueroa (1970); 22, 25, 29, 31, 32, 34, 35 from Suárez (personal communication, 1985); 11, 21 from Duda (1965); 39, 42 from González-Ruíz *et al.* (1983); 33 from Chael *et al.* (1982).

As the M_s for events 9, 10, 14, 31, 36 was not available, the magnitude reported by Figueroa was used instead.

recordings. Events 36 and 37 were also excluded due to the incompleteness of the isoseismal maps. Finally, the sample used consisted of 32 events.

The events included in the sample (Table 1) were classified in three groups according to their epicentral location, focal mechanism, and depth, as follows: group 1, 18 events belonging to the subduction zone, with thrust mechanisms and depths between 15 and 20 km (González-Ruíz and McNally, 1983; Singh *et al.*, 1984b; González-Ruíz, 1986); group 2, 10 intermediate-depth events in south-central Mexico, with normal faulting mechanisms and depths varying from 65 to 150 km (González-Ruíz and McNally, 1983; Toledo and Nava, 1983; González-Ruíz, 1986); group 3, four events with epicenters located on the Trans-Mexican Volcanic Belt, (TMVB), with reverse and normal mechanisms and depths shallower than about 20 km (G. Suárez, 1985, personal communication).

In Figures 1a to 1c, the distribution of the data for groups 1 to 3 are presented and Figure 1d includes the data for all 32 events. Notice in these figures that the minimum value for *I* is 5. This limit was chosen by considering that from this value onward the effect of earthquakes on structures would be of interest for engineering purposes. It should also be mentioned that a large percentage of the isoseismal maps were drawn by Figueroa and, therefore, the data can be considered uniform.

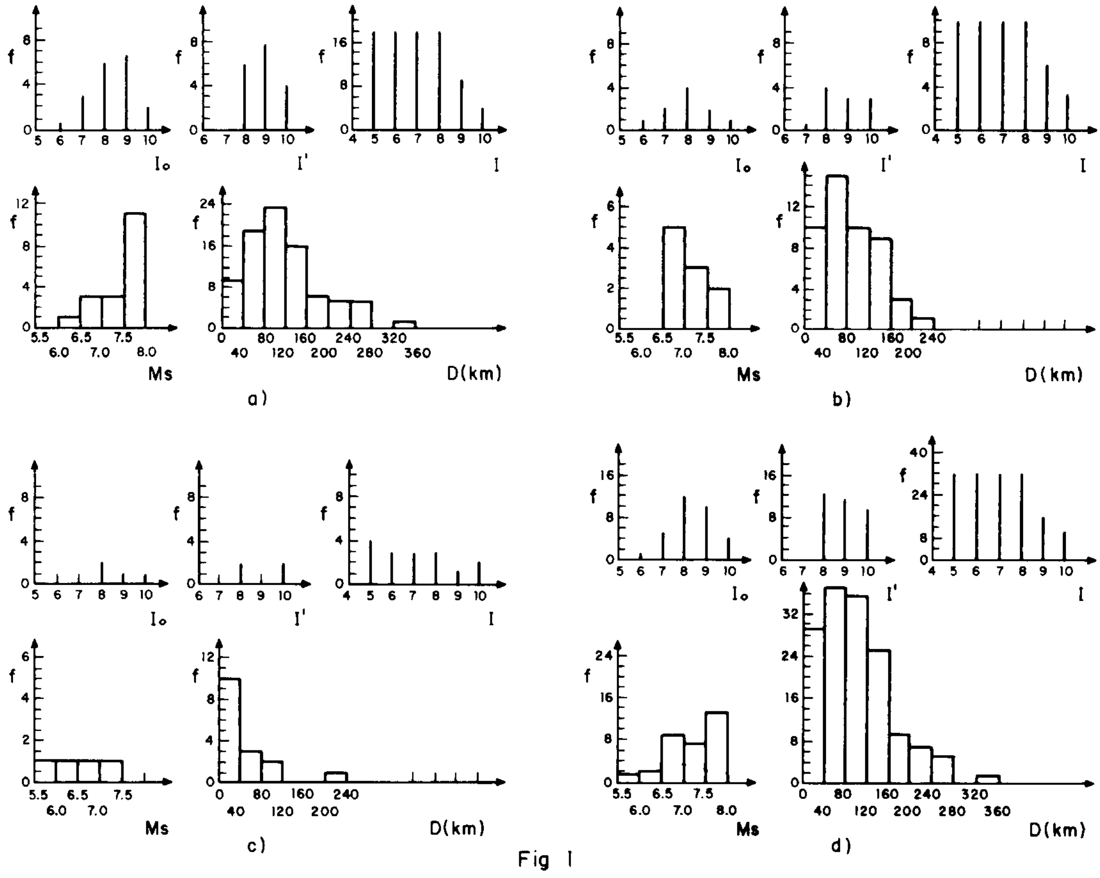

FIG. 1. Histograms of the parameters I_0, I', I, M_s and D from the Appendix for the sample of events: a) group 1 (subduction zone earthquakes), b) group 2 (south-central Mexico earthquakes), c) group 3 (Trans-Mexican Volcanic Belt earthquakes), d) all groups

PROCEDURE

In order to determine which of the relations tested (Chávez and Castro, 1987) best predicts the attenuation of I with D and M_s, the average radii of the isoseismal values with $I > 5$, of events 9 to 42 (except 36 and 37) of Table 1 were calculated and fitted to the relations. The radii were computed assuming that the area (A) corresponding to an isoseismal value of irregular shape could be assumed to be a circle of radius equal to $[2 \sum (A_i/\gamma_i)]^{1/2}$; the A_i were calculated by using a planimeter, and represent the areas associated with the angles γ_i subtended by the segments of isoseismal lines. The latter are equal to 2π or to a fraction of this value, depending if the corresponding isoseismal line was onshore or offshore, respectively (Chávez and Castro, 1987). The fitting of the relations was performed by using a linear multiple regression code.

RESULTS

The values of the coefficients of equations (2) and (3), as well as the statistical parameters t and F and root-mean-square (rms) values of the residuals about the predictions of I obtained from the regression analysis, are shown in Table 2. Based on the 90 per cent test of significance, the critical statistical values of $t = 1.67$ and $F = 2.76$ for group 1; $t = 2.68$ and $F = 2.84$ for group 2; and $t = 1.78$ and $F = 3.49$ for group 3 were obtained. These values together with the smaller rms value were used to select equations (2) and (3) from the set considered in Chávez and Castro, (1987).

Notice from Table 2 that when the mentioned selection criteria was applied to groups 1, 2, and 3, equations (2) and (3) were the best for the first two and the later group, respectively (Chávez and Castro, 1987).

In Figures 2a to 2f the normalized residuals of the equations (2) and (3) are shown. Since these residuals do not show any trend with respect to the independent variables (D, M_s), it is considered that the equation (2) for groups 1 and 2 and equation (3) for group 3 are adequate for the prediction of I. The standard deviations of the mentioned equations correspond approximately to one unit in the I scale.

To validate equation (2) for group 1 (Table 2), the average isoseist values for the

TABLE 2

COEFFICIENTS OF THE PROPOSED ATTENUATION RELATIONS

Relation	Group	B_0	B_1	B_2	B_3	t_{B_1}	t_{B_2}	t_{B_3}	F	RMS
2	1	1.1090	−0.1399	−0.0011	0.5209	−4.3376	−4.6161	2.8068	92.25	0.71
	2	1.5188	−0.0627	−0.0021	0.3314	−1.4427	−4.3523	1.2923	61.03	0.67
	3	3.0021	−0.3057	0.0019	−0.0325	−2.9327	1.3609	−0.0641	5.80	0.95
3	1	1.3891	−0.0475	−0.0220	0.3627	−6.5185	−5.7646	1.6904	61.86	0.80
	2	0.6013	−0.0337	−0.0224	0.7745	−4.7493	−4.1788	2.4386	33.18	0.83
	3	2.0922	−0.0881	−0.0233	0.0351	−3.2648	−2.4270	0.0830	15.05	0.79

B_i ($i = 0, 1, 2, 3$) = Coefficients obtained by the regression of M_s and D data of the 32 events of the sample.

t_{B_i} ($i = 1, 2, 3$) = "t" statistics of the B_i ($i = 1, 2, 3$).

RMS = root-mean-square values of the residuals about the predictions computed as

$$\sqrt{\frac{1}{n} \sum_{i}^{n} (I_i - \hat{I}_i)^2}$$

where I = observation, $\hat{I}$ = prediction, n = number of observations.

The critical values of the "F" and "t" statistics for the 90 per cent test of significance for each of the groups are the following: group 1, F=2.76, t=1.67; group 2, F=2.84, t=1.68; group 3, F=3.39, t=1.78.

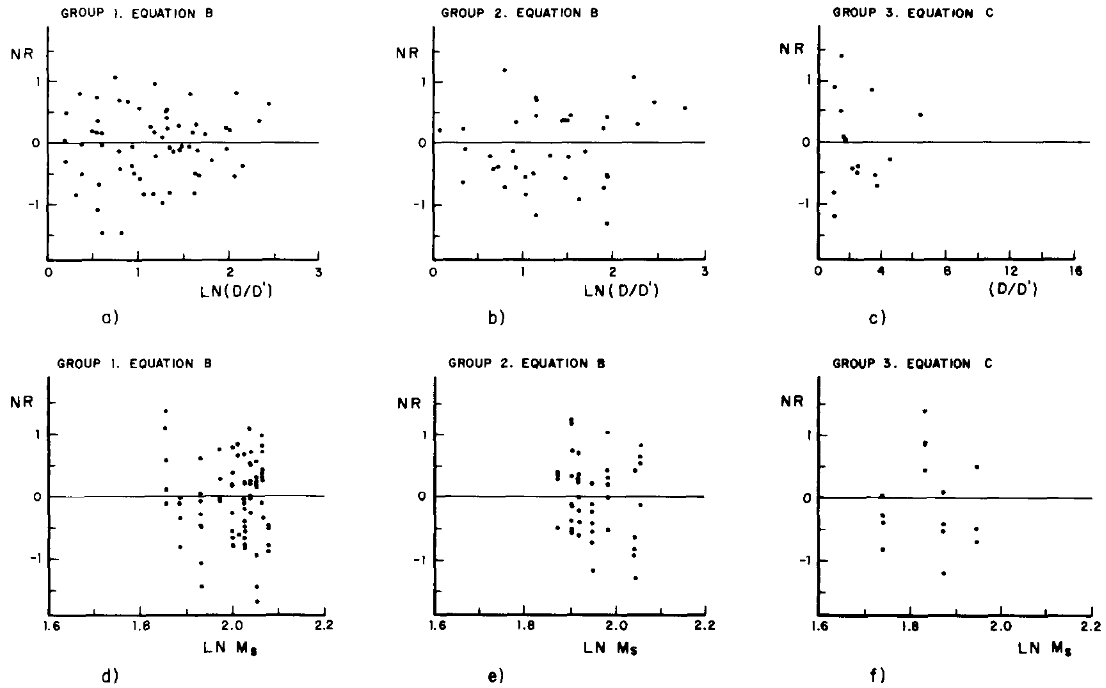

Fig 2

FIG. 2. Normalized residuals for equations (2) and (3) with distance a), b), c); with M_s d), e), f). Equations B and C in the figures are the same as equations 2 and 3 in the text.

Mexico earthquake of the 19 September 1985 (Figueroa, 1987; UNAM, Seismology Group, 1986) not included in the fitting (Table 1) were used to compare with those predicted by that equation. The comparison is shown in Figure 3. From this figure it can be concluded that the predicted values compare well, as a whole, with the observed ones. There was no information available to validate the proposed equations for groups 2 and 3. However, those equations were used as the first step for computing the expected predicted peak ground accelerations for events of groups 2 and 3 with $M_s = 7$, $D = 380$ km and $M_s = 4.8$, $D = 50$ km, respectively (Chávez, 1988). The predicted values were 12 and 50 cm/s^2 and the observed ones 9 and 64 cm/s^2, as the differences between the predicted and observed values can be considered reasonable for seismic risk analysis, we concluded that the mentioned relations can be used for this purpose.

A parametrical study of relations (B) and (C) for the three groups of event was carried out. As a sample of the results obtained in the study, the attenuation curves corresponding to $M_s = 7$, $D' = 30$ km are shown in Figure 4. For other combinations of those parameters the results are similar to the mentioned ones (Chávez and Castro, 1987). From Figure 4 it can be concluded: 1) that the attenuation of I with D and M_s, predicted by equations (2) and (3), is different for each type of event; 2) that the attenuation is greatest for events of the TMVB; 3) that for D less than about 200 km, the attenuation of the subduction type of events is larger than the attenuation corresponding to the events of south-central Mexico. For D larger than that value, the opposite behavior is observed. Results similar to conclusion 3 were found by González-Ruíz and McNally (1983) when modelling two subduction type of earthquakes and two south-central Mexico type of events, quoted in Munguía *et al.* (1986).

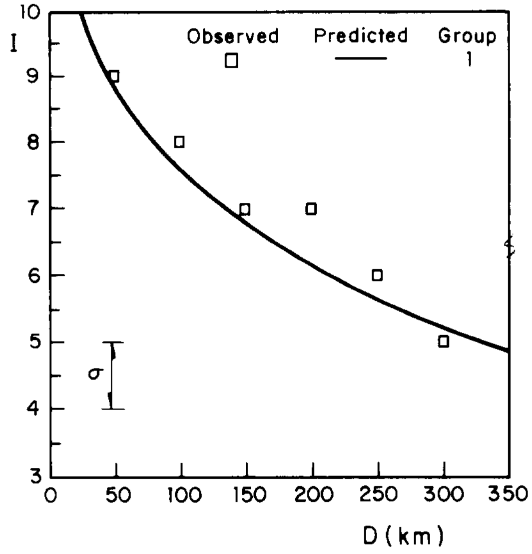

Fig 3

FIG. 3. Comparison of predicted with observed I values using equation (2) for the group 1 of events: □ Subduction zone earthquake occurred September 1985 (M_s=8.1, D'=44 km)

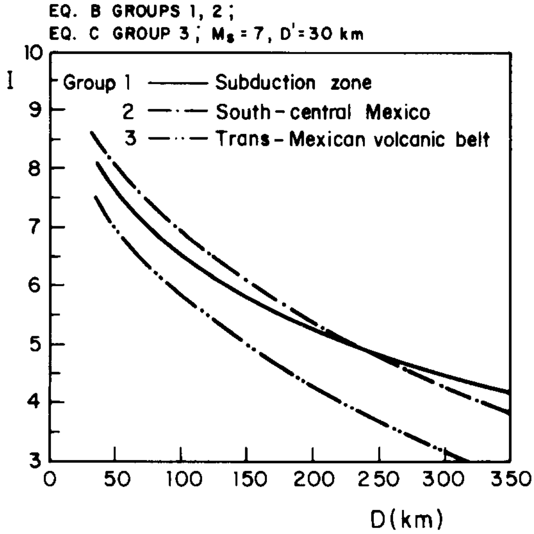

Fig 4

FIG. 4. Comparison of predictions of the Modified Mercalli Intensity (I) from equations 2 and 3 for groups 1, 2, and 3, respectively. Equations B and C in the figures are equations 2 and 3 in the text.

DISCUSSION

The possible causes of the differences in attenuation for the three types of events considered in the study (subduction, south-central Mexico, and TMVB) may be related to the following:

a) The higher attenuation observed for the earthquakes occurring in the TMVB, compared with the attenuation of events of the other two types of events, may be caused by their source depths and the scattering of seismic waves due to the apparently fractured crust (Mooser, 1972) which may be partially molten (Ziagos *et al.*, 1985). This has been confirmed by the high Q values reported by Canas (1986); these values are significantly larger than the ones reported for the rupture areas of several subduction and intermediate-depth Mexican earthquakes (Acosta y Rodríguez, 1988; Yamamoto, 1986).

b) Concerning the differences in the attenuation of the events occurring in the subduction and south-central Mexico regions, these may be explained as follows: the differences at distances of less than about 200 km may be related to the greater scattering of seismic waves by a more fractured crust existing in the subduction zone, compared to the one of south-central Mexico and/or to the radiation pattern characteristics of their respective sources (González-Ruíz and McNally, 1983; Lefevre and McNally, 1985; González-Ruíz, 1986). For distances larger than about 200 km, the smaller attenuation of the subduction type of events compared with the observed attenuation for the intermediate-depth earthquakes may be explained by the high content of surface waves which seems characteristic of the Mexican subduction type of events (Singh *et al.*, 1984b).

CONCLUSIONS

The main conclusions of the study are the following: a) two attenuation relations have been proposed to predict the attenuation of the Modified Mercalli Intensity with distance and surface-wave magnitude for Mexican earthquakes, b) the attenuation of I with distance for the sample of events is different for each of the three groups in which the data set was classified; c) for distances of less than about 200 km the earthquakes associated with the subduction zone have a larger attenuation than the ones generated in the south-central region of Mexico, but for larger distances the opposite behavior is observed; d) the events that originate in the Trans-Mexican Volcanic Belt have a larger attenuation with distance than the earthquakes which occur in the other regions; e) it seems advisable in Mexico to use several attenuation relations to estimate the seismic hazard at a site, depending on the particular tectonic setting and the source-site path of the events under consideration.

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