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Seismic hazard assessments for El Salvador

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RESUMEN

Se describe la evolución de las normas sísmicas en El Salvador, incluyendo un enfoque probabilística en la norma vigente. Se compara esta última norma con tres trabajos anteriores y se atribuyen las discrepancias a diferencias en cada paso de la estimación y no únicamente en las relaciones de atenuación. Se discuten las atenuaciones espectrales para América Central.

PALABRAS CLAVE: Riesgo sísmico, sismos, El Salvador, América Central, zonificación sísmica.

ABSTRACT

The development of seismic building codes in El Salvador is described, including the incorporation of a probabilistic hazard study into the latest regulations. This hazard study is compared with three other assessments that cover El Salvador, and it is shown that discrepancies arise from differences in each step of the hazard evaluation, leading to considerably divergent results. Although it may have been expected that the major uncertainty would result from the attenuation relationships employed, this review shows that the definition of the seismicity model is also poorly controlled. Attenuation relationships for spectral ordinates in Central America are also discussed.

KEY WORDS: Seismic hazard, earthquakes, El Salvador, Central America, seismic zoning.

INTRODUCTION

The Central American republic of El Salvador bears testimony to the observation by historian William Durant that "*civilization exists by geological consent*", with its history marked by volcanic eruptions and earthquake destruction. With an area of only 21,000 km^2, El Salvador (Figure 1) is the smallest country in the isthmus, but with more than 5 million inhabitants it also has the highest population density and most of the major settlements, which coincide with the axis of six active volcanoes, are in areas exposed to geological hazards.

The capital city of San Salvador, which now has about 1.3 million inhabitants, has the unenviable claim of being the city most often damaged by earthquakes in all of Latin America. San Salvador was established in its present location in 1539, on the plain between Lake Ilopango to the east and the Boquerón volcano to the west, in an area known as the *Valle de las Hamacas* (Valley of the Hammocks), presumably because of the frequency of seismic movements, (Lardé, 1960). There are accounts of earthquake damage throughout its history and San Salvador has been severely damaged at least 14 times since 1700 (Harlow *et al.*, 1993). The most recent earthquakes occurred in May 1965 (Lomnitz and Schulz, 1965) and October 1986 (Bommer and Ledbetter, 1987; Harlow *et al.*, 1993), with death tolls of 120 and 1,500, respectively. Earthquake destruction has not been confined to the capital: the towns of Jucuapa and Chinameca in the east of the country were destroyed by a series of earthquakes in May 1951, resulting in the loss of 400 lives, (Meyer-Abich, 1952). Coastal areas have also been affected by earthquakes, and tsunamis -reported to have occurred in 1859 and 1902 (Cruz and Wyss, 1983)- pose a threat to the port of Acajutla through which 45% of El Salvador's external trade passes.

A vital component of the efforts to mitigate seismic risk in El Salvador, particularly in light of the multitude of problems faced after 12 years of civil war and the limited resources available for their solution, is an accurate assessment of the level of hazard. The assessment needs to be presented in the form of a zoning map of El Salvador and response spectra for earthquake-resistant design. The primary objective of this paper is not to produce a new zonation of the country nor to propose design spectra, but rather to review the work that has been carried out by other researchers. There are considerable discrepancies amongst the different seismic hazard assessments that have been made for El Salvador and this papers explores some of the reasons for this divergence of the results.

This paper fulfills two purposes, the first of which is to make available a review of seismic hazard studies for El Salvador as an addenda to the global summary of hazard assessments recently published by IASPEI (McGuire, 1993), in which the only Central American country included was Costa Rica. The second purpose is to identify the point of departure for a three-year research project commencing in 1995, funded by the European Community, for hazard assessment in El Salvador. The research will be carried out as a collaboration between the Universidad Centroamericana in El Salvador and a network comprising the Universidad Complutense and the Instituto Geográfico Nacional in Madrid, the Institut de Physique du Globe in Paris, the National Technical University in Athens and Imperial College in London.

TECTONICS AND SEISMICITY OF EL SALVADOR

El Salvador is situated close to the western edge of the Caribbean plate, which interacts with four other litho-

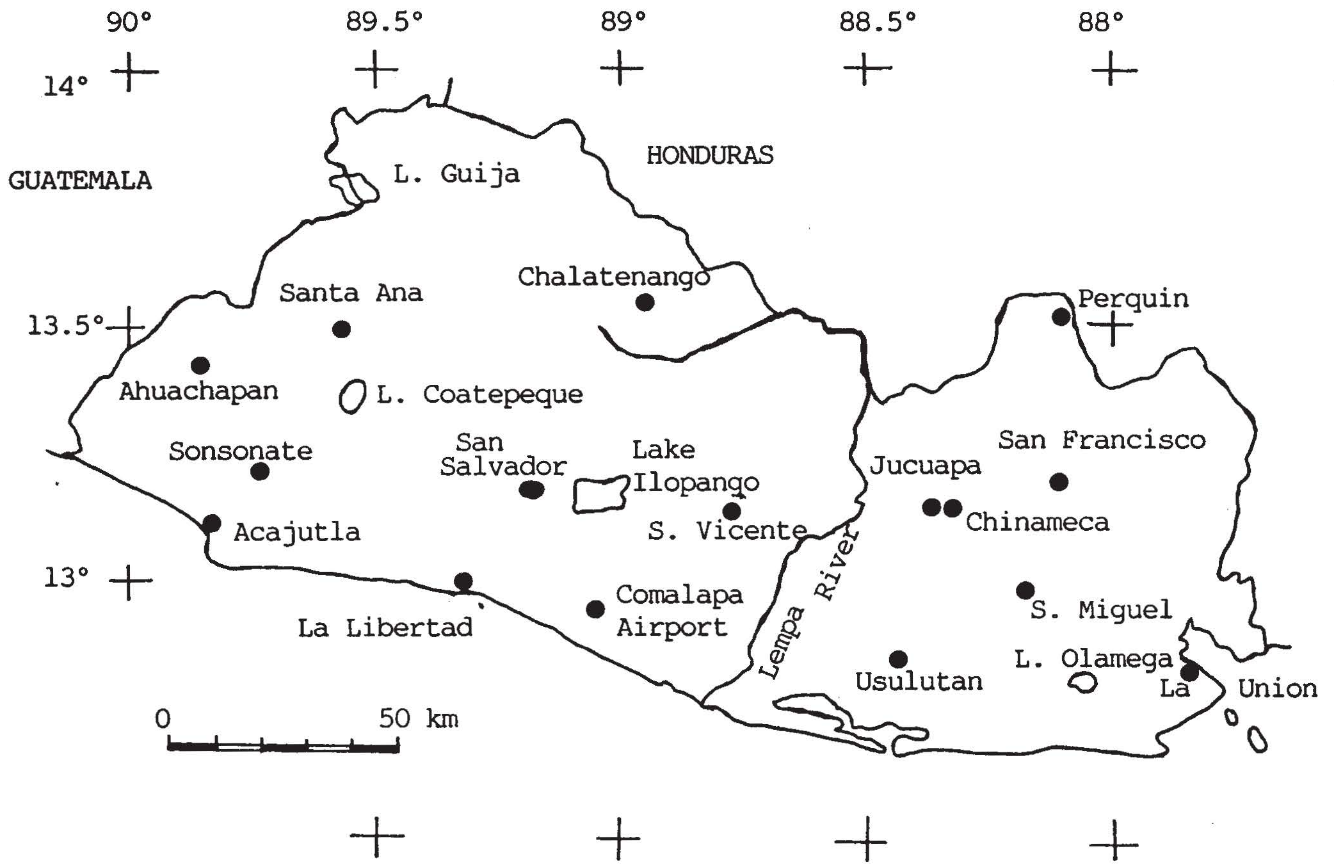

Fig. 1. Map of El Salvador.

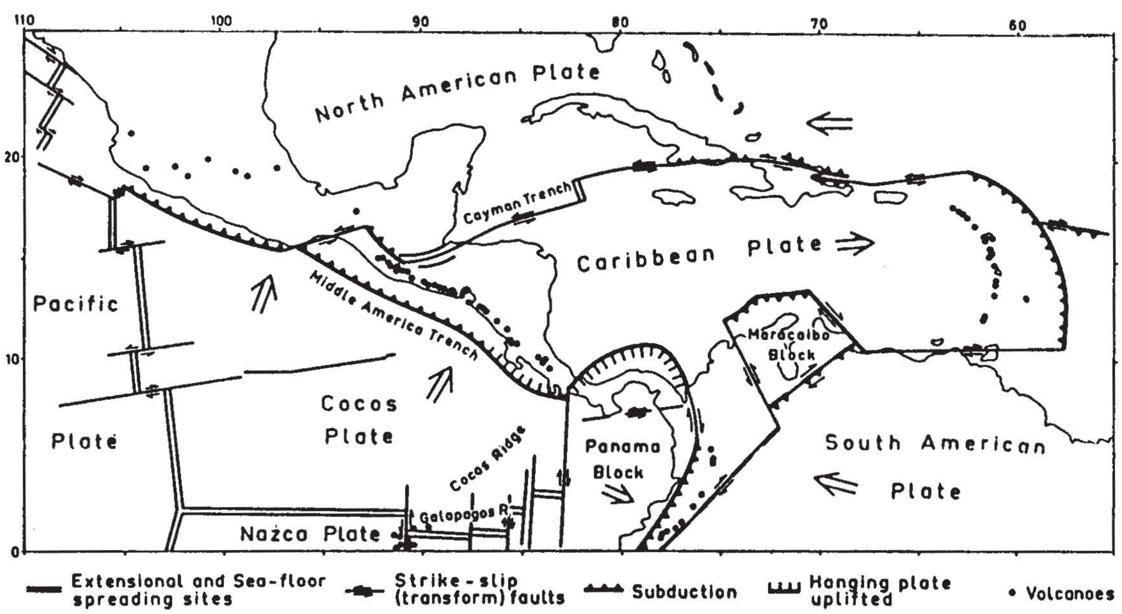

Fig. 2. Tectonics of Central America and the Caribbean (Weyl, 1980).

spheric plates in the region of Central America. The plate boundaries were first delimited by Molnar and Sykes (1969) on the basis of seismicity data. The principal tectonic structures in Central America are reproduced in Figure 2 from Weyl (1980). The principal features that affect El Salvador are the Middle America trench, where the Cocos plate is subducted below the Caribbean plate at a rate of 7 cm/yr, and the resulting chain of Quaternary volcanoes that extends from Guatemala, through El Salvador and Nicaragua, to Costa Rica. The subduction in the Middle America trench is steep and the associated seismicity extends to depths of the order of 200 km; the largest instrumentally recorded earthquakes on the Central American thrust interface have had magnitudes of about 8 (Dewey and Suarez, 1991). Seismicity associated with the volcanic chain is generally confined to the upper 20 km of the crust and within a nearly continuous belt of 20 km width along the axis of the principal Quaternary volcanoes. Earthquakes within the volcanic arc reach magnitudes between 6 and 6.5, except in Guatemala where they can reach magnitude 6.9, and are usually associated with left-lateral slip on faults striking perpendicular to the volcanic arc and right-lateral slip on those striking parallel to the arc. This seismicity has been interpreted as the result of a right-lateral shear zone driven by an oblique component of convergence between the Caribbean and Cocos plates (White, 1991). Nine of the 14 earthquakes that have damaged San Salvador since 1700 were associated with the volcanic arc, whereas only five have been subduction zone events (Harlow *et al.*, 1993).

El Salvador is also affected by seismicity associated with the Caribbean-North American plate boundary, which is manifested as a left-lateral transform zone on the Chixoy-Polochic and Motagua faults that extend across Guatemala from the Cayman Trench in the Caribbean Sea. Large magnitude earthquakes can be generated in this zone, the most recent example of which was the magnitude 7.5 Guatemala earthquake of 4 February 1976 (White, 1991).

There is also an area of seismicity remote from any of the plate boundaries, associated with a zone of extension tectonics bounded by the Honduran Depression, the volcanic chain and the Motagua faults. Two earthquakes of magnitude greater than 7 are reported to have occurred in the eighteenth century near the junction of El Salvador, Guatemala and Honduras (White, 1991). Normal faulting earthquakes in the rest of this zone, including all of Honduras (Sutch Osiecki, 1981) are generally smaller.

A more complete understanding of the seismotectonics of Central America is hampered by the relatively poor quality of teleseismic data for the region, especially for the earlier years of instrumental recording. Ambraseys and Adams (1994) have shown that many teleseismic locations prior to 1964 are subject to very gross errors, some of which can be improved using macroseismic data. A particular problem in the region, and one of prime importance in view of the tectonic configuration, is the reliable determination of focal depths. For example, the Jucuapa-Chinameca earthquakes of 1951 were reported by all contemporary seismological agencies as having focal depths between 90 and 120 km, whereas the macroseismic reports show that these were clearly upper-crustal events, (White and Harlow, 1993).

SEISMIC ZONING AND BUILDING CODES

Lara (1987) has reviewed the evolution of earthquake-resistant design in El Salvador, and reports that in the period from 1942-57, when the first buildings of more than three storeys were erected in the capital, seismic analysis was carried out on a rule-of-thumb basis, applying a horizontal acceleration of 0.10 *g* uniformly distributed over the height of the structure. The first national code for earthquake-resistant provisions was introduced in 1966 in response to the destructive earthquake of the previous year. The code was based very closely on the regulations of Acapulco (Guerrero, Mexico) following recommendations made in a report to UNESCO by Rosenblueth (1965), who suggested that either this Mexican code, or the Chilean regulations, could be applied since they corresponded to conditions comparable with those of El Salvador. Rosenblueth refers to a report by Ulrich (1946), which stated that a regulation for earthquake-resistant design was to be introduced in 1946, requiring the application of a base shear coefficient of 0.2, but there is no evidence of this code having ever been put into use. Rosenblueth suggested that a variety of US codes were employed by different engineers prior to 1965, adopting a base shear coefficient of 0.03.

The zoning presented in the 1966 code simply divides the country into two zones, with the higher seismicity Zone I including the volcanic chain and the coastal areas (Figure 3). It is interesting to note that in his original report Rosenblueth recommended that it would be appropriate to make two regionalizations of the country: one zonation would represent the hazard from subduction events, with parallel bands representing decreasing intensity with increasing distance from the coast, and the other zonation the hazard from shallow events associated with the volcanic chain, which would be represented by another zone parallel to the coast and would show a rapid decrease of intensity with distance in both directions away from the chain. The first zonation would correspond to ground motions of long duration and long period, and the second to much shorter durations with higher frequency content. These recommendations were not incorporated into the code, which presents a single spectral shape anchored to zoning factors, which for Zone II are half the values for Zone I. At the time of the 1965 earthquake there were no accelerographs in operation in San Salvador, but Rosenblueth estimated maximum ground accelerations in the range of 0.50-0.78 *g* from the displacement of heavy machinery in factories near the epicentre. He also analyzed a seismoscope record obtained further away from the source and estimated a corresponding ground acceleration of 0.44 *g*. The maximum base shear coefficient prescribed in the code is 0.39, which is actually higher than the maximum of 0.312 in the Acapulco code of 1966 (Dowrick, 1977). The site geology was not considered in the specification of design loads (IAEE, 1988).

The second code for earthquake-resistant design in El Salvador was drafted by a committee appointed by the Salvadorean Association of Engineers and Architects (ASIA) in response to the earthquake of 10 October 1986. The code was published in 1989, under the title of "emergency regulations", as a temporary provision while a definitive code was written. The drafting of the 1989 code did not include a probabilistic hazard assessment, but the zoning

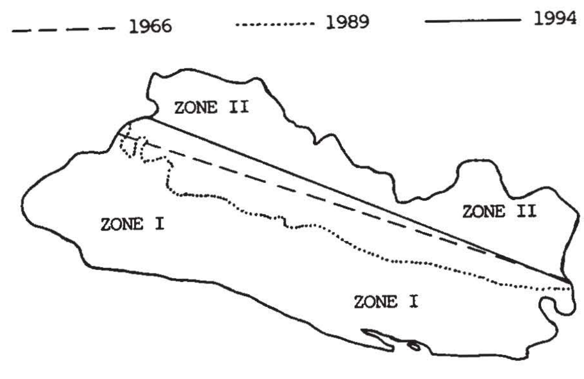

Fig. 3. Zoning maps of El Salvador from seismic building codes of 1966, 1989 and 1994.

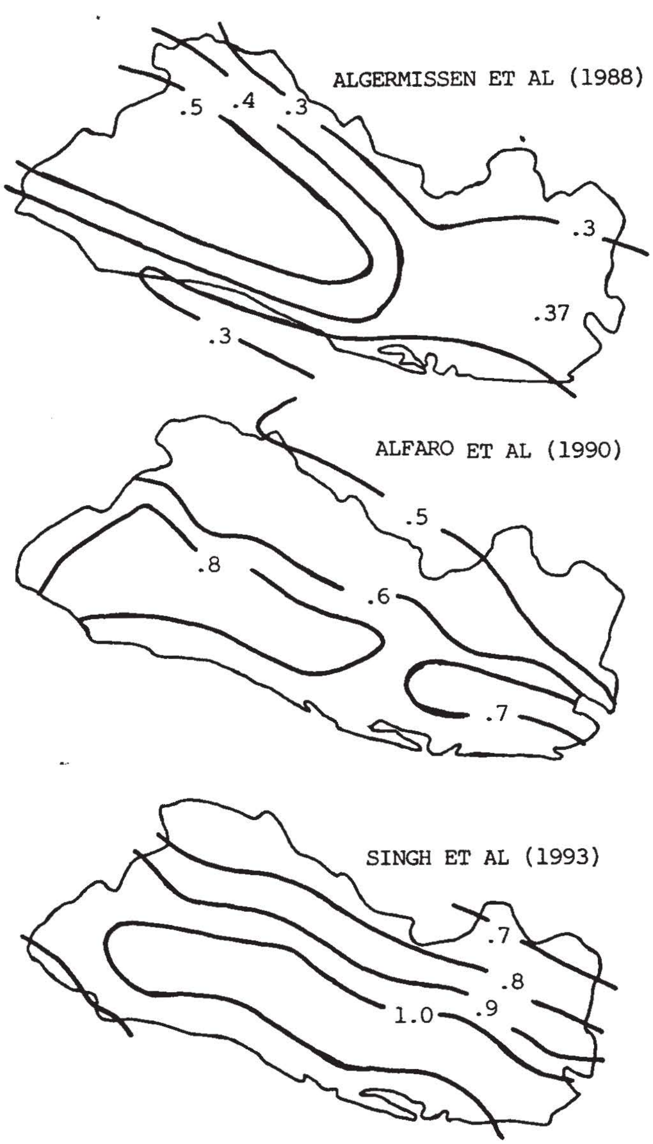

Fig. 4. Hazard maps of maximum ground acceleration with 10% probability of exceedance in 50 years from three different seismic hazard studies by Algermissen *et al.* (1988), Alfaro *et al.* (1990) and Singh *et al.* (1993).

map was altered slightly, as shown in Figure 3, although the two zone division was maintained, as was the ratio of two for seismic loads in the two zones. The design loads were increased such that the maximum base shear coefficient rose to 0.45; this change was made to reflect the nature of the accelerograms obtained in the epicentral area of the earthquake (Shakal *et al.*, 1987), which showed maximum ground accelerations of the same order as those estimated by Rosenblueth for the 1965 earthquake and also reflected his prediction that future earthquakes could generate strong vertical accelerations. The 1989 code mentions the amplification of ground motion by soil layers, but does not explicitly relate the seismic loads to the site geology.

The 1989 regulations have now been superseded by a new comprehensive building code, published in May 1994, which has been drafted in a project financed by a loan from the World Bank. The provisions for earthquake resistance have been based on the hazard study by Singh *et al.* (1993), which is reviewed in the following section. The simple division of the country is maintained in the zoning map; the hazard study recommended using the 10 $m.s^{-2}$ iso-acceleration curve from the 1,000-year hazard map, adjusted to follow political boundaries. In the published code the division is shown as a straight line, as shown in Figure 3. The soil profile at the site is incorporated into the specification of earthquake loads in this code, resulting in maximum base shear coefficients of 0.30 for rock sites and 0.36 for the softest soil sites. Vertical design loads are specified for cantilevered structural elements.

It is difficult to assess the spectra presented in the three codes in terms of the level of hazard that they represent, because the basic elastic response spectra are not given. In the 1966 and 1989 codes, the zero-period acceleration to which the spectral shape is tied is presented in the zoning factor, which also includes the structural behaviour factor related to ductility. The design spectra proposed by Singh *et al.* (1993) are based on the recommendations of the Applied Technology Council, which anchor a spectral shape to the effective peak acceleration (EPA), as defined by Donovan *et al.* (1978), for a 10% probability of exceedance in 50 years. The maximum spectral amplification is 2.75 up to 0.5 seconds period, and then decays with $T^{2/3}$, where T is the period; Singh *et al.* (1993) suggested using a decay with $T^{1/2}$, but the code has maintained the ATC shape. The peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years in Zone I, according to the hazard map of Singh *et al.* (1993) shown in Figure 4, is of the order of 10 $m.s^{-2}$. On the basis of inspection of some response spectra from accerelograms recorded in El Salvador, the EPA was taken to be equivalent to 70% of the maximum ground acceleration, giving 7 $m.s^{-2}$ for Zone I, but this was further reduced by two other factors. Firstly, on the basis of the argument that the scatter in values for EPA is significantly less than for PGA, the design EPA for Zone I is reduced to 4.8 $m.s^{-2}$. The second reduction was made to take account of the relatively short duration of strong-motion, which for upper-crustal events is usually lower than for accelerograms from other parts of the world, such as California and Mexico. Although it is true that records from upper-crustal earthquakes in the volcanic chain generally have short durations, such as those from the 1986 earthquake which have strong-motion durations of 4-8 seconds, (Shakal *et al.*, 1987), records from larger subduction zone events can have very considerable durations: the accelerogram of the 19 June 1982 earthquake, with moment magnitude 7.3, recorded in El Salvador, shows amplitudes above 0.05 *g* for a duration of almost 40 seconds, (Campbell and Algermissen, 1987). The ratios of Arias intensity of the response of oscillators of different periods for one of the 1986 San Salvador accelerograms to the Arias intensity of the response for the 1940 El Centro record were found, and the average value of 0.75 used as the duration correction factor. Therefore, the EPA for Zone I is reduced to 3.6 $m.s^{-2}$, resulting in a maximum response on the elastic design spectra of just over 1.0 *g*; seismic loads for Zone 2 are now equal to 0.75 of those specified for Zone I.

Figure 5 shows the maximum Modified Mercalli intensities that have been observed in El Salvadòr, which is consistent with the recommendations for zoning made by Rosenblueth (1965). This suggests that in the north of the country design levels could be considerably lower than for the central portion of the country, and that the Zone II loads in the 1994 code are relatively conservative.

HAZARD STUDIES FOR EL SALVADOR

The hazard study carried out for the latest Salvadorean earthquake-resistant design regulations has been based on a constant spectral shape scaled according to a single ground motion parameter, for which an attenuation relation has been derived. Another hazard study for El Salvador (Algermissen *et al.*, 1988) proposed a spectrum for San Salvador using a PGA value and the construction technique of Newmark and Hall (1982). McGuire (1977) showed that the use of this approach for site-specific evaluations could lead to inconsistencies in terms of hazard in certain circumstances, and recommended instead the use of frequency-dependent attenuation relations for spectral ordinates. This practice has now begun to be incorporated into hazard mapping and in the United States, for example, hazard maps have been produced not only for PGA but also for spectral accelerations at 0.3 and 1.0 second periods, (Shedlock *et al.*, 1994). The ultimate objective of our project will be to produce similar maps for El Salvador, but that is beyond the scope of this paper. In the following sections four different hazard assessments for El Salvador, made in terms of peak ground acceleration, are reviewed, and subsequently attenuation relations for spectral ordinates for El Salvador are explored.

Since the San Salvador earthquake of 1986, three seismic hazard studies have been carried out for El Salvador and another for Central America as a whole. The first study specifically for El Salvador (Algermissen *et al.*, 1988), the second at Stanford University (Alfaro *et al.*, 1990) and the third at the Universidad Nacional Autónoma de México (UNAM), which was referred to in the preceding section, (Singh *et al*, 1993). Figure 4 depicts hazard maps from each of these three studies, which show PGA levels with a 10% probability of exceedance in 50 years. There is considerable disagreement amongst the three maps both in terms of the geographical distribution of hazard and of the expected levels of acceleration.

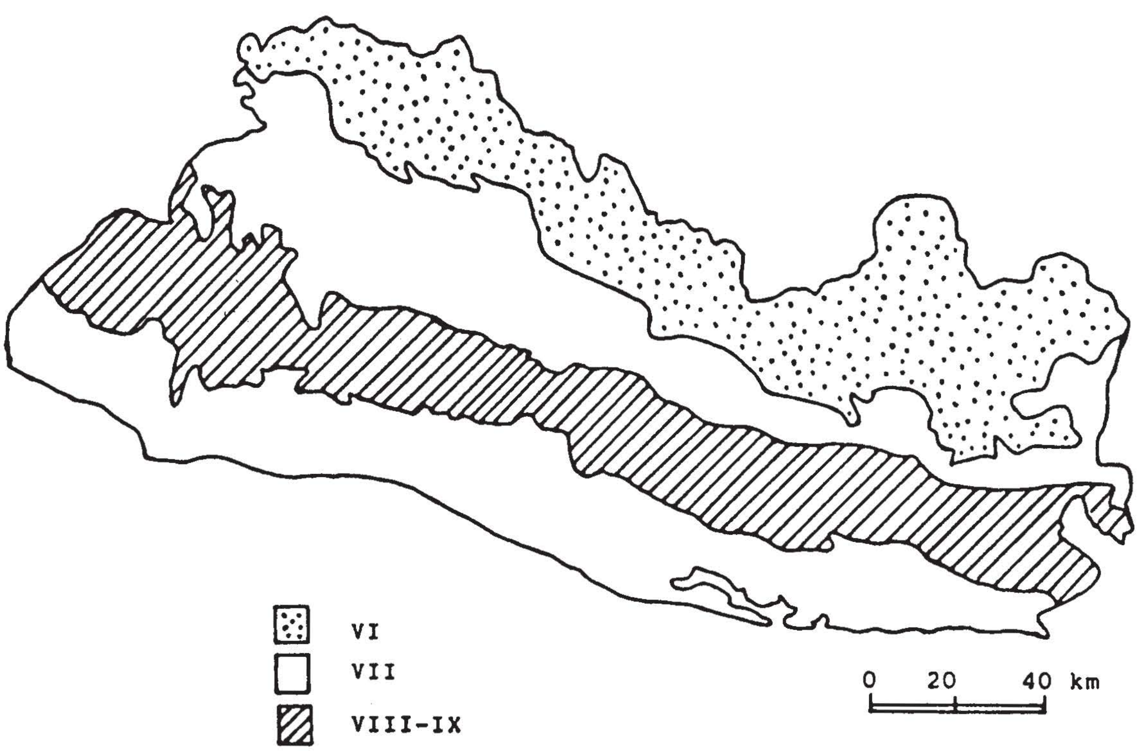

Fig. 5. Maximum observed Modified Mercalli intensities in El Salvador.

Seismic hazard has also been evaluated throughout Central America in a project that has run from 1991-94, co-ordinated by CEPREDENAC and supported by NORSAR, the Norwegian Geotechnical Institute and the University of Bergen. Hazard maps have been published for Panama (Camacho *et al.*, 1994) and for Costa Rica (Laporte *et al.*, 1994), but for the remainder of the region only a preliminary assessment giving PGA values for a few selected sites, including San Salvador, is available (Rojas *et al.*, 1993). The average PGA with a 10% probability of exceedance in 50 years presented in each of the four hazard studies for three Salvadorean towns (Figure 1) are as follows:

	Peak Ground Acceleration (g)		
Hazard study	S. Salvador	S. Miguel	Perquin
Algermissed *et al.* (1988)	0.50	0.38	0.25
Alfaro *et al.* (1990)	1.05	0.70	0.50
Singh *et al.* (1993)	1.02	1.02	0.71
Rojas *et al.* (1993)	0.76	-	-

The variation in these values and in the maps presented in Figure 4 begs the question as to the source of the differences, in order to identify where future research needs to focus. The approach used by each of the four studies is examined for each of the following inputs to the hazard analysis: delimitation of seismic source zones, magnitude-frequency relations, attenuation relations and hazard methodology.

SEISMOGENIC SOURCE ZONES

In conventional seismic hazard analysis the delimination of the source zones has a very strong influence on the results, especially in terms of the shape of the hazard maps. The seismogenic zones used by Alfaro *et al.* (1990) are shown in Figure 6; Singh *et al.* (1993) used almost exactly the same delimination, although they pointed out the necessity of using larger areas for extraction of data from the earthquake catalogues because of systematic location errors. This seismogenic zonation is broadly consistent with the description of the tectonics given earlier, the dominant zones being the volcanic chain, which is modeled as a narrow band of about 30 km width, and the Benioff-Wadati zones which are grouped as shallow (0-35 km), intermediate (36-60 km) and deep (>60 km). One difference is that Singh *et al.* did not subdivide the volcanic chain; Alfaro *et al.* separated the chain in east and west El Sal-

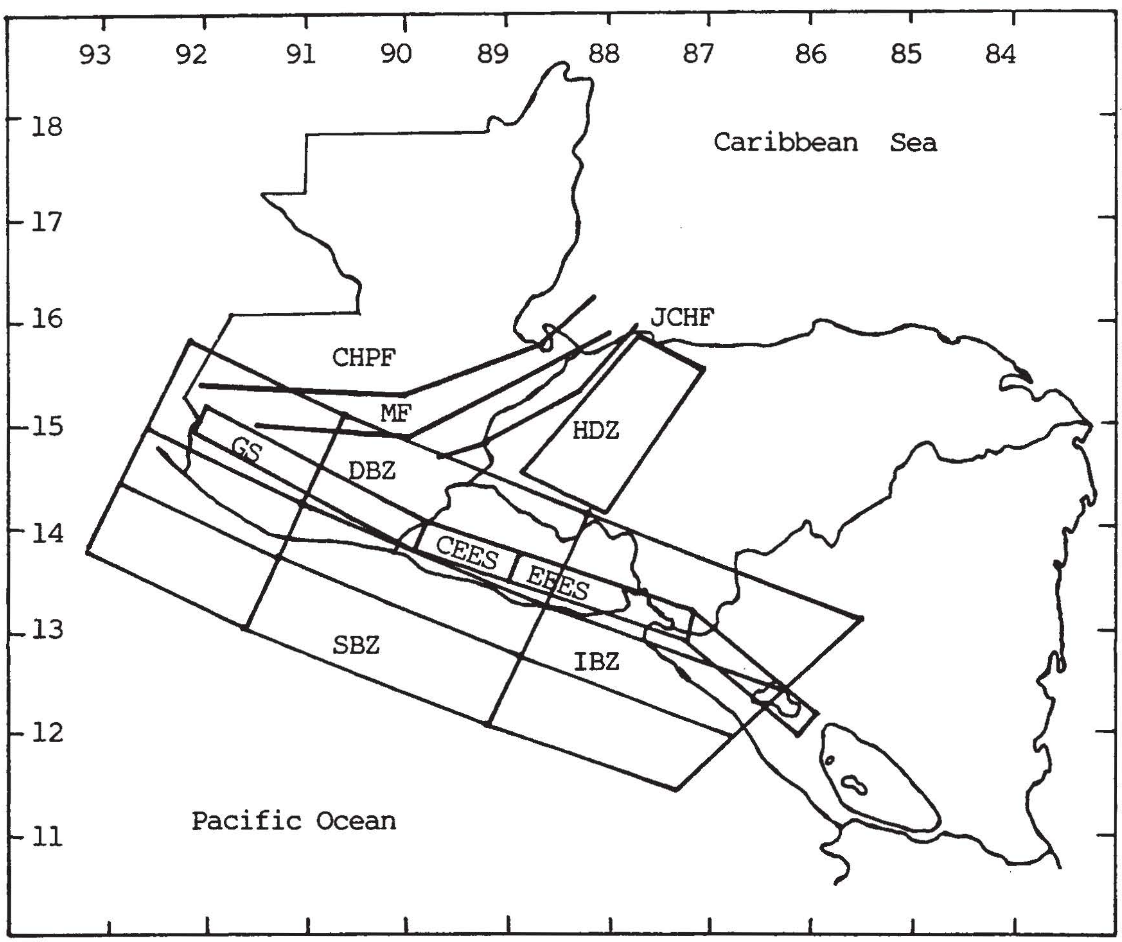

Fig. 6. Seismogenic sources used in hazard study by Alfaro *et al.* (1990). SBZ-shallow Benioff zone, IBZ-intermediate Benioff zone, DBZ-deep Benioff zone, CHPF-Chixoy-Polochic fault, MF-Motagua fault, JCHF-Jocotan-Chamelecon fault, HDZ-Honduran depression, GS-Guatemalan section of volcanic chain, EEES-eastern El Salvador section of volcanic chain, CEES-central El Salvador section of volcanic chain.

vador. In our own preliminary hazard study (Bommer *et al.*, 1994), we opted to subdivide the volcanic chain according to the segmentation of Stoiber and Carr (1974), in which the Salvadorean portion of the arc is a single unit.

The approach adopted in the earlier study of Algermissen *et al.* (1988) is somewhat different, as can be seen from Figure 7. As in the other studies, the Motagua, Jocotan-Chamelecon and Chixoy-Polochic faults are modeled as line sources, but in the Algermissen *et al.* study they are embedded in an area source of floating earthquakes with smaller magnitudes (zone 3). Zone 4 represents the boundary fault of the Cordillera Entre Rios in Honduras, where Algermissen *et al.* report that a magnitude 7.0 earthquake has occurred. On the other hand, the Honduran Depression, which appears as a source zone in the other two studies, is simply included in a regional zone of background seismicity (zone 5). The volcanic chain is subdivided into three segments (2, 2A and 2B) to reflect the non-uniform spatial distribution of events in the earthquake catalogue. In the vicinity of the Rio Lempa, the volcanic seismogenic zones narrows to about 30 km, but to the east and west it widens, almost extending across the width of the country. The modeling of the subduction zone is also different, although all three studies coincide in the conclusion that there is no important shallow seismicity within a distance of about 50 km offshore, which is expected for this accretionary wedge. However, Algermissen *et al.* modeled the subducted Cocos plate as a single source zone dipping at only 16° and extending to a depth of 65 km; this places the zone about 60 km below San Salvador, whereas in the other two studies the depth is closer to 100 km.

The seismogenic source zonation employed in the study by Rojas *et al.* (1993) is designed for a regional study and is therefore somewhat less refined in the area of El Salvador. It is interesting to note that the volcanic chain zone is at least 65 km wide within El Salvador and the subduction is modeled more steeply than in the other studies, with the Benioff-Wadati zones being at depths greater than 110 km below San Salvador. This last model appears to be more consistent with the study by Burbach *et al.* (1984), in which selected earthquake hypocentres were used to define the dip of the subducted Cocos plate as 60° in this area.

RECURRENCE RELATIONS AND MAXIMUM MAGNITUDES

Three of the hazard studies have employed the relationship between earthquake magnitude and frequency of Gutenberg and Richter (1954):

$$\log (N) = a\text{-}bM \tag{1}$$

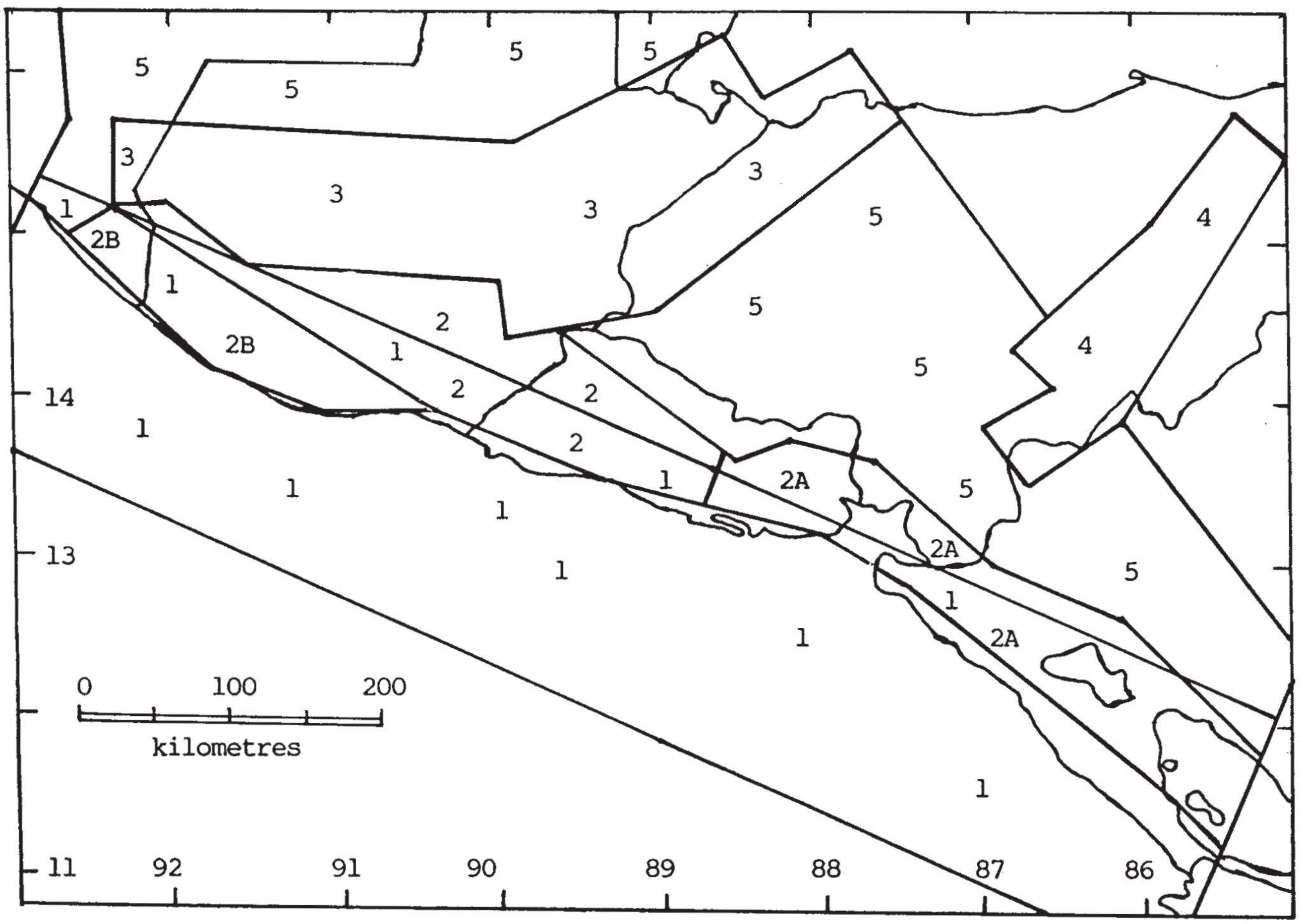

Fig. 7. Seismogenic sources used in hazard study by Algermissen *et al.* (1988). 1-subducted Cocos plate, 2, 2A, 2B-volcanic chain, 3- Guatemalan faults, 4- Cordillera Entre Rios, 5- Regional (background) seismicity.

where N is the annual number of earthquakes with magnitude greater than or equal to M, although one of the studies employed different values of *a* and *b* over different magnitude ranges. The fourth study employed a different seismicity model, which makes its comparison with the others more difficult.

Algermissen *et al.* (1988) used the earthquake catalogue of the NEIC supplemented by unspecified historical sources. Recurrence relations of the Gutenberg-Richter model were determined using the methods of Weichert (1980) and Bender (1983). The *b*-values obtained were nearly the same for all of the source zones, with a value of 0.95 for both the subduction and volcanic chain zones.

Alfaro *et al.* (1990) used the instrumental earthquake catalogues of PDE, ISC and the USC&GS, supplemented by other catalogues, and extended using the historical data retrieved by R. A. White and colleagues. Recurrence relations were determined by linear regression, and for half of the seismogenic source zones a bi-linear relationship was found to provide the best fit to the data. In our own preliminary hazard assessment, we obtained similar bi-linear magnitude-frequency relationships when performing regressions on the full instrumental catalogue, but after correcting for the incomplete reporting at lower magnitude levels, using the method of Stepp (1971), linear relationships were found. The *b*-values we obtained were very close to 0.90 for the subduction zone and between 0.85 and 1.00 for the volcanic chain segments. In the study by Alfaro *et al.* (1990), for the volcanic chain segments in El Salvador, the *b*-values were as low as 0.13 for magnitudes below about 5.5, increasing to values of 0.85 and 1.14 for larger events. In the same study, for the subduction zone in front of El Salvador, linear relations were found for the shallow and deep Benioff-Wadati zones, with *b*-values of 0.47 and 0.57 respectively, and for the intermediate zone the bi-linear relation has a value of 0.16 up to magnitude 7.0 and then increases to 1.26.

The study by Rojas *et al.* (1993) used an extensive catalogue, also based on the ISC and PDE catalogues, and extended by numerous other catalogues and special studies. This catalogue was further improved by comparison with the catalogue prepared by the Panamerican Institute of Geography and History project on Seismic Hazard in Latin America, (Shepherd and Tanner, 1994). All earthquakes were assigned a moment magnitude obtained either directly from seismic moment or converted via empirical relations from other scales. Completeness of this catalogue was estimated visually from plots of the distribution of magnitudes as a function of time. Linear magnitude-frequency relations were determined, yielding a value of 0.82 for the volcanic chain in the region of El Salvador, and 1.39, 1.17 and 1.37 for the shallow, intermediate and deep Benioff-Wadati zones respectively.

The study by Singh *et al.* (1993) used a catalogue comprising the NEIC files, supplemented by other sources such as BCIS, ISS, and NGDC, covering the instrumental period. The maximum likelihood method of Rosenblueth and Ordaz (1987) was used to evaluate the completeness of the catalogue, and the results of this analysis were incorporated into the determination of the magnitude-frequency relation, for which the model proposed by Cornell and Vanmarcke (1969) is used in place of the Gutenberg-Richter relationship:

$$N = N_0\left[\frac{e^{-\beta M} - e^{-\beta M_{max}}}{e^{-\beta M_{min}} - e^{-\beta M_{max}}}\right] \qquad (2)$$

where M_{min} is the magnitude value above which the catalogue is considered complete, M_{max} is the maximum magnitude, and N_0 is the annual frequency for events of magnitude greater than or equal to M_{min}. This relationship is linear over the range of smaller magnitudes and then curves downwards at higher magnitudes. For the volcanic chain zone, the value of β is 1.133 and the relationship is linear over the magnitude range from 4.5 to 6.0, with an equivalent *b*-value of 0.50. The catalogue used by Singh *et al.* (1993) includes several earthquakes in the volcanic chain zone with reported magnitudes greater than 7.0 (all of which occurred before 1940), which will have significantly affected the curve fitting. For the Benioff-Wadati zones, the relationships are linear almost up to magnitude 7.0 and the equivalent *b*-values are between 0.92 and 1.03.

The question of the maximum earthquake magnitude considered to be possible in each source zone is also treated differently in each of the studies. Algermissen *et al.* (1988) do not give the maximum magnitudes for all of their source zones, although they do state that it is taken as 7.6 for the Guatemalan faults. From the presentation of the recurrence data it can be inferred that for the subduction zone the maximum magnitude is at least 7.3 and for the volcanic chain at least 6.7.

Alfaro *et al.* (1990) based their estimates of M_{max} on different criteria, such as rupture lengths for the Guatemala faults, the maximum distance between volcanoes for events in the volcanic chain and the maximum known magnitudes for the subduction zone. This results in values of 6.5-6.6 for the volcanic chain in El Salvador, 7.8-8.2 in different parts of the subduction zone, 7.4-7.8 on the Guatemalan faults and 6.2 in the Honduran Depression.

In the study by Singh *et al.* (1993) the maximum magnitude is determined statistically as part of the curve fitting procedure for the recurrence relationship, and the estimate is therefore strongly influenced by the largest magnitude in the earthquake catalogue. The values for the subduction zone vary from 8.0 to 8.2, for the Guatemalan faults values range from 7.6 to 8.1, and for the Honduran Depression M_{max} is fixed at 6.9. The value of M_{max} assigned to the volcanic chain is 7.7; an earthquake of this size would be associated with a fault rupture of at least 100 km in length, whilst the geological map of El Salvador shows a highly fractured crust with many faults, none of which exceed about 25 km in length. This large value has been arrived at through the inclusion in its statistical determination of historical earthquakes extracted from the catalogue of Alfaro *et al.* (1990), the largest of which has been assigned a magnitude of 7.4, even though more recent studies suggest that the largest earthquake to have occurred in the volcanic chain, in 1854, had a magnitude of 6.6 (Harlow *et al.*, 1993).

Rojas *et al.* (1993) infer maximum magnitudes from the largest events to have occurred within each source zone and they propose values of 7.0 for the Honduran Depression, 8.0 for the Guatemalan faults, 7.5-8.0 for the different Benioff-Wadati zones, and 7.0 for the volcanic chain.

PGA ATTENUATION RELATIONS

Each of the hazard studies has derived a separate attenuation relationship for peak ground acceleration. In order to asses the relations, the data on which the regression was based, the ranges of applicability in terms of magnitude and distance, and the equation itself are presented, and then their predictions are compared graphically. For the purpose of this paper, we have not reviewed the magnitudes, distances and acceleration values reported for each data set.

Algermissen *et al.* (1988) used 82 records obtained in the vicinity of San Salvador between 1966 and 1986, although no more details are given. The equation developed for peak acceleration $A(g)$, using the mean of the two horizontal components, is:

$$\ln(A) = -1.987 + 0.604M_s - 0.9082\ln(R) - 0.00385(R) \qquad (3)$$

where R is the hypocentral distance in km. In this relations the standard deviation σ is 0.68.

Alfaro *et al.* (1990) is the only study which separated crustal and subduction data because of differences in travel paths and stress conditions. For the near-field equation a data set of 20 records obtained at epicentral distances between 1 and 27 km from 12 earthquakes in Guatemala, Nicaragua and El Salvador with magnitudes in the range of 4.1 to 7.5 was used. The equation obtained for $A(g)$, using the larger horizontal component, is:

$$\log(A) = -1.116 + 0.312M_s - \log(r^2 + 7.9^2)^{\frac{1}{2}} \qquad (4)$$

where r is the epicentral distance in km; σ=0.21. For far-field events, the data set was comprised of 20 single recordings from San Salvador of earthquakes with magnitudes from 4.2 to 7.2 and depths between 36 and 94 km, obtained at epicentral distances from 31 up to 298 km. The equation obtained from the regression on this data set is:

$$\log(A) = -1.638 + 0.438M_s - 1.181\log(r^2 + 70.0^2)^{\frac{1}{2}} \qquad (5)$$

with the same standard deviation as equation (4).

Rojas *et al* (1993) used an equation developed by Taylor Castillo *et al.* (1992), which was obtained from regression analysis of 89 records from 27 earthquakes in Nicaragua, El Salvador and Costa Rica. The magnitude range is from 3.0 to 7.6 and the hypocentral distances range from 6 to 210 km. The equation obtained using the larger of the two horizontal components for A (m.s^{-2}) is:

$$\ln(A) = 0.339 + 0.455M_s - 0.671\ln(R) - 0.00207R \qquad (6)$$

in which the standard deviation is σ=0.61.

Singh *et al.* (1993) used the strong-motion data set of Taylor Castillo *et al.* (1992) but performed their own regressions, employing several different fitting techniques. The equation they selected for use in the hazard study was found by Bayesian methods; the equation for A (cm.s^{-2}), using the vectorial resolution of the two horizontal peaks, is:

$$\log(A) = 2.74 + 0.212M - 0.99\log[G(R_0)] - 0.000943R_0 \qquad (7)$$

in which,

$$R_0^2 = R^2 + (e^{0.47M})^2$$

$$G(R_0) = R_0 \quad R_0 \leq 100\text{km} \quad G(R_0) = \sqrt{(100R_0)} \quad R_0 > 100\text{km}$$

and the scatter is represented by σ=0.26.

In Figures 8 and 9 the values of peak acceleration predicted by the equations used in the four studies, for a moderate upper-crustal event and a large subduction event, are compared. There is generally good agreement amongst the predictions for the case of the volcanic chain earthquake, the differences not being greater than the standard deviations of the individual regressions. For the subduction event there is more divergence, although in both cases, if the treatment of the two horizontal components is taken into account, the differences are actually smaller; for the PGA data set of Singh *et al.* (1993), on average the mean value of the two components in 12% smaller than the larger of the two, while the vectorial resolution of the two is 26% greater than the larger component. One point of interest is the difference between the equations used by Rojas *et al.* (1993) and those used by Singh *et al.* (1993), since they are based on the same data set, illustrating yet another source of uncertainty in the hazard determination.

The apparent agreement amongst the four equations does not mean that further research is not required into the prediction of strong-motion in Central America. A point of particular interest is that all these equations predict much higher accelerations than widely used North American and European relations, and it is important to determine if this is a genuine regional characteristic. The database of strong-motion records from Central America will need to be considerably expanded for this to be possible.

METHODOLOGIES FOR HAZARD ASSESSMENT

Three of the studies use the classic assumption of a

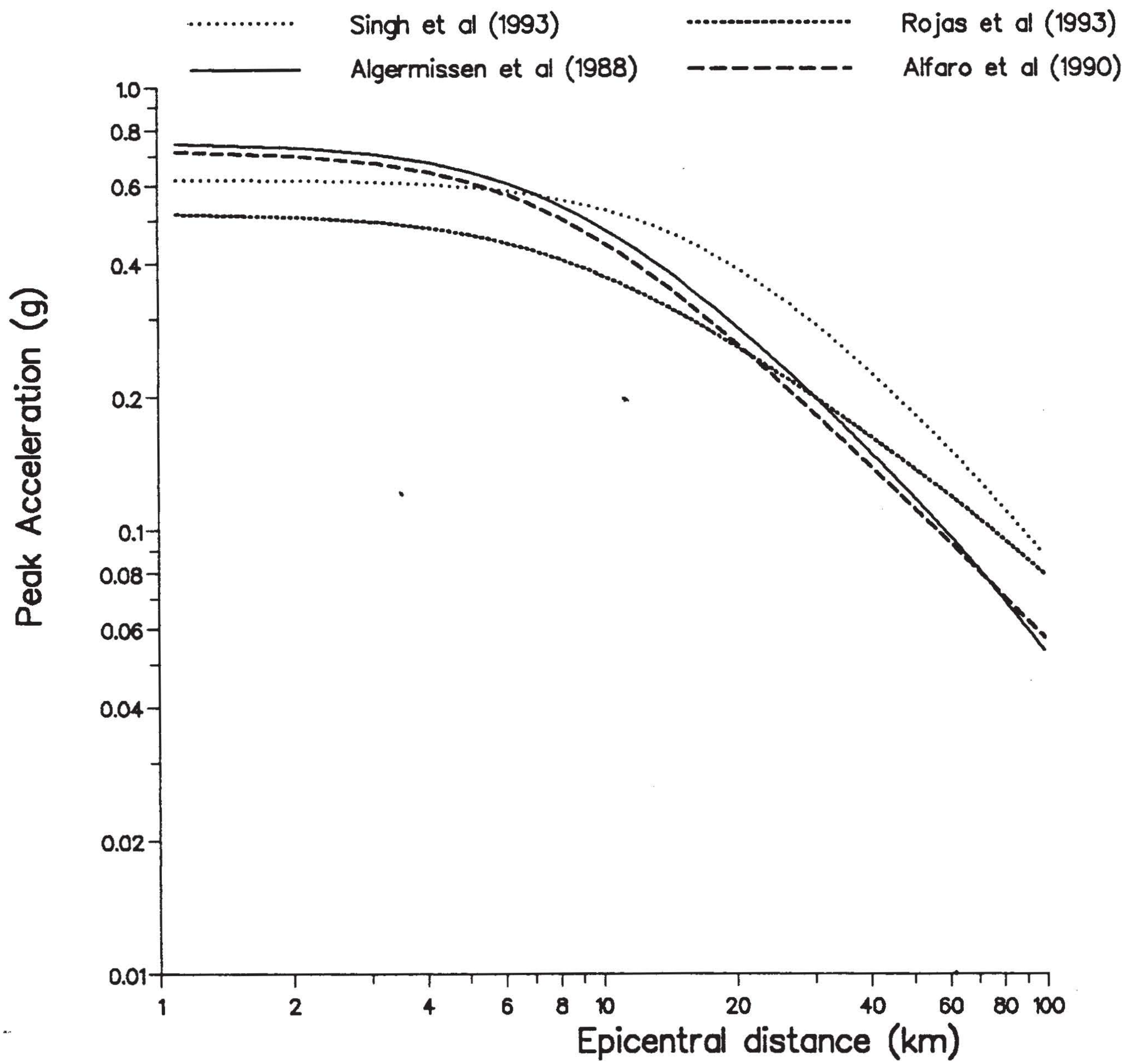

Fig. 8. Comparison of PGA attenuation curves for an earthquake with magnitude 6.0 and focal depth 8 km, predicted by equations (3), (4), (6) and (7), as used in the different hazard studies.

Poisson distribution for earthquake occurrence (Cornell, 1968), although Singh *et al.* (1993) refer to the fact that the time intervals between large subduction earthquakes follow a lognormal rather than exponential distribution. It is not clear, however, if the model developed for the Mexican subduction zone (Jara and Rosenblueth, 1988) was actually applied in the analysis for El Salvador. Algermissen *et al.* (1988) followed the hazard methodology described in Algermissen *et al.* (1982).

The study by Alfaro *et al.* (1990) adopted a different approach, combining a Bayesian model (Mortgat and Shah, 1979) for the crustal seismicity and a Markov process for subduction earthquakes (Kiremidjian and Anagnos, 1984), in the hazard assessment that they recommended for adoption. They also presented another hazard map obtained using only Bayesian analysis and it shows significantly different acceleration levels, particularly in the north of El Salvador.

It is at least implied in each of the studies that the variance in the attenuation relationship was incorporated into the computations. Bender (1984) has shown that for attenuation equations of the type employed by Algermissen *et al.* (1988) and Rojas *et al.* (1993), if the *b*-value is 1.0, then the incorporation of the attenuation scatter into the analysis will result in accelerations about 20% higher than those found using the mean values of acceleration.

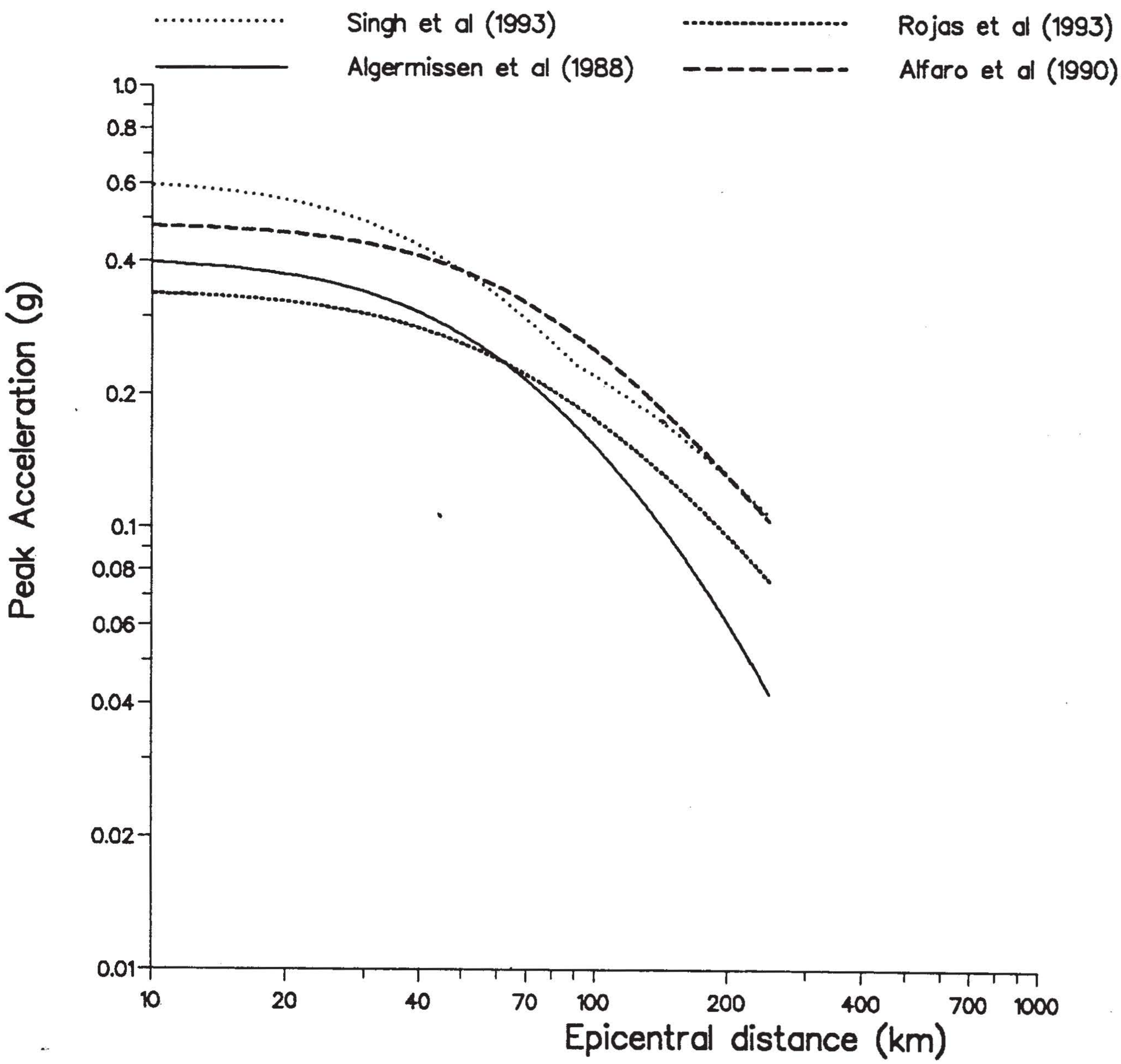

Fig. 9. Comparison of PGA attenuation curves for an earthquake with magnitude 8.0 and focal depth 50 km, predicted by equations (3), (5), (6) and (7), as used in the different hazard studies.

It is not possible in this review to determine quantitatively the relative influences of each of the components of hazard assessment in bringing about the differences amongst the four studies. It is surprising that such large discrepancies are found when the strong-motion attenuation equations employed are so similar, although the differences amongst the equations nonetheless will have influenced the hazard assessments. The lowest accelerations are those presented by Algermissen *et al.* (1988), whose equation shows the highest attenuation with distance, and the highest accelerations are those of Singh *et al.* (1993), whose equation shows the slowest attenuation over 100 km from the earthquake source.

A sensitivity study (Avalos *et al.*, 1995) carried out on the results of our own preliminary hazard assessment suggests that the attenuation equation is the factor exercising greatest influence over the results, but for the four studies under review this is unlikely to explain all the differences. The Avalos *et al.* study also found that the *b*-value of the recurrence relation in equation (1) does not affect the results significantly, and more important factors are the limits of the seismogenic zones and their corresponding maximum magnitudes. The hazard level at a point within a seismogenic zone is not greatly affected by the geometric limits and the maximum magnitude of the same zone, but points outside the limits are strongly influenced. For example, it is found that the hazard level estimated for northern El Salvador - which the historical record suggests is comparatively low - depends very much on the width of the volcanic chain zone source and the magnitude of the largest earthquake that could be expected to occur in that source. The high accelerations presented by Singh *et al.* (1993) seem in part to be the result of the high maximum magnitudes assigned to the volcanic chain and the Honduran Depression seismogenic sources.

A revised regional hazard assessment presented by Lindholm *et al.* (1995) was made available to us after making our comparative review of the studies discussed in this paper. In this latest study the 475-year return period acceleration near San Salvador is about 0.3*g*; the available assessments for the capital now vary by a factor of three. A much earlier regional study, which has not been included in this review, was presented by Hattori (1979) using the method of extreme value fitting and gives a 200-year return period acceleration for San Salvador of less than 0.2*g*.

ATTENUATION RELATIONS FOR SPECTRAL ORDINATES

A recently published study by NORSAR has produced the first equations for the attenuation of spectral ordinates in Central America (Climent *et al.*, 1994). The equations are obtained from regression analysis on 280 records generated by 72 earthquakes in Central America and Mexico. On the basis of inspection of observed to predicted values, this study concluded that there was no clear difference between the data sets corresponding to upper-crustal and to subduction zone events, and the equations are presented for the region as a whole regardless of the earthquake source.

We have identified from various sources 372 triaxial accelerograms generated by 167 earthquakes in Central America between 1947 and 1993, and we obtained the response spectra of 53 of the records, all from El Salvador and Nicaragua. Joyner and Boore (1988) suggest that the source processes of subduction-zone and shallow crustal earthquakes may be similar, but that there are significant differences in geometry and propagation path between the two types of earthquake data. For this reason we decided to obtain separate equations for subduction events. We do not recommend that these equations be used for hazard analysis, since they are derived only for the exercise of investigating the equations of Climent *et al.* (1994). The model chosen for the subduction zone events is that used by Crouse *et al.* (1988):

$$\ln(PSV) = a + bM + d\ln(R) + qh \quad (8)$$

where PSV is the larger horizontal pseudo-velocity response in cm.s^{-1}, M the surface-wave magnitude, R the hypocentral distance and h the focal depth, both in km; a, b, d and q are the coefficients found by regression. Our data set included 36 records obtained at hypocentral distances of between 62 and 260 km from 20 earthquakes with magnitudes between 3.7 and 7.0. The resulting coefficients of equation (8) and the standard deviations, presented without smoothing, are as follows:

T	a	b	d	q	σ
0.1	3.19	0.471	-1.481	0.0161	0.53
0.15	4.11	0.433	-1.468	0.0148	0.66
0.2	4.32	0.365	-1.349	0.0153	0.72
0.3	2.82	0.482	-1.055	0.0136	0.72
0.4	3.87	0.644	-1.434	0.0137	0.50
0.5	3.38	0.742	-1.501	0.0189	0.57
0.75	1.44	0.884	-1.359	0.0202	0.64
1.0	0.90	0.941	-1.278	0.0144	0.63
1.5	0.60	0.813	-1.077	0.0126	0.69
2.0	0.26	0.786	-1.055	0.0140	0.69

The corresponding equation for peak ground acceleration A(*g*), for which σ=0.54, is:

$$\ln(A) = -1.47 + 0.608\,M - 1.181\,[\ln(R)] + 0.0089h . \quad (9)$$

The started errors are slightly worse for some periods than those found by Crouse *et al.* (1988), but they are of the same order. In Figure 10 the spectrum predicted by these equations for a large subduction zone earthquake of magnitude 8 with focal depth 50 km, at a hypocentral distance of 75 km - which could represent the effect in San Salvador - is compared to those predicted by Crouse *et al.* (1988) and by Climent *et al.* (1994). There is reasonable agreement amongst the three predictions, although the equation of Crouse *et al.*, which is based on data from northern Honshu, uses the randomly oriented, as opposed to the larger, horizontal component. The apparent underestimation of the long-period response by our equations is probably due to the absence of very large magnitudes in our data set.

For shallow crustal earthquakes there were far fewer records available, and our data set of 17 records is insufficient to perform a regression analysis. Nearly all of the records that are available for this zone have been obtained at relatively short distances, so it is not yet possible to make meaningful inferences about the distance dependence. It is also known that the records that have been obtained are mainly from sites in San Salvador covered by the *tierra blanca* volcanic ash which has been shown to produce strong amplification of ground motion, (Atakan and Torres, 1993).

Historical data reveals that the average return period of earthquakes that severely damage San Salvador is less than 25 years (Harlow *et al.*, 1993), so it is debatable whether it is meaningful for this situation to define a hazard level corresponding to 10% exceedance probability within 50 years. In the particular case of San Salvador, which may not be true elsewhere along the volcanic chain, there is convergence between probabilistic and deterministic approaches to hazard assessment. This fact, combined with the importance of soil layer response in the city, have led to many studies for microzonation of San Salvador and the original plan for the new building code was to include a national seismic zonation and additionally a microzonation for the capital. Extensive work on the seismic microzonation of San Salvador was carried out by the Consorzio Italiano after the 1986 earthquake, (Faccioli *et al.*, 1988).

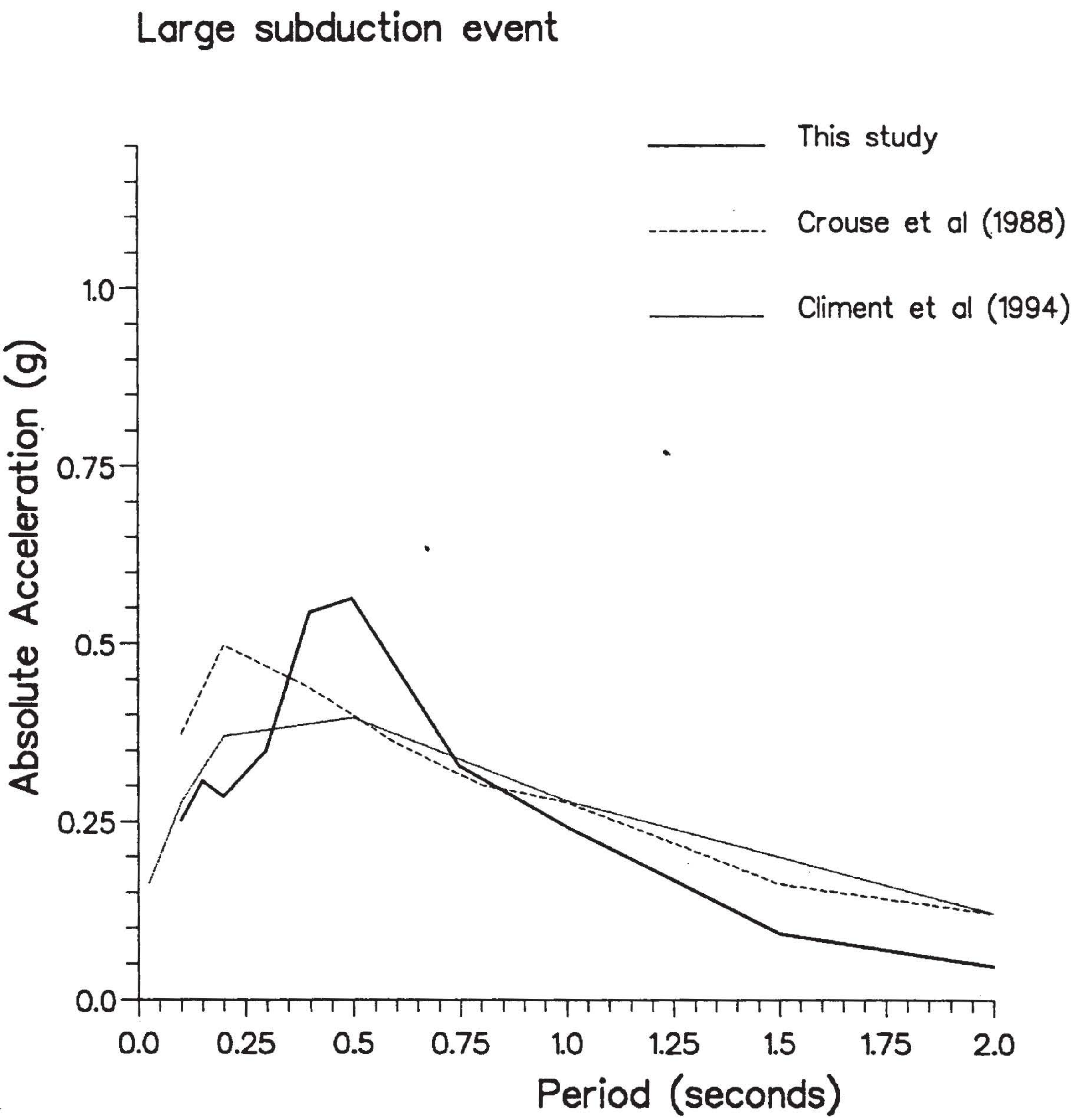

Fig. 10. Comparison of spectra predicted for subduction zone event with magnitude 8.0 and focal depth 50 km, at a hypocentral distance of 75 km, by this study and by the equations of Crouse *et al.* (1988) and Climent *et al.* (1994).

In order to explore the applicability of the existing spectral attenuation relations to the case of volcanic chain earthquakes, which are characterized by being intensely damaging over a small near-field area, we have compared three real spectra with the predictions. In Figure 11 the response spectra from the horizontal recordings of the 10 October 1986 earthquake at the CIG, IGN and UCA stations are compared with the predictions from the frequency-dependent equations presented by Dahle *et al.* (1995), slightly modified from those of Climent *et al.* (1994). The predictions from the recent North American equations of Boore *et al.* (1994) and the European equations of Ambraseys *et al.* (1996) are also shown; values of pseudo-velocity (PSV) response from the Central and North American equations are converted to acceleration response (PSA) via the relation PSA=(2π/T)PSV. The appropriate values of magnitude employed are M_s=5.4 in the European relation and moment magnitude $\mathbf{M}$=5.7 in the others. Epicentral distances have been calculated as 3.8, 5.2 and 6.1 km for the CIG, IGN and UCA respectively and used as source distances in the North American and European relations; for the Central American equations, which use hypocentral distance, the focal depth was taken as 10 km, (White and Harlow, 1993). The three equations employed include in the prediction the foundation conditions, for which we have made use of the shear wave velocity V_s profiles determined in down-hole measurements by the Consorzio Italiano (Faccioli *et al*, 1988). In the Boore *et al.* (1994) equations the site parameter is the average value of V_s over 30 m for which we calculate 526 m.s^{-1} at CIG, the volcanic chain zone source and the magnitude of the largest earthquake that could be expected to occur in that source. The high accelerations presented by Singh *et al.* (1993) seem in part to be the result of the high maximum magnitudes assigned to the volcanic chain and the Honduran Depression seismogenic sources.

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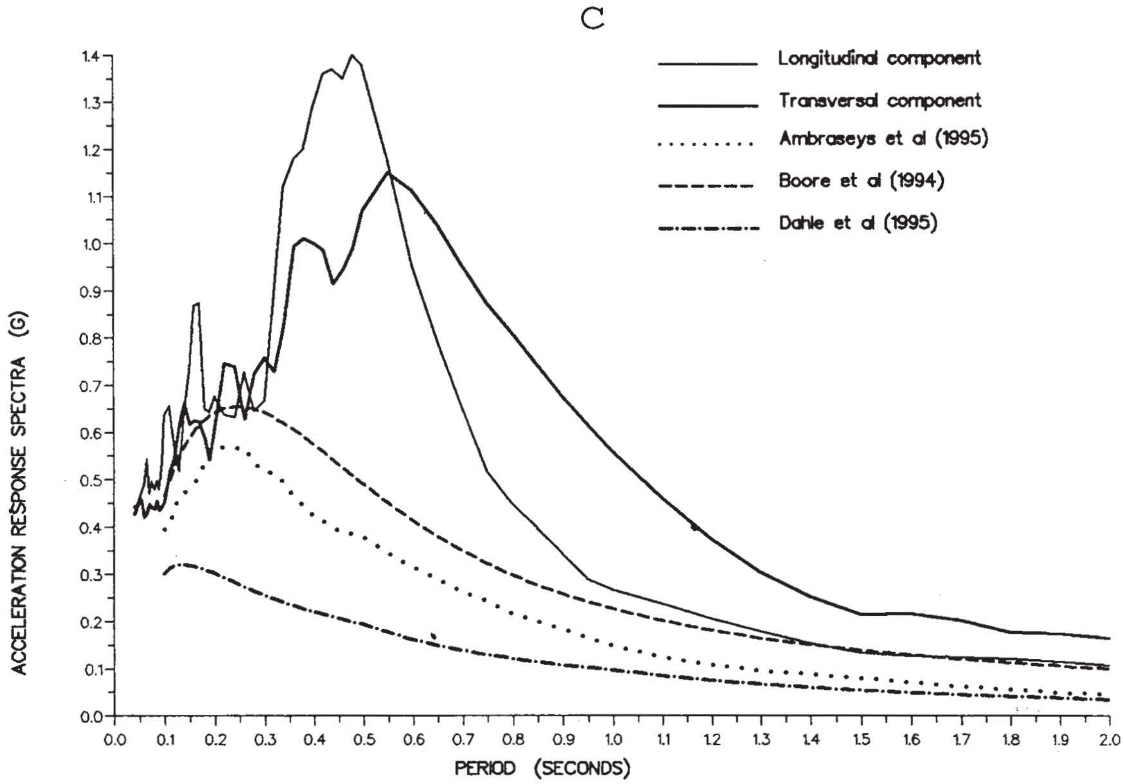

Fig. 11. (Cont.).

272 m.s-1 at IGN and 247 m.s-1 at UCA. For the site parameter in the Ambraseys *et al.* (1996) equations this results in CIG being classified as "rock" and IGN and UCA as "soft soil". The Dahle *et al.* (1995) equations classify sites simply as rock or soil and in this case all three stations are "soil" sites: bedrock is only encountered within 30 m at the CIG site, where it is located at 10.5 m and the average value of V_s over this soil layer is 220 m.s-1.

The most striking observation is the considerable underestimation of the spectral amplitudes by all of the equations, particularly those of Dahle *et al.* (1995), although these would give slightly higher amplitudes using the lower estimate of 7 km for the focal depth. There are several factors that could have affected the nature of these strong-motion recordings, all of which are from the basement of low-rise reinforced concrete buildings, including topographical effects since all three stations are located on sites of pronounced relief. It would appear that the attenuation equations do not take full account of the amplification caused by the fluviatile pumice which may be the source of the high spectral amplitudes in the intermediate period range; the highest response acceleration, on the CIG record, is close to the fundamental period of the soil layer at that station. It is also possible that there are errors in the magnitude determinations and in the epicentral location, and so close to the source it could be the case that even for this small event the rupture dimensions are important in calculating the distance. Nonetheless, assuming that the input parameters are correct, another observation can be made which is that the degree of underestimation decreases with increasing distance from the source. This suggests that such general attenuation equations are not suitable for predicting motions in the very near-field; since the volcanic chain events are typically destructive over only a small area, the normal methods of hazard assessment may not be appropriate for locations such as San Salvador.

DISCUSSION

Several important studies have been carried out which contribute significantly to a greater understanding of the earthquake hazard in El Salvador and Central America. A code for earthquake-resistant building design has been issued which reflects some of the findings of these studies, and although it should be periodically revised as more data becomes available, it is important that its provisions are enforced and that engineers in El Salvador are trained in its application. This is especially important in this post-war period, with extensive reconstruction and the planning of several new urban settlements along the volcanic chain.

Further studies are currently underway to examine the sensitivity of the hazard estimates to the variation of the input parameters and the methodology applied to the calculations, but it is recognized *a priori* that the results will continue to be limited by the quality and extent of the available data. For this reason, additional studies will undertake a thorough revision of the regional and local tectonics, including faults, and a reappraisal of the seismicity data, including magnitudes (Ambraseys, 1995). The strong-motion data will also be re-analyzed and compared with data from other tectonically similar regions where strong-motion recordings are more abundant, in order to explore the possibility of supplementing the rather limited data base, and attenuation characteristics are also being inferred from intensity and from seismoscope recordings. A new network of digital accelerographs is also being established in El Salvador within the framework of the CEC project. This network will complement the existing array of SMA-1 instruments and one of the main objectives of its operation will be to investigate the attenuation of strong-motion from volcanic chain earthquakes.

Different approaches to hazard assessment across the country and particularly for the major settlements along the volcanic chain need to be explored. It can be expected that these studies will attach greater confidence to the hazard assessments, which is important since underestimations of the hazard can result in unsafe buildings and overestimations can lead to unnecessarily high investments, depriving other aspects of recovery and development. For this assessment to be genuinely useful and to obtain applicable *design* spectra, the appropriate structural behaviour factors for El Salvador need to be investigated. The other component of the risk equation, the vulnerability of structures, is less well-known and therefore needs to be evaluated in parallel with the hazard. As a result of the short return period of damaging events in San Salvador, the next earthquake can be expected to strike the capital before the new building regulations have had wide-spread impact through the replacement of old building stock. Demographic and environmental changes, as well as the evolution of construction practices, have important consequences for the seismic risk in El Salvador, as elsewhere. Rosenblueth (1965) reported that in May 1965 the principal cause of fatalities was the collapse of *bahareque* (timber and bamboo frame with earth infill) houses. In October 1986, the collapse of *bahareque* dwellings - more due to deterioration of the untreated building materials rather than an inherent lack of resistance - did contribute to the death toll of 1,500, but the main causes of loss of life were the collapse of large reinforced concrete structures (several of which had been damaged and poorly repaired in 1965 or in 1982) and slope failures in ravines and on hillsides where shanty towns have settled. The combination of a rapidly expanding population and increased slope instability due to deforestation and erosion, as well as the large number of multi-storey reinforced concrete structures that were affected by the 1986 earthquake, result in a very high level of risk which the new building code will not affect at all.

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