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Deterministic Seismic Zoning of Eastern Cuba

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Abstract—A deterministic seismic zoning of Cuba is performed by modelling, with modal summation, the complete *P-SV* and *SH* waves fields generated by point-source earthquakes buried in flat-layered anelastic media. The results of the computation, performed for periods greater than 1 second, are presented in two sets of maps of maximum displacement (d_{max}), maximum velocity (v_{max}) and design ground acceleration (DGA), obtained by using two different criteria in the definition of the input magnitude: (1) values reported in the earthquake catalogue (M_{obs}) and (2) values determined from seismotectonic considerations (M_{max}). A comparison with the results of a previous probabilistic seismic zoning is made to test the possibility of making intensity—ground motion conversion with the aid of log-linear regressions.

Key words: Seismic hazard, synthetic seismograms, deterministic modelling, Cuba.

1. Introduction

Cuba, part of the North American plate, is at the boundary of the Caribbean plate, where an approximately sinistral transcurrent movement is dominant. The known seismic history begins with the Spanish settlements in the XVI century, and since that time several major and large earthquakes are reported in the Greater Antilles. In particular, eastern Cuba, where Santiago de Cuba City has been partially destroyed several times since its foundation, is the part of the Cuban territory most affected by earthquakes. The remaining part of the territory is affected by intraplate seismicity that reaches maximum epicentral intensity of VIII degrees (MSK seismic intensity scale).

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Seismic zoning began with a deterministic approach based on felt intensities (ALVAREZ, 1970; CHUY *et al.*, 1983), and the map presented by CHUY *et al.* (1983) has been long used in the antiseismic building code in Cuba. In the mid 1980s a qualitative change was due to the introduction of probabilistic approaches (RUBIO, 1985a; ALVAREZ and BUNE, 1985a,b). The majority of the subsequent studies are based on the methodology introduced by ALVAREZ and BUNE (1985a,b) and discussed by ALVAREZ (1995). The detailed seismic zoning for the siting of nuclear power plants, radioactive waste deposits and hydroelectric complexes, which are summarized in the new proposal for the seismic building code (CHUY and ALVAREZ, 1995), is made following the probabilistic approach. Finally, a new probabilistic investigation follwing GSHAP philosophy has been performed (RODRÍGUEZ *et al.*, 1999).

The parameter commonly used for hazard description in Cuba is the macroseismic intensity, due to no records of acceleration or any other ground-motion parameter during strong or felt earthquakes. Therefore, to obtain hazard estimates in terms of acceleration or other ground-motion parameters, it is necessary to follow an indirect path to transform macroseismic intensity into ground-motion parameters.

A means to estimate seismic ground-motion parameters is complete waveform modelling. In this paper we formulate a new deterministic seismic zoning of eastern Cuba, produced by modelling *P-SV* and *SH* wave fields with the modal summation method (PANZA, 1985; PANZA and SUHADOLC, 1987; FLORSCH *et al.*, 1991).

The procedure for the deterministic seismic zoning, developed by COSTA *et al.* (1992, 1993), is based on the use of available information of the earth's structure, seismic sources and the level of seismicity of the investigated area to generate synthetic seismograms, from which parameters representative of the ground motion are then obtained.

In the definition of seismic sources a distribution of the maximum magnitude (M_{max}) over the territory is needed. The data available from earthquake catalogues are, on the contrary, discrete and punctual, after which a smoothing must be applied. It may be accomplished in several ways as discussed by COSTA *et al.* (1992, 1993). Furthermore M_{max} can be assessed not only from catalogues, but also in other ways, e.g., from seismotectonical maps.

Once the structures and the sources are defined, sites are considered on a grid covering the whole territory and synthetic seismograms are efficiently computed by the modal summation technique (PANZA, 1985; FLORSCH *et al.*, 1991). The synthetic signals are computed for an upper frequency content of 1 Hz, and the scaled point-source approximation is still acceptable. The finiteness of the source is in fact accounted for applying the spectral scaling law proposed by GUSEV (1983), as reported in AKI (1987). At each site the horizontal components are first rotated to a reference system common to the entire territory (N–S, E–W) after which the vector sum is computed.

From these seismograms the maximum ground displacement, velocity and acceleration (d_{max}, v_{max} and a_{max}) are determined, however it is also possible to calculate integral quantities that can be of interest in earthquake engineering or engineering seismology. Computed accelerations can be extended to frequencies higher than 1 Hz using design response spectra (PANZA *et al.*, 1996), for instance EC8 (EUROCODE 8, 1993).

The validity of the use of log-linear transformations between ground-motion parameters and intensity for Cuban conditions is controlled by studying the relationships between our results, based on ground-motion modelling, and the results of RODRÍGUEZ *et al.* (1999), based on calculated intensity.

2. Seismicity Data

We use an earthquake catalogue for the period from 1502 to 1994 for the region between 67°–85°W and 16°–24°N. The magnitude of all historical earthquakes has been determined by the inversion of intensity data through the adjustment of an elliptical model of isoseismals (ALVAREZ and CHUY, 1985). The magnitudes of earthquakes in the catalogue are M_s, m_b, M_I (estimated from macroseismic data), M_D (estimated from signal duration) and K_r—energetic class (RAUTIAN, 1964). The conversion relationships to M_s are $M_I \cong M_D \cong M_s$, $M_s = 1.51\ m_b - 3.69$, $M_s = 0.48\ K_r - 2.11$ (ALVAREZ *et al.*, 1999). In Figure 1 the map of epicenters for $M_s \geq 5$ is

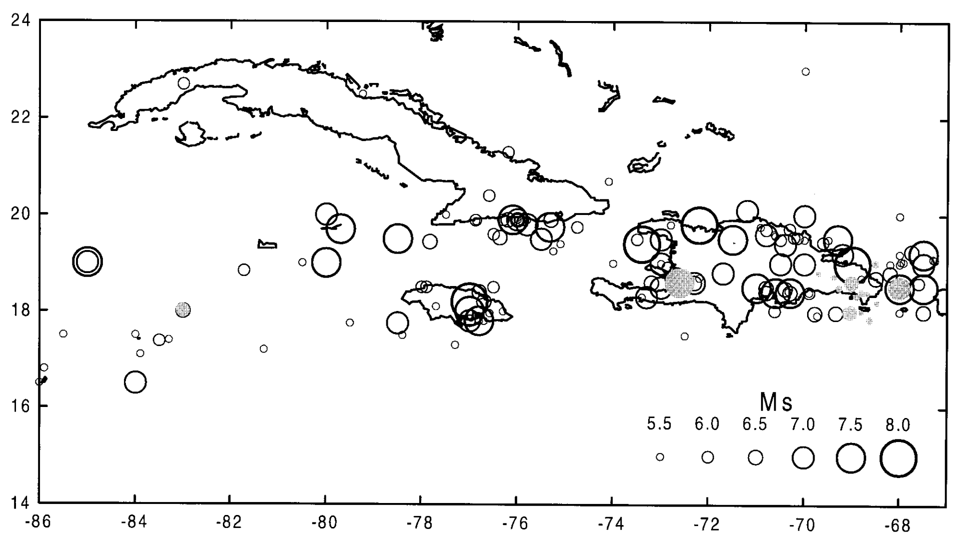

Figure 1
Map of epicenters from 1502 until the present in Cuba and neighbouring territories. Open circles—shallow events, full circles—intermediate depth events.

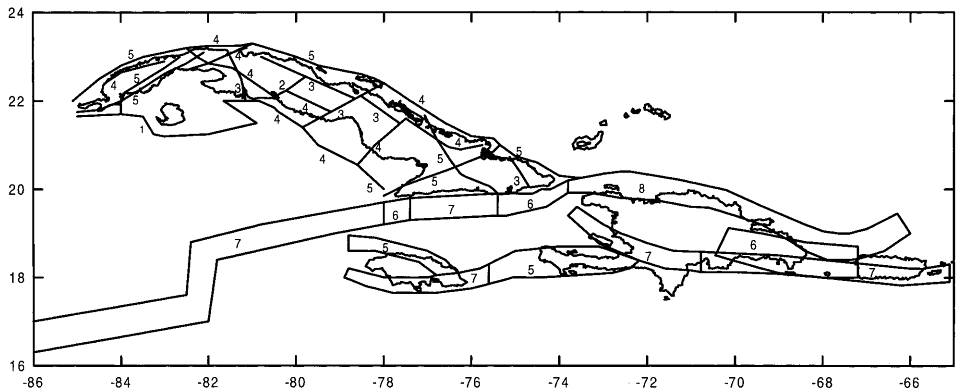

Figure 2
Map of seismogenetic zones with M_{max} values (COTILLA and ALVAREZ, 1991). The seismic source zones in the Cuban Island are about 10 km wide. Therefore they are represented by lines. 1.—$4.5 < M_{max} \leq 5$, 2.—$5 < M_{max} \leq 5.5$, 3.—$5.5 < M_{max} \leq 6$, 4.—$6 < M_{max} \leq 6.5$, 5.—$6.5 < M_{max} \leq 7$, 6.—$7 < M_{max} \leq 7.5$, 7.—$7.5 < M_{max} \leq 8$, 8.—$8 < M_{max}$.

presented: the seismicity of the region is mainly shallow ($h \leq 70$ km) with the presence of deeper foci ($70 < h \leq 220$ km) only in the eastern part of Hispaniola Island (the second largest island in Figure 1).

The region considered in this study [18°–24°N, 72°–78°W] comprises eastern Cuba and surrounding territories. The catalogue for this zone is characterized by a good pre-instrumental part (XVI–XIX centuries) followed by an instrumental part complemented by macroseismic epicenters of weaker, instrumentally non-recorded events. The instrumental catalogue is based until 1967 on locations made by the worldwide network and only after 1967 does the determination of local epicenters by Cuban stations begin, with variable quality in time.

The studied region is divided into cells of $0.2° \times 0.2°$ and the maximum observed magnitudes M_{obs} of the earthquakes which occurred within each cell is determined. These data are smoothed following the procedure described in COSTA *et al.* (1993). The obtained smoothed seismicity is intersected with the seismic source zones (SSZ) derived from the map of seismogenetic zones of Cuba and its surroundings, shown in Figure 2. This map is an updated version of a seismotectonic map of Cuba based mainly on remote sensing techniques complemented with geological, tectonical and seismological data (COTILLA and ALVAREZ, 1991; COTILLA *et al.*, 1996). As a result, a smoothed map M_{obs} is obtained (Fig. 3).

Taking into account the vast difference between the space distribution of M_{obs} and M_{max}, the maximum possible magnitude expected from seismotectonic considerations taken from Figure 2, it has been decided to make the calculation considering both M_{obs} and M_{max}.

3. Focal Mechanism in the Region

For the definition of the focal mechanism of each SSZ, we have collected all the available data relevant to fault plane solutions and CMT determinations for the region. Thusly we assembled 46 solutions (Table 1), corresponding to 30 earthquakes or groups of earthquakes that cover all the SSZ delineated for the interplate seismicity zone (Fig. 4). For each SSZ we select the more reliable solution as the typical mechanism to be used in the modelling of the seismic motion. Nevertheless, for the intraplate SSZ no focal mechanism or CMT solutions are available, and the expected mechanisms have been chosen only on the basis of general considerations of the geodynamics of the region.

4. Structural Model

The uppermost 150 km of the structural model are shown in Figure 5 and represent a modification of the *P* and *S* waves velocities model used for earthquake hypocenter's location (MINBAS, 1989). The density values are adapted from those proposed by ORIHUELA and CUEVAS (1993). Since *Q* values are not available in the literature, we assumed standard values of $Q_\alpha = 200$ and $Q_\beta = 100$ for all the layers.

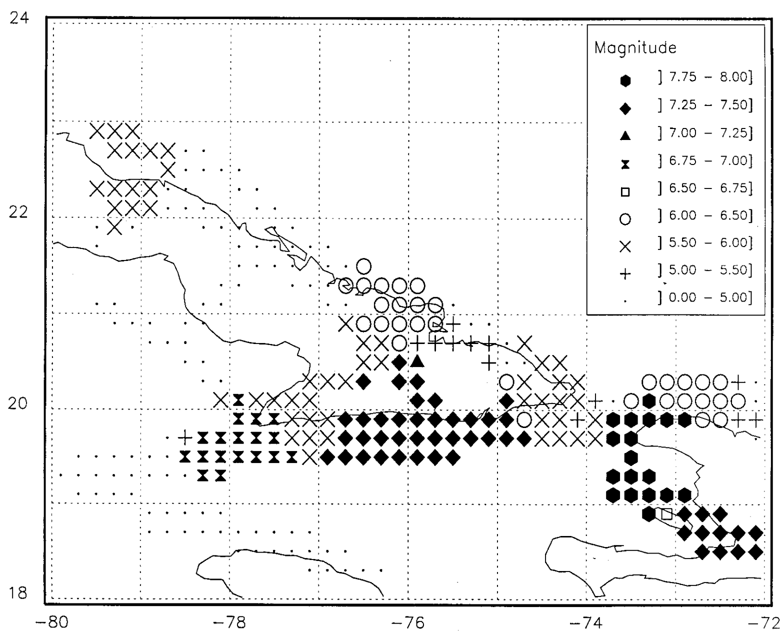

Figure 3
Map obtained by smoothing the maximum observed magnitudes M_{obs}.

Table 1

Focal mechanisms in the region (16°–24°N, 72°–82°W). We give all available solutions. Original data have been reprocessed to unify the representation of fault plane solutions; in each case the two orthogonal planes are presented. Az—azimuth, D—dip, Ra—Rake, Q—quality of solution, h—depth in km, La—North Latitude, Lo—West Longitude, Date—day/month/year, Time—hour:minute:second, M_s and m_b—magnitudes, R—bibliographic reference [WH—Wickens and Hodgson (1967), MS—Molnar and Sykes (1969), SB—Stauder and Bollinger (1964), R—Rubio (1985a,b), AS—Alvarez et al. *(1984), A—Alvarez (1985), M—Mendiguren (1966), C—Calais (1990), N—NEIS, C—University of Harvard CMT solutions].*

No.	Date	Time	La	Lo	h	M_s	m_b	R	Q	Az1	D1	Ra1	Az2	D2	Ra2
01	09/07/56	09:56:13.7	20.01	72.98	54	6.4	–	WH	B	343	70	17	247	75	158
02	20/04/62	05:47:51.1	20.50	72.13	0	6.8	–	WH	B	90	71	96	287	22	104
02a	–	–	–	–	–	–	–	MS	B	234	47	44	110	60	128
02b	–	–	–	–	–	–	–	SB	–	86	46	96	279	46	98
03	25/07/62	04:37:42.9	18.90	81.19	64	6.0	–	WH	B	271	89	6	180	86	178
03a	–	–	–	–	–	–	–	MS	A	81	90	10	351	80	90
03b	–	–	–	–	–	–	–	SB		77	60	8	344	84	150
04	03/09/71	13:19:30.3	17.96	81.66	16	–	4.7	R	C	250	31	−55	344	88	−120
05	11/04/72	11:56:54.9	19.09	80.74	19	5.0	4.7	AS	B	75	88	−20	165	70	−178
05a	–	–	–	–	–	–	–	R	C	302	68	42	201	48	165
06	03/08/73	15:44:25.5	19.97	73.05	24	–	5.2	R	C	316	28	−55	99	68	−106
07	19/02/76	13:59:59	19.87	76.87	15	5.7	5.2	AS	B	80	80	4	356	86	170
07a	–	–	–	–	–	–	–	A	B	346	80	64	233	28	154
07b	–	–	–	–	–	–	–	R	B	192	82	132	290	47	11
08a	23/02/76	21:58:46.5	19.84	77.12	17	4.6	4.9	R	C	319	69	19	221	69	157
08b	24/02/76	11:28:34.2	19.84	77.12	24	–	4.8	R	C	228	36	−1	327	85	−125
08*	Compound	solution	19.84	77.12	–	–	–	AS	B	310	60	−71	95	35	−120
09	17/10/76	00:09:44.3	19.74	75.48	33	4.1	4.9	R	C	294	52	27	187	79	138
10	18/11/78	03:04:26.9	18.65	73.39	13	4.7	4.9	R	C	8	34	−62	156	60	−118
11	13/11/78	03:43:13.0	19.85	76.02	0	4.7	5.1	R	C	289	53	50	162	52	130
11a	–	–	20.18	76.6	15	–	–	H	A	190	26	127	330	69	73
12	08/02/80	20:38:52.0	19.58	75.56	53	4.2	4.9	R	C	248	88	−15	339	75	−177
12a	–	–	–	–	–	–	–	C	C	70	40	25	320	74	137
13a	22/12/70	17:09:56.0	19.92	75.29	34	–	4.7	R	C	292	45	5	199	86	135
13b	20/05/73	03:00:09.3	19.71	75.58	33	–	4.5	R	C	294	52	26	187	70	138
13c	11/10/68	02:38:24.0	19.88	75.92	48	–	4.3	–	–	–	–	–	–	–	–

Table 1 (continued)

13d	16/02/69	23:07:28.0	19.92	75.74	23	–	4.2	–	–	–	–	–	–	–	–
13e	16/03/70	22:48:52.0	20.14	74.6	89	–	4.3	–	–	–	–	–	–	–	–
13*	Compound	solution	19.91	75.59	–	–	–	AS	B	248	58	26	144	70	145
14*	57–66	11_events	19.00	72.00	50	–	–	M	B	276	69	27	172	56	155
15	29/09/76	09:52:34.9	18.91	80.65	50	4.9	5.2	R	C	93	90	0	13	90	0
16	26/02/78	05:07:22.5	18.20	76.52	23	3.9	4.9	R	C	326	81	26	234	68	170
17	25/05/92	16:55:04.1	19.61	77.82	33	7.0	6.3	N	A	182	80	12	90	78	170
17a	–	–	19.84	77.70	15	–	–	H	B	248	43	−1	339	89	−133
18	01/09/85	01:00:55.2	19.75	75.30	5	5.1	5.1	C	C	70	54	46	310	54	146
18a	–	–	19.67	75.20	10	–	–	H	A	61	38	100	228	53	82
19	26/09/85	08:03:24.5	18.37	71.96	8	3.9	4.8	C	C	100	27	53	320	69	107
20	12/11/88	03:34:48.7	18.15	76.64	20	4.7	5.4	H	B	306	72	87	135	18	98
21	12/02/89	14:26:50.2	19.98	74.52	25	4.3	5.2	H	A	286	29	43	157	71	112
22	16/08/84	03:09:45.9	18.24	81.62	10	5.0	5.0	H	A	323	32	−96	150	58	−86
23	22/05/90	20:35:38.0	19.79	76.07	15	4.8	5.0	H	A	290	43	27	179	72	130
24	26/08/90	07:53:45.2	19.43	78.04	15	5.2	5.7	H	B	166	42	−135	39	62	−57
25	04/09/90	08:03:04.2	19.86	75.58	15	4.5	5.2	H	B	302	21	21	192	83	109
26	26/08/91	10:01:59.2	19.05	80.97	10	5.2	5.3	H	B	258	77	12	175	79	166
27	27/06/92	14:16:23.2	18.81	80.64	15	5.0	5.3	H	A	165	85	−178	75	88	−5
28	19/01/93	17:11:13	18.69	76.97	15	–	5.71	H	A	282	33	23	172	77	121
29	02/03/94	03:38:04.6	19.95	72.67	34	5.0	5.2	H	B	110	68	12	16	79	157
30	27/06/95	10:10:02.2	18.82	81.78	15	5.7	5.8	H	A	352	71	−163	257	74	−20
30a	–	–	–	–	–	–	–	N	A	357	84	−169	266	79	−6

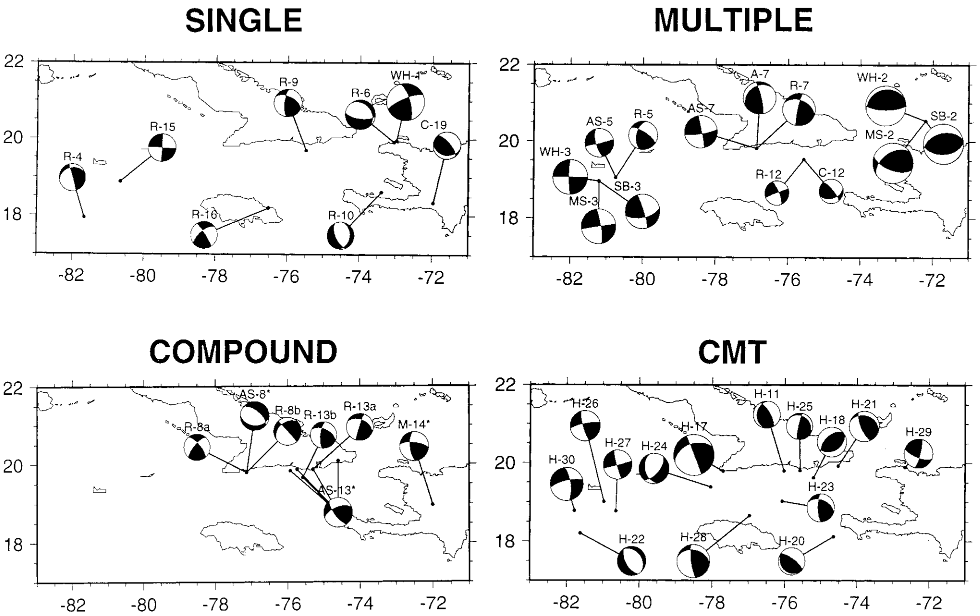

Figure 4
Focal mechanisms for the studied region divided into four groups: single—only one fault plane solution (FPS); multiple—more than one FPS determination from several sources; compound—compound mechanism of several earthquakes; CMT—a centroid-moment tensor solution is also available. A code corresponding to columns R and No. in Table 1 identifies each FPS.

5. *Results*

The calculation of synthetic signals has been performed following the procedure described by Costa *et al.* (1993). The maximum frequency used is 1 Hz, because the available details regarding input structure and source properties do not warrant

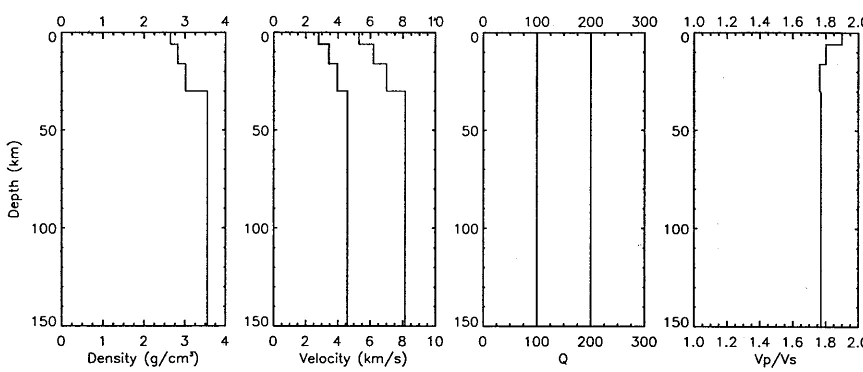

Figure 5
Uppermost 150 km of the structural model used for the computation of synthetic signals.

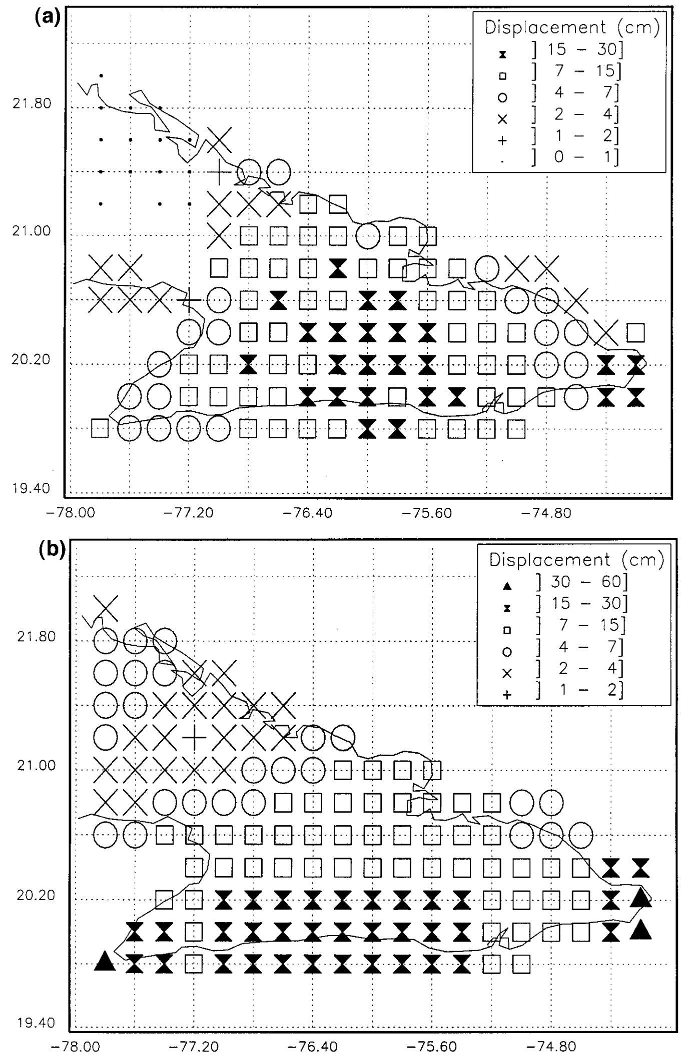

Figure 6
Maximum expected displacement d_{max}: (a) from M_{obs}, (b) from M_{max}.

the computation of synthetic signals at higher frequencies. All seismograms are scaled to the magnitude associated with the relevant cell, using the scaling law of GUSEV (1983) as reported by AKI (1987). For each point of the 0.2° × 0.2° grid we select the maximum values of displacement (d_{max}) and velocity (v_{max}), and we draw a set of maps of d_{max} (Fig. 6) and v_{max} (Fig. 7).

As pointed out by PANZA *et al.* (1997), the maximum ground accelerations are observed for frequencies greater than 1 Hz, i.e., outside of the range considered. The extension to larger frequencies can be made using standard or, if available, local response spectra (PANZA *et al.*, 1996). This suggestion is supported by the results obtained by YOUNGS *et al.* (1997) for subduction earthquakes (50–200 km, $M = 6.5–8.5$) and SADIGH *et al.* (1997) for shallow earthquakes (10–50 km, $M = 5.5–7.5$), dependent on the ratio MSV/PGA (MSV—maximum spectral value of response spectra and PGA—peak ground acceleration) with respect to magnitude and distance. These authors obtain values of MSV/PGA between 1 and 2 for periods from 0.1 to about 1 second, with an abrupt reduction to values of 0.1–0.2 for periods on the order of 3 seconds. For periods between 0.8–1.2 seconds the ratio

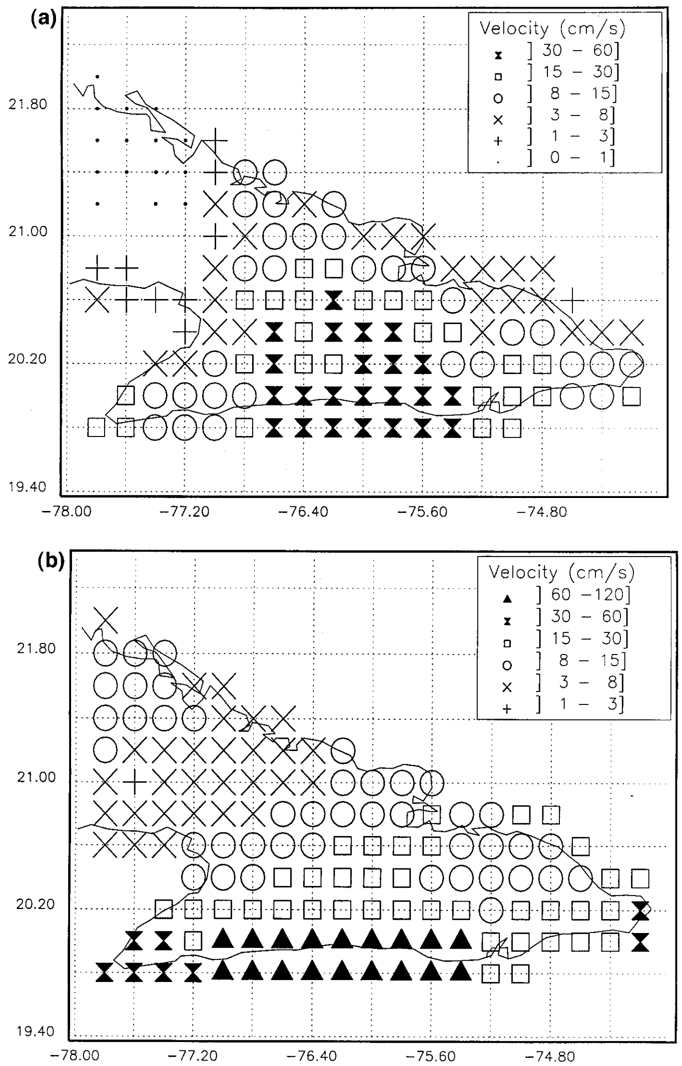

Figure 7
Maximum expected velocity v_{max}: (a) from M_{obs}, (b) from M_{max}.

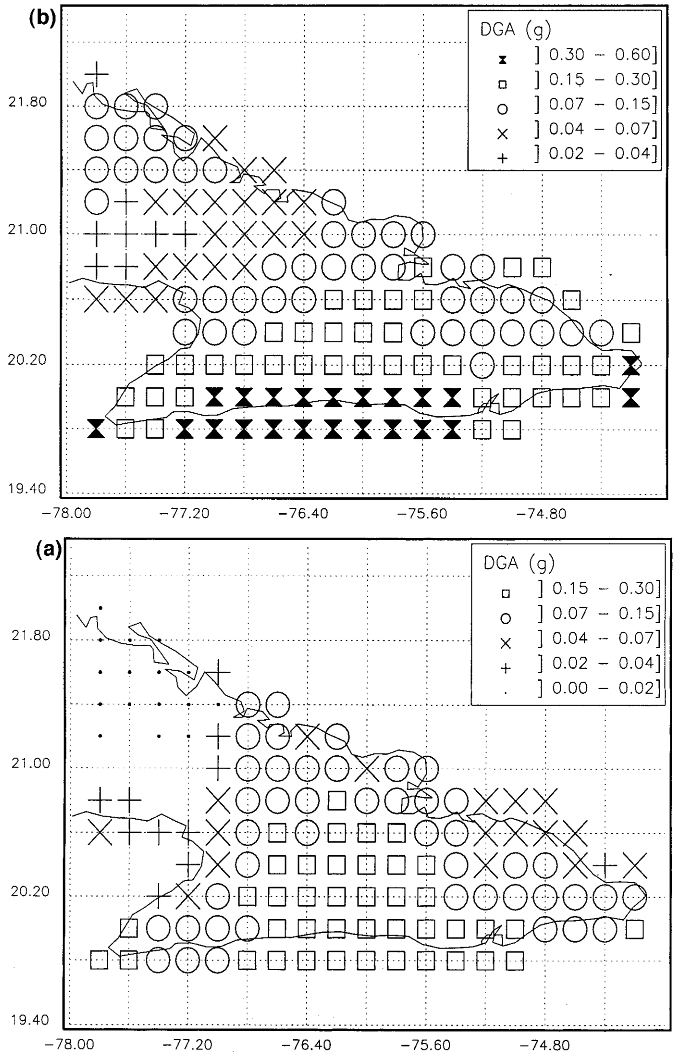

Figure 8
Expected design ground acceleration (DGA) according to Eurocode 8: (a) from M_{obs}, (b) from M_{max}.

MSV/PGA varies in the range (0.7–1.2), which means that in the period range in which we compute the a_{max} values, the peak ground acceleration is comparable to the maximum of the response spectra. The results obtained with the use of the design ground acceleration (DGA) as defined by EUROCODE 8 (1993) are presented in Figure 8.

6. Discussion

As can be seen from Figures 6–8, there is a sizable difference in the estimations made for the two considered variants. This is a normal problem in low seismic activity zones. In high seismic activity regions, for which the input earthquake catalogue can be considered representative of the seismic regime, the differences between the observed seismicity and that which is expected by seismotectonical considerations is generally small, sometimes on the order of the error in magnitude determination. In low activity zones, as a rule, the earthquake catalogue does not contain a good characterization of seismicity, and for zoning purposes it is

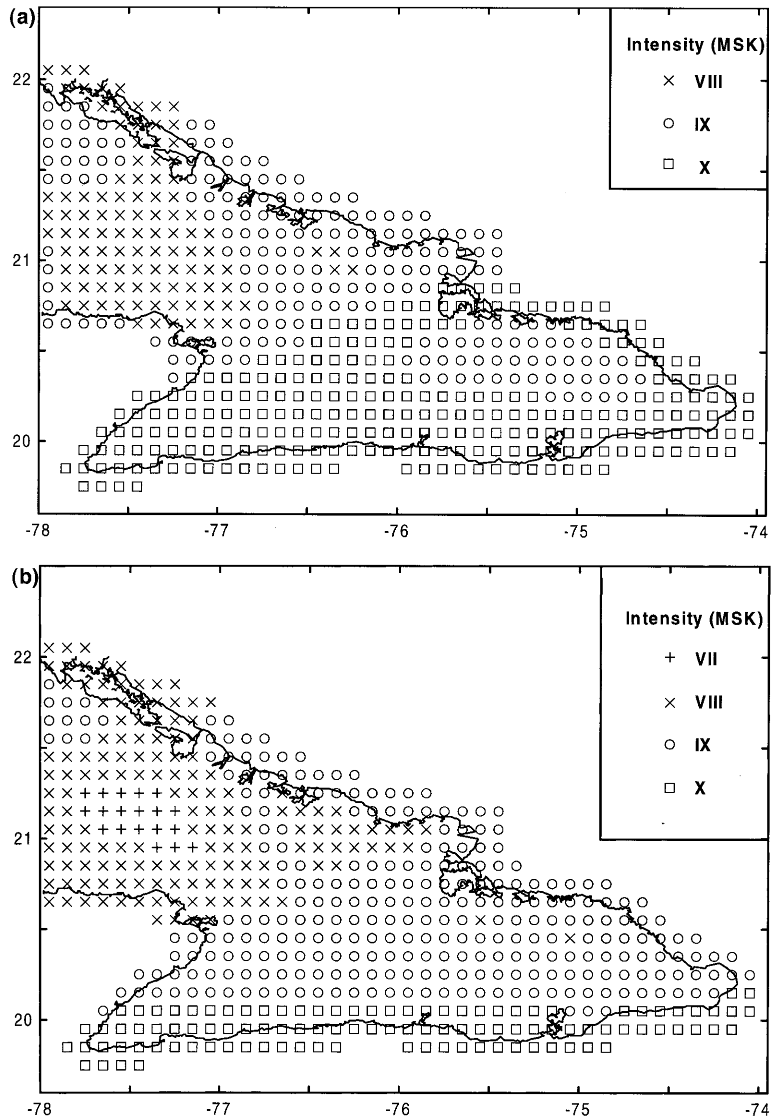

Figure 9
Space distribution of I_{max} prepared from the original data of the probabilistic seismic hazard assessment (RODRÍGUEZ *et al.*, 1999): (a) Cornell's approach (data set 1), (b) McGuire's approach (data set 2).

Table 2

Parameters of the regression lines (d_{max}, v_{max}, DGA) vs. I_{max}. σ_a and σ_b are the dispersions of the estimated parameters and r is the correlation coefficient: (a) for data set 1, (b) for data set 2.

y	A	σ_a	b	σ_b	R
(a)					
$d_{\max}$	−1.889	0.326	0.308	0.036	0.993
$v_{\max}$	−2.204	0.545	0.364	0.060	0.987
DGA	−0.980	0.418	0.335	0.046	0.991
y	A	σ_a	b	σ_b	r
(b)					
$d_{\max}$	−1.451	0.237	0.275	0.028	0.990
$v_{\max}$	−2.134	0.340	0.376	0.040	0.989
DGA	−0.856	0.153	0.338	0.018	0.997

necessary to consider the possibility of activating faults that until the present did not show any activity. This problem was pointed out by JOHNSTON (1989) regarding earthquakes in stable continental regions, and its relevance for Cuban

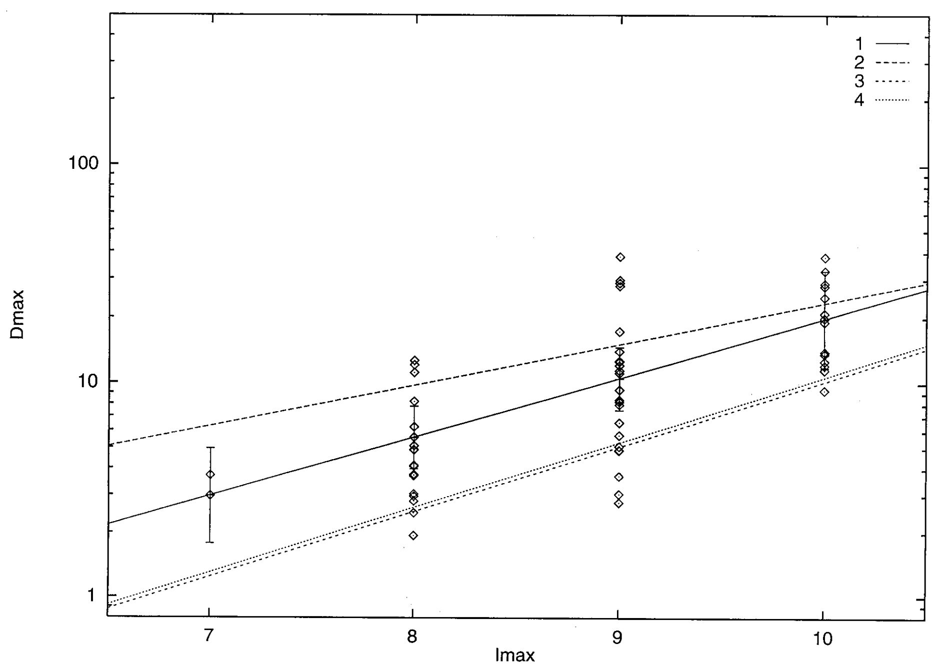

Figure 10

Relationship $d_{\max}$ (from $M_{\max}$) vs. $I_{\max}$ for data set 2. 1—regression line obtained by least-squares method, the 95% confidence intervals of the mean are represented by bars, 2—TRIFUNAC and BRADY (1975) relationship for the horizontal component of motion, 3—PANZA *et al.* (1997) relationship for ING data, 4—the same as 3 but for ISG data.

conditions is documented by COTILLA and ALVAREZ (1991). Therefore our results should be considered as interval estimations: expected ground-motion parameters will lie between the values obtained with the two variants, based on M_{obs} and M_{max} respectively.

Due to the lack of recordings of strong events, in Cuba the common practice (ALVAREZ, 1995) for the estimation of ground-motion parameters is to use log-linear transformations of macroseismic intensity. It is quite prevalent to use the regressions obtained by TRIFUNAC and BRADY (1975), even if until the present it has been impossible to make any test on their effective applicability to the Cuban territory.

We cannot obtain an empirical "first-hand" correlation between maximum felt intensity, I_{max} and "calculated by modelling" ground-motion parameters as was done by PANZA *et al.* (1997) in other parts of the world, since there is no updated map of I_{max} for the region. Nevertheless, for the studied part of Cuba, there is a recent probabilistic seismic hazard assessment (RODRÍGUEZ *et al.*, 1999) made using the same seismic source zones and seismotectonical, M_{max}, values that we used in this paper. RODRÍGUEZ *et al.* (1999) processed the data with two methods: the well-known Cornell's and McGuire's approaches. From their original data we have

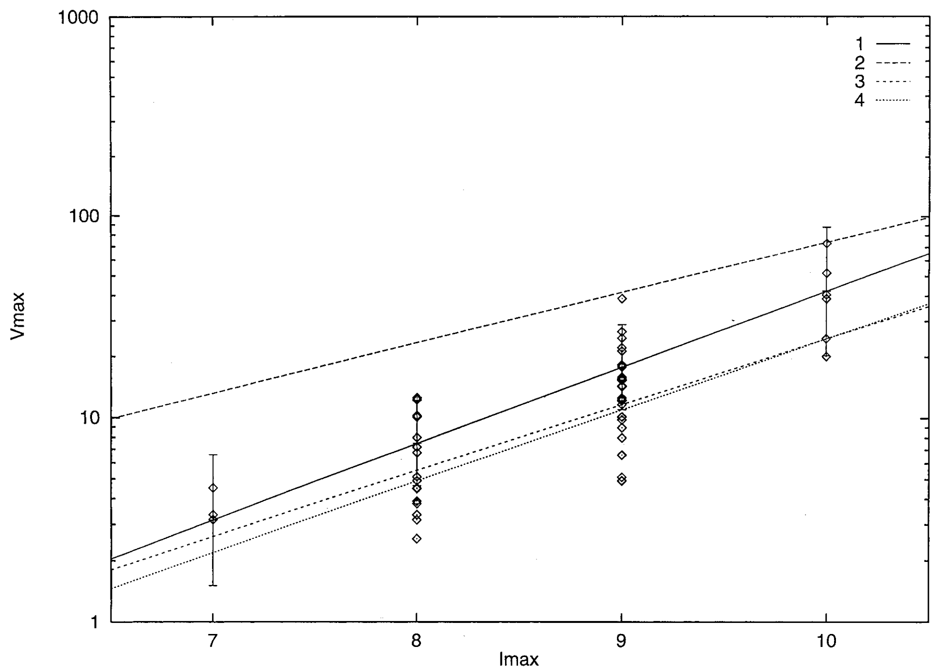

Figure 11
Relationship v_{max} (from M_{max}) vs. I_{max} for data set 2. 1, 2, 3 and 4—the same as in Figure 10.

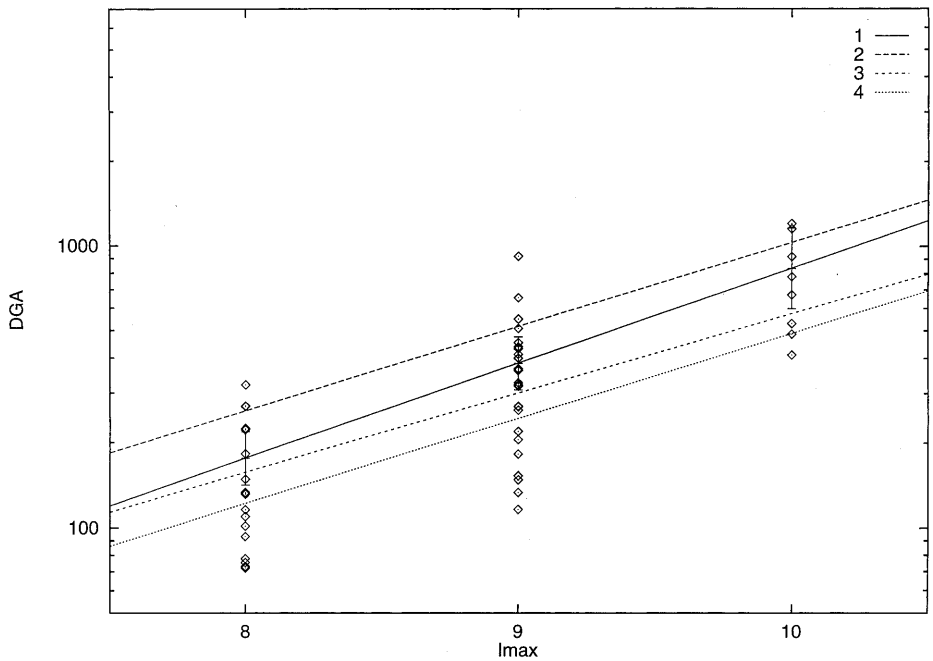

Figure 12
Relationship MSV (from M_{max}) vs. I_{max} for data set 2. 1—the same as in Figure 10, 2—TRIFUNAC and BRADY (1975) relationships for peak horizontal acceleration, 3—PANZA *et al.* (1997) relationship for DGA (converted to MSV) for ING data, 4—the same for ISG data.

prepared two maps of I_{max} (Fig. 9). The expected I_{max} for Cornell's approach is, in 37% of the cases, one degree larger than the one determined with McGuire's approach. In general, the use of M_{max} generates ground-motion values that are twice the ones obtained using M_{obs}, and this corresponds roughly speaking to a difference of one degree in intensity. Therefore the probabilistic treatment of intensity attenuation of McGuire's approach seems to reduce the hazard estimates, and makes them quite close to observations.

For both data sets of expected I_{max} values and the ground-motion parameters determined in Section 5 for the case of M_{max} [I_{max} (Cornell) vs. (d_{max}, v_{max}, DGA)] (data set 1) and [I_{max} (McGuire) vs. (d_{max}, v_{max}, DGA)] (data set 2), we calculate the logarithmic average value of the ground motion corresponding to each value of the macroseismic intensity, and from these data the regression lines of the kind

$$\lg(y) = a + b * I$$

by the least-squares method. The obtained values for the parameters a and b are presented in Table 2.

Although the kind of data utilized by TRIFUNAC and BRADY (1975) (observed intensities and ground-motion parameters) and PANZA *et al.* (1997) (observed intensities and modelled ground-motion parameters) is different from the data used here (modelled intensities and modelled ground-motion parameters) it is quite instructive to make a comparison among the different relationships.

For data set 2, the original values (not averaged) for d_{max} and v_{max}, as well as the regression lines, are shown in Figures 10 and 11, with the 95% confidence interval for the mean. Comparatively we have also plotted the relationships obtained by TRIFUNAC and BRADY (1975) and PANZA *et al.* (1997).

The PANZA *et al.* (1997) regression lines (3 and 4 in the figures) fit our data quite well for velocity although not for displacement. On the other hand, the TRIFUNAC and BRADY (1975) regression (2 in figures) predicts higher ground-motion values in both cases, slightly outside the 95% confidence interval. Nevertheless, the TRIFUNAC and BRADY (1975) relationship for peak horizontal acceleration agrees quite well with our DGA data converted to MSV (Fig. 12). The same agreement is obtained with the curves for MSV which can be deduced from the relationships of PANZA *et al.* (1997).

PANZA *et al.* (1999) considering the release NT 4.1 (CAMASSI and STUCCHI, 1996) of the Italian seismic catalogue has obtained regressions with slope values very similar to the ones reported here, but with doubled intercept values, i.e., very close to the solid lines shown in Figures 10, 11 and 12.

The obtained relationships between ground-motion parameters and macroseismic intensity can be applied for the prediction of mean ground-motion values in the intensity range from VII to X, alternatively to TRIFUNAC and BRADY's (1975).

7. Conclusions

The deterministic seismic zonation of eastern Cuba is made under two alternative hypotheses:

(a) The maximum possible magnitudes of earthquakes in each seismic zone are determined by the known seismic history (M_{obs}).

(b) The maximum possible magnitudes of earthquakes in each seismic zone are determined from seismotectonical criteria (M_{max}).

The results are presented in a set of maps which supply the space distribution of important mean ground-motion values (d_{max}, v_{max} and DGA). Expected ground-motion values will lie in the intervals defined by means of the two variants.

The ground-motion values obtained in the hypothesis (b) are compared with the results of a previous probabilistic study to obtain the parameters of log-linear regressions ground-motion (d_{max}, v_{max}, DGA)—intensity (I_{max}). These regressions may be used for the estimation of ground-motion parameters in the intensity range of VII to X, alternatively to those of TRIFUNAC and BRADY's (1975).

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