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The El Salvador earthquakes of January and February 2001: context, characteristics and implications for seismic risk

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Abstract

The small Central American republic of El Salvador has experienced, on average, one destructive earthquake per decade during the last hundred years. The latest events occurred on 13 January and 13 February 2001, with magnitudes M_w 7.7 and 6.6, respectively. The two events, which were of different tectonic origin, follow the patterns of the seismicity of the region although neither event has a known precedent in the earthquake catalogue in terms of size and location. The earthquakes caused damage to thousands of traditionally built houses and triggered hundreds of landslides, which were the main causes of fatalities. The earthquakes have clearly demonstrated trends of increasing seismic risk in El Salvador due to rapid population expansion in areas of high shaking and landslide hazard, exacerbated by deforestation and uncontrolled urbanisation. The institutional mechanisms required for the control of land use and building practice are very weak and present a major obstacle to risk mitigation. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: El Salvador; Earthquakes; Strong motion; Landslides; Seismic risk; Vulnerability

1. Introduction

The earthquake of 13 January 2001 that struck El Salvador was the first major seismic disaster of the third millennium and the fifth destructive earthquake to affect the small Central American republic in 50 years. The earthquake was followed exactly 1 month later by a second event, of different tectonic origin, on 13 February, which compounded the destruction. These two earthquakes claimed almost 1200 lives. In addition, 20% of houses were damaged, with 12% either completely destroyed or declared uninhabitable. Economic losses were estimated by the UN Economic Commission for Latin America (ECLA/CEPAL) at US$ 1.6 billion, which is equivalent to 12% of the GDP of the previous year [1]. Estimates by the IMF and the World Bank give a higher figure of US$ 1.9 billion [2].

This paper presents the context in which these earthquakes occurred, including their precedent in the seismic history of El Salvador, and describes the characteristics of the events and their impact on the built and natural environments, and on the population. The primary objectives of the paper are firstly to provide an overview of the characteristics and effects of the earthquakes, and secondly to assess the relative importance of the different factors, physical and social, which have been demonstrated as contributing to the high level of seismic risk in El Salvador.

2. Geophysical, geological and geographical contexts

With an area of just over 20,000 km^2 El Salvador is the smallest of the Central America republics, located on the

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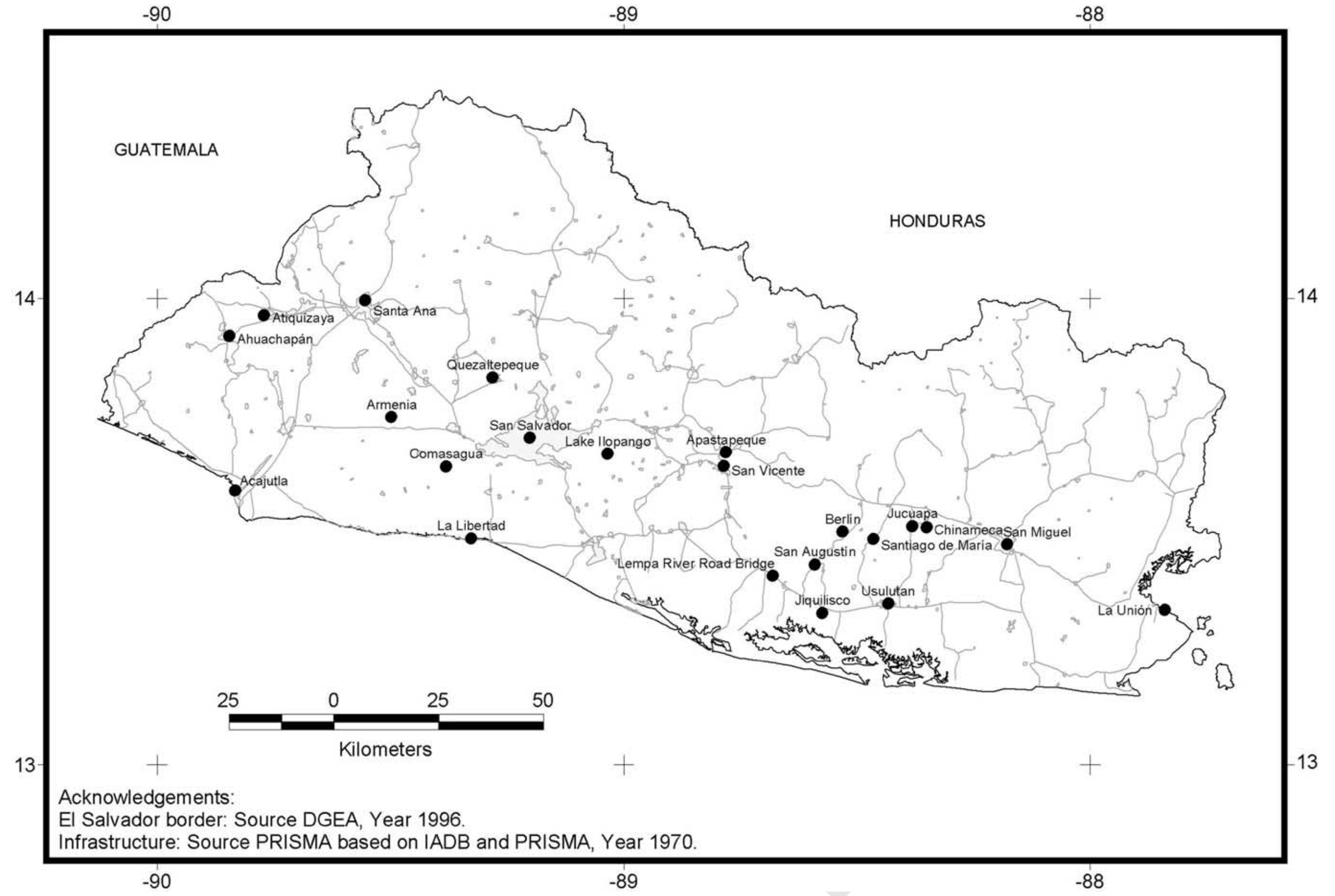

Fig. 1. El Salvador.

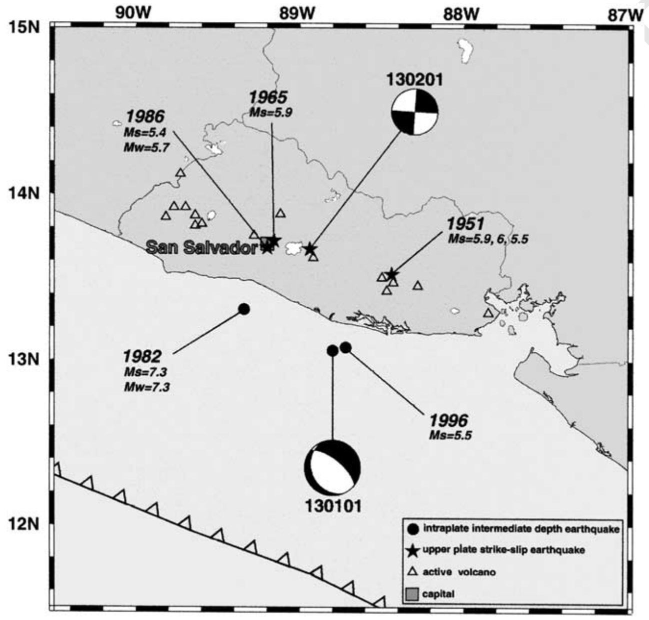

Fig. 2. Focal mechanisms determined for the earthquakes of 13 January and 13 February 2001. Stars are epicentral locations from NEIC. Red line is the Middle America Trench and yellow triangles are volcanoes. Locations of previous earthquakes are indicated by black stars.

Pacific coast of the isthmus and bordered by Guatemala to the west, and Honduras to the north and east (Fig. 1).

2.1. Tectonics, seismicity and seismic hazard

El Salvador is affected by earthquakes from two main sources of seismicity. The largest earthquakes are generated in the Benioff–Wadati zones of the subducted Cocos plate, which is converging with the Caribbean plate in the Middle America Trench (Fig. 2) at an estimated rate of 7 cm/year [3]. The largest earthquake in this zone during the 20th century, in the vicinity of El Salvador, occurred on 7 September 1915, with a reported magnitude of M_s 7.8 and a focal depth between 45 and 60 km [4]. This earthquake caused widespread destruction in western El Salvador, affecting particularly the town of Juayúa [5]. Large subduction earthquakes on 28 March 1921 (M_s 7.4) and 21 May 1932 (M_s 7.1) caused minor and moderate damage in eastern and central El Salvador, respectively; the relatively small impact of these earthquakes was probably the result of their focal depths of 170 and 150 km, respectively [4]. An earthquake on 19 June 1982, offshore from western El Salvador, did cause widespread damage in the southwest of the country, mainly in *adobe* (sun-dried clay brick) and *bahareque* (wattle-and-daub) houses, and triggered many landslides [6,7]. This earthquake shared many similarities with the earthquake of 13 January in terms of mechanism and focal depth, although somewhat smaller with a magnitude of M_w 7.3. The damage patterns were similar to those of the January 2001 earthquake, but much less severe with a total of just eight fatalities. The worst destruction occurred in the town of Comasagua, which was also very severely affected by the January 2001 earthquake.

The second source of seismicity affecting El Salvador is a zone of upper-crustal earthquakes that coincide with the Quaternary volcanoes that extend across the country from west to east, forming part of a chain extending throughout the isthmus from Guatemala to Panama. Due to their shallow foci and their coincidence with main population centres, these earthquakes (Fig. 2) have been responsible for far more destruction in El Salvador, as in neighbouring Nicaragua, than larger earthquakes in the subduction zone [8]. During the 20th century, such shallow focus earthquakes caused destruction on at least seven occasions, sometimes occurring in clusters of two or three similar events separated by periods of minutes or hours. On 8 June 1917 an earthquake occurred west of the capital, San Salvador, assigned a magnitude M_s 6.7 by Ambraseys and Adams [4] and M_s 6.5 by White and Harlow [8], causing destruction in Armenia, Ateos, Quetzaltepeque and other towns. The earthquake was followed by an eruption of the San Salvador volcano, which resulted in lava flows to the north. White and Harlow [8] report a second event of M_s 6.4, on the eastern side of San Salvador, less than an hour later, but this is contested by Ambraseys and Adams [4]. On 28 April 1919 San Salvador was again damaged, this time by a shallow earthquake of M_s 5.9. On 20 December 1936, an earthquake of M_s 6.1 caused very heavy damage to the town of San Vicente, 40 km east of San Salvador, with more than 100 deaths [9]. The 1936 earthquake is of particular interest since the location was similar to that of the earthquake of 13 February 2001.

On 25 December 1937 an earthquake of M_s 5.8 near the Salvadorian border with Guatemala caused damage and a few deaths in the towns of Ahuachapán and Atiquizaya. A series of three destructive earthquakes occurred in eastern El Salvador on 6–7 May 1951, with magnitudes M_s 5.9, 6.0 and 5.5, destroying the towns of Jucuapa and Chinameca, leaving about 400 dead [10].

The capital city of San Salvador, amongst the Latin American city most frequently damaged by earthquakes, was badly hit on 3 May 1965 (M_s 5.9) and on 10 October 1986 (M_s 5.4, M_w 5.7). The 1965 earthquake left about 120 dead [11] whereas the 1986, despite being of smaller magnitude, resulted in 1500 deaths and more than 100,000 homeless [12–14]. Many engineered structures that collapsed in 1986 had been damaged by the 1965 earthquake and possibly further weakened by the 1982 subduction event.

The shallow focus, moderate magnitude earthquakes that occur along the volcanic chain are generally tectonic rather than volcanic in origin, and are probably the result of a right-lateral shear zone caused by an oblique component of the Cocos–Caribbean collision [15]. However, swarms, which may have volcanic origin, are also relatively frequent. In March and April 1999 an important seismic swarm occurred in an area close to the San Vicente (Chichontepec) volcano, with almost 1000 small earthquakes registered, none exceeding M 4.5, registered, and as many as 160 occurring per day. A similar swarm had affected approximately the same area in July 1975. The 1999 swarm, despite the size of the individual events, caused minor to moderate damage to a number of adobe houses and also the church in Apastepeque. The same area was also affected by the earthquakes of January and February 2001; it is very likely that the level of damage was exacerbated by the damage inflicted during the 1999 swarm.

Major earthquakes also occur on the Motagua and Chixoy-Polochic faults that traverse Guatemala and mark the boundary between the Caribbean and North American plates, but they are sufficiently distant to not produce damaging motions in El Salvador. The M_s 7.5 Guatemala earthquake of 4 February 1976 caused shaking that did not exceed MM intensity of V within El Salvador [16].

White [15] also describes a fourth source of seismicity as a zone of tensional tectonics near the common borders of El Salvador, Guatemala and Honduras, bounded by the Motagua fault to the north, the volcanic chain to the south and the Honduran Depression to the east. White [15] asserts that an earthquake of M_s 7.5 occurred in this zone in June 1765. The largest earthquake during the 20th century in this zone was that of 29 December 1915 (M_s 6.4), for which Ambraseys and Adams [4] relate press reports alleging two deaths in San Salvador due the collapse of walls, although the effects in El Salvador were clearly not overly important.

There have been a number of probabilistic seismic hazard assessments carried out for El Salvador [17–19] and for Central America [20,21]. The hazard maps produced for a 475-year return period, despite being based on generally similar seismological and strong-motion data, differ significantly in terms of the geographical distribution of the hazard and by more than a factor of three in terms of the maximum ground accelerations [22]. Following the San Salvador earthquake of May 1965, Rosenblueth and Prince [23] proposed two separate seismic zonations for El Salvador, one for suduction earthquakes and one for upper-crustal seismicity. Although the application of this proposal has been explored [24,25], it has not been incorporated into seismic design codes.

2.2. Geology, geomorphology and landslide hazard

El Salvador is made up of four morphological-geological units, each of which forms an east–west strip across the country parallel to the coast [26]. The northernmost unit, along the border with Honduras, is a mountain range consisting mainly of plutonic rocks from the Tertiary. To the south of these mountains is the Great Interior Valley that forms the central area of the country; the southern part of the valley includes the Salvadorian segment of the chain of Quaternary volcanoes, six of which are active. To the south of the valley are three coastal mountain ranges: Tacuba on the western border with Guatemala; the Cordillera del Bálsamo to the south and west of the capital; and the Jucuarán range bordering the Gulf of Fonseca to the east. Between the coastal ranges are two coastal plains, the larger one, in the centre and east of the country, including the estuary of the Río Lempa, El Salvador's main river.

The geology of El Salvador is entirely volcanic. The youngest and most commonly encountered volcanic soil is the *tierra blanca* ash, which originates from eruptions in the Coatepeque and Ilopango calderas. The *tierra blanca* occurs as silty sand or sandy silt, and is generally relatively well-consolidated and stable only where it is thick [27]. The strength of the tierra blanca, which permits it to stand in near-vertical slopes of up to 15 m or more, derives from a combination of weak cementation, probably due to silica gels, and negative pore water pressure, resulting from partial saturation, which have been measured in the range 400–500 kPa [28].

Earthquake-induced landslides are common in Central America although different mechanisms of slope failure dominate in the northern countries of Guatemala and El Salvador compared to southern countries of Costa Rica and Panama [29]. In the south, the most abundant and most damaging slope failures are translational soils in residual soils, whereas in the north soil and rock slides on volcanic slopes, and more commonly, soil falls and slides in steep slopes of pumitic ash, dominate. Although these volcanic ash deposits are able to form almost vertical slopes in incised ravines (*barrancas*) and in road cuts, they are susceptible to sudden and catastrophic failure under sustained or intense rainfall and under earthquake shaking. The numbers of landslides triggered by earthquakes in these ash deposits tend to be disproportionately high compared to the numbers of landslides triggered by earthquakes of similar magnitude in other parts of the world. In the global database of Keefer [30], the 1976 Guatemalan earthquake stands out as having caused an order of magnitude more landslides than any other earthquake of the same size; the 1986 San Salvador stands out in the same way amongst the cases in the database of Rodríguez et al. [31], which extends the Keefer [30] database from 1980 to 1997.

The record of landslides induced by earthquakes in El Salvador dates back to 1576, when landslides in the Sierra Los Texacuangos were reported to be triggered by an earthquake [32]. Since then more than 20 earthquakes have been found to cause widespread landsliding within the Salvadorian territory [33]. Areas affected by earthquake-induced landslides in El Salvador are much higher than those affected by earthquakes of comparable magnitude that occur in other geological, geomorphological and climatic environments [29,31]. Historical evidences show that landslides triggered by earthquakes in El Salvador occur as soil and rock slides on volcanic slopes but more abundantly as soil falls and slides in slopes of pumitic volcanic ash [29, 33]. Subduction earthquakes generally trigger landslides over areas that are large compared to crustal earthquakes, which tend to concentrate landsliding around the epicentral area. The 13 January and 13 February earthquakes have confirmed these trends.

Rymer and White [34] reviewed topography, lithology, rainfall, seismic hazard and historical cases of earthquake-induced landslides, and concluded that landslide hazard in El Salvador is high, the susceptible areas being the coastal mountain ranges, the volcanic chain and the interior valley areas. This evaluation has been confirmed by observations during the 2001 earthquakes.

Fig. 3 shows a landslide hazard map prepared by the Planning Office for the Metropolitan Area of San Salvador (OPAMSS) as part of PLAMADUR in 1997. The map identifies most of the metropolitan area of the capital as being of medium landslide hazard with several areas highlighted, in dark red, as being of high hazard: amongst these is the area affected by the catastrophic landslide at Las Colinas (Section 5.1).

2.3. Demographic and socio-economic conditions

The current population of El Salvador is about 6.3 million, very unevenly distributed throughout the national territory. There has been a steady trend for the population to concentrate in the south-western third of the country, which was home to 53% of the population in 1971, a figure that had risen to 64% by 1992 [35]. Probably three-quarters of the population now live in the region west of Lake Ilopango and south of Santa Ana, which is also the area of greatest seismic hazard [36].

The main agricultural export of El Salvador is coffee, having replaced *anil* (indigo) as the main cash crop at the turn of the 20th century, following the introduction of synthetic dyes in Europe. A large section of the rural population depends directly or indirectly on the cultivation of coffee for its livelihood, often in precarious conditions. Even before the earthquakes of 2001, the coffee industry was in a difficult situation as a result of low prices on the international market, partly as a result of a bumper crop in 1999–2000, and a delay in the previous year's harvest due to particularly wet weather that affected Mexico, Guatemala, El Salvador and Honduras [37].

During recent years the relative importance of the coffee industry in El Salvador has declined, with its contribution to the GDP dropping from close to 10% in the early 1980s to around 3% in recent years [38]. The main source of income to the Salvadorian economy is now the dollars sent back to relatives by Salvadorians living, often illegally, in the USA. The migration of Salvadorians to the United States was accelerated by the civil war that engulfed the country from

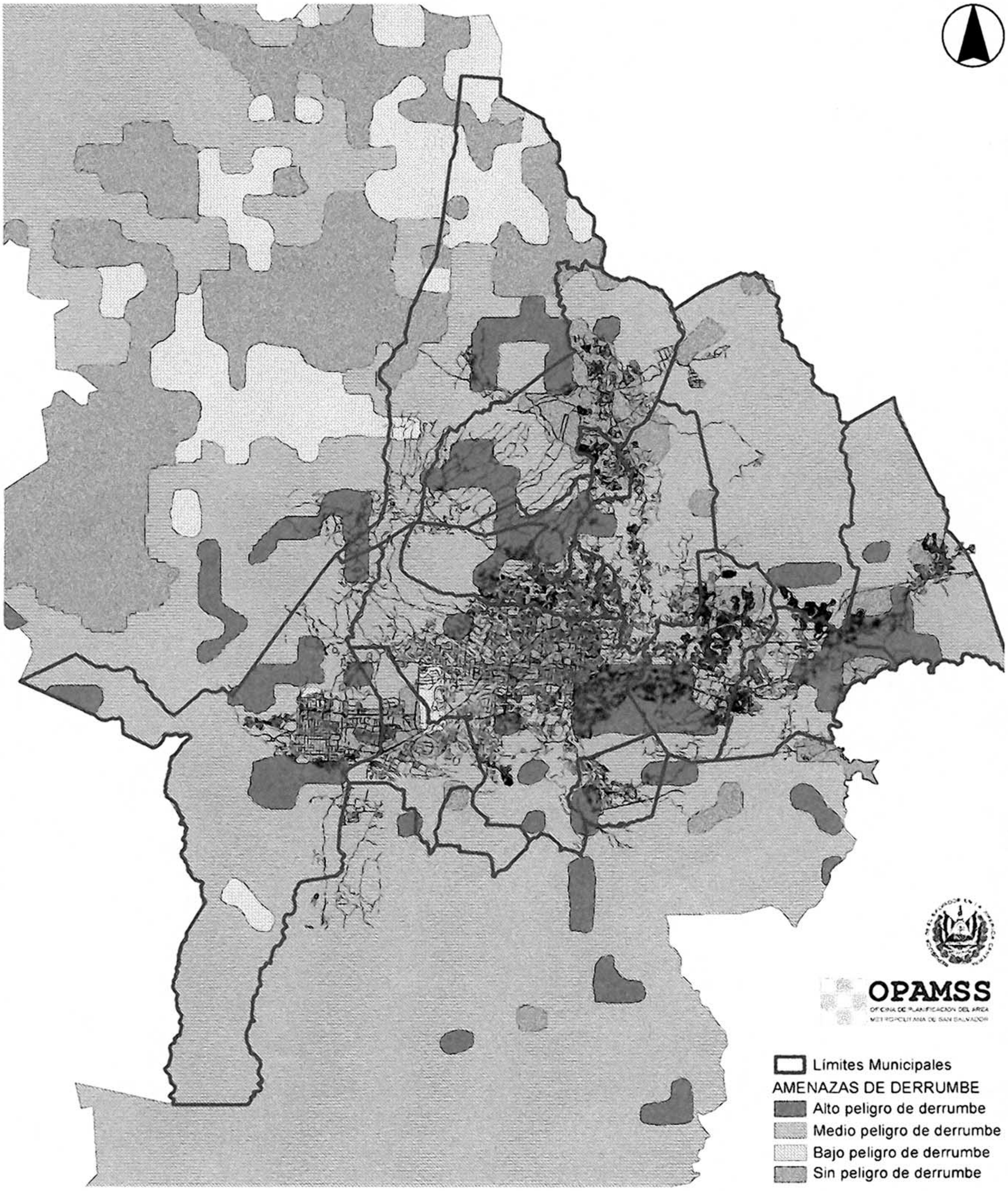

Fig. 3. OPAMSS map of landslide hazard in the Metropolitan Area of San Salvador.

1980 to 1992, but poverty and increasing crime rates have maintained the exodus since the peace accords were signed between the Salvadorian government and the FMLN (Farabundo Martí National Liberation Front). Income from remittances (known in Spanish as *remesas*) reached US$ 1751 million in 2000, almost six times the total value of coffee exports (US$ 298 million) and 2.7 times the net foreign exchange generated by the assembly (*maquila*) industry (US$ 654 million).

El Salvador is classified as a lower middle-income

Table 1
Source parameters for 13 January 2001 earthquake

Time (UTC)	Epicentre		Depth (km)	Magnitudes	Agency
	N°	W°			
17:33:32	13.049	88.660	60	M_w 7.7, M_s 7.8, m_b 6.4	NEIC
17:33:46	12.97	89.13	56	M_w 7.7, M_s 7.8, m_b 6.4	HRV
17:33:30	12.868	88.767	60	M_w 7.7	CASC

economy with an average GDP per capita of a little over \$2000, although the distribution of wealth is enormously uneven. The economic fragility of the small republics of Central America when subjected to natural disasters is well established. Coburn and Spence [39] list the economic losses inflicted by major earthquakes from 1972 to 1990; the three highest losses, when expressed as a percentage of the GNP for the year of the earthquake, of 40%, 18 and 31% were caused by the 1972 Managua, 1976 Guatemala and 1986 San Salvador earthquakes, respectively.

3. Source characteristics of the 2001 earthquakes

The earthquake sequence that began on the 13 January 2001 lasted for a total of over 6 weeks. Within this sequence were distinct and tectonically separate main shocks, on 13 January and 13 February, whose characteristics are described in the next sections. A third event that occurred on 17 February, with an epicentre on the western side of San Salvador, was sufficiently remote from the two main shocks not to be considered as an aftershock of either. However, this was a small event, assigned a magnitude of M_L 5.1 by the Centre for Geotechnical Investigations (CIG) of the Ministry of Public Works and m_b 4.1 by NEIC, and caused only very minor damage and caused less intense ground shaking than many of the aftershocks of the 13 January event; its impact was primarily psychological, owing to the understandably agitated state of the population after 5 weeks of tremors.

3.1. The 13 January 2001 earthquake

The first earthquake struck just after 11:30 am (local time) on Saturday 13 January 2001. Table 1 gives the source parameters determined by different agencies, which in terms of size and depth of the earthquake are remarkably consistent.

We determined fault mechanism, depth, source time function and seismic moment of earthquakes of 13 January and 13 February using very broadband digital data. In order to avoid multi-pathing, upper mantle and core arrivals, we only inverted body-waveforms from stations in the range $30° < \Delta < 90°$. We modelled the earthquakes as single point double-couple sources. The velocity structure near the source and beneath the stations was approximated by a half space with standard upper mantle wave velocities. We modelled the direct waves (P and S) and the reflected phases from free surface (pP, sP, sS, pS). In order to simulate seismic attenuation; we assumed $t^* = 11$ s for P waves and 4 s for SH waves. We used a maximum likelihood principle to obtain the source parameters that provide the best fit between observed and synthetic waveforms [40,41]. During the inversion, we solved simultaneously for focal mechanism and source time function using the CMT solutions as a priori models. We selected a set of teleseismic stations that gave us the best azimuthal coverage as possible in order to have a good constraint of the fault plane parameters. We used displacement seismograms, deconvolving them from their instrumental response and then reconvolving each signal to a common instrumental response. Band-passed filters were applied to the displacement records with a band-pass Butterworth filter of order 3.

Fig. 4 shows body-waveform inversion results for the earthquake of 13 January. For this event, P waves were relatively well fitted by our simple point source model. For P- and S-waves the first arrivals were not very well modelled because the S-waves—which are much stronger—dominate the inversion. The strong SH arrivals force the source time function of the earthquake to start with a very strong impulse. The peak appears to be much weaker for P-waves. The depth we found was 50 km. The more vertical fault plane was well constrained by the azimuthal coverage. The source time function can be divided into two sub-events: the first one had higher amplitude and a duration of 22 s; the second sub-event occurred during 24 seconds. The seismic moment was 5.54×10^{20} N m; it is difficult to observe any directivity effect. However, if we compare signals from LBNH and KIP stations with their synthetics (which were modelled with a point source), we observe a possible directivity effect. If we assume that the fault plane is the sub-vertical one, as is commonly observed for intraplate events, there could be an upward rupture propagation (Fig. 4); more data is required in order to constrain this directivity. The M_w 7.7 earthquake of 13 January 2001 was an intermediate depth earthquake that occurred inside the down-going Cocos plate; its tension axis was sub-parallel to the dip direction of the descending slab.

Large magnitude, normal faulting earthquakes are not unknown in subduction zones, indeed the El Salvador earthquake of 19 June 1982 was of very similar rupture mechanism. The highly destructive Peru earthquake (M_s 7.7) of 31 May 1970 was also associated with a normal rupture, as was the large M 8.1 Chillan (Chile) earthquake in 1939. In the case of the Peruvian earthquake, the large-scale extensional fracture in the underthrusting Nazca plate was interpreted as being due to tensional stresses caused by the denser descending plate [42]. In the case of the Cocos plate in Central America, the cause of normal faulting may be both extensional stresses due to slab pull and flexural stresses induced as the slab begins to descend at a greater dip angle inside the mantle [43].

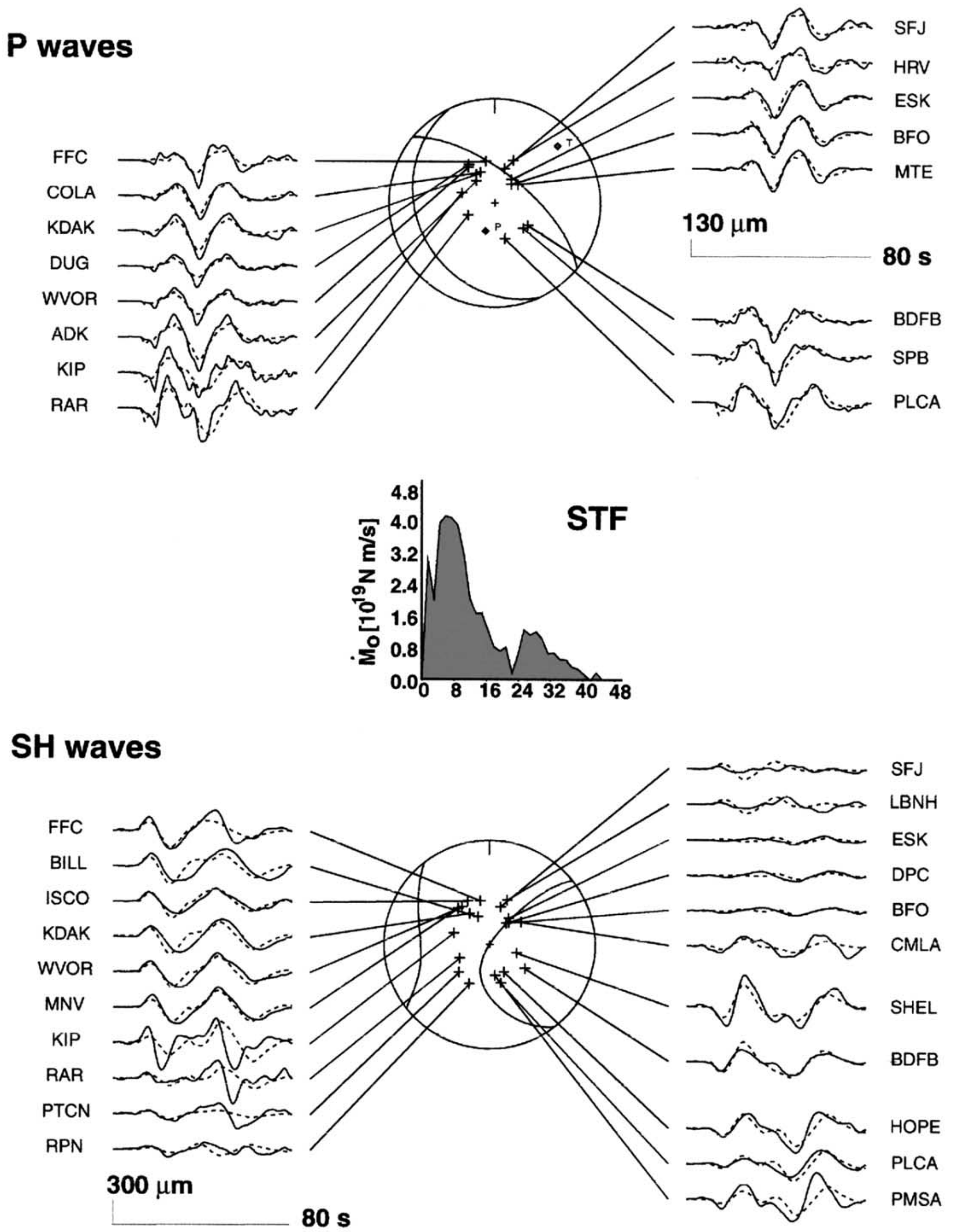

Fig. 4. Analysis of broadband body waves for the 13 January 2001 earthquake. Top: observed P-wave seismograms (solid lines) are in general fitted well by synthetics (dashed lines) computed for a point source model with focal mechanism and source time function shown. Bottom: as above but for SH waves.

In view of the agreement that the focal depth was of the order of 50–60 km, the earthquake would not have been expected to generate tsunami, even though there have been reports of a minor seismic sea wave [44]. Fig. 5 shows a tide gauge record from the port of Acajutla in which it can be seen that no tsunami occurred; the fluctuation in sea level at the time of the earthquake was comparable with ambient noise levels, and possibly due to the arrival of P-waves at the surface.

The earthquake was felt from Mexico City in the north to Colombia in the south. Our field observations from extensive travel throughout the interior valley and the coastal areas of El Salvador suggest that MM intensities throughout the southern half of the country were between VI and VII with local pockets of higher intensity between VII and VIII.

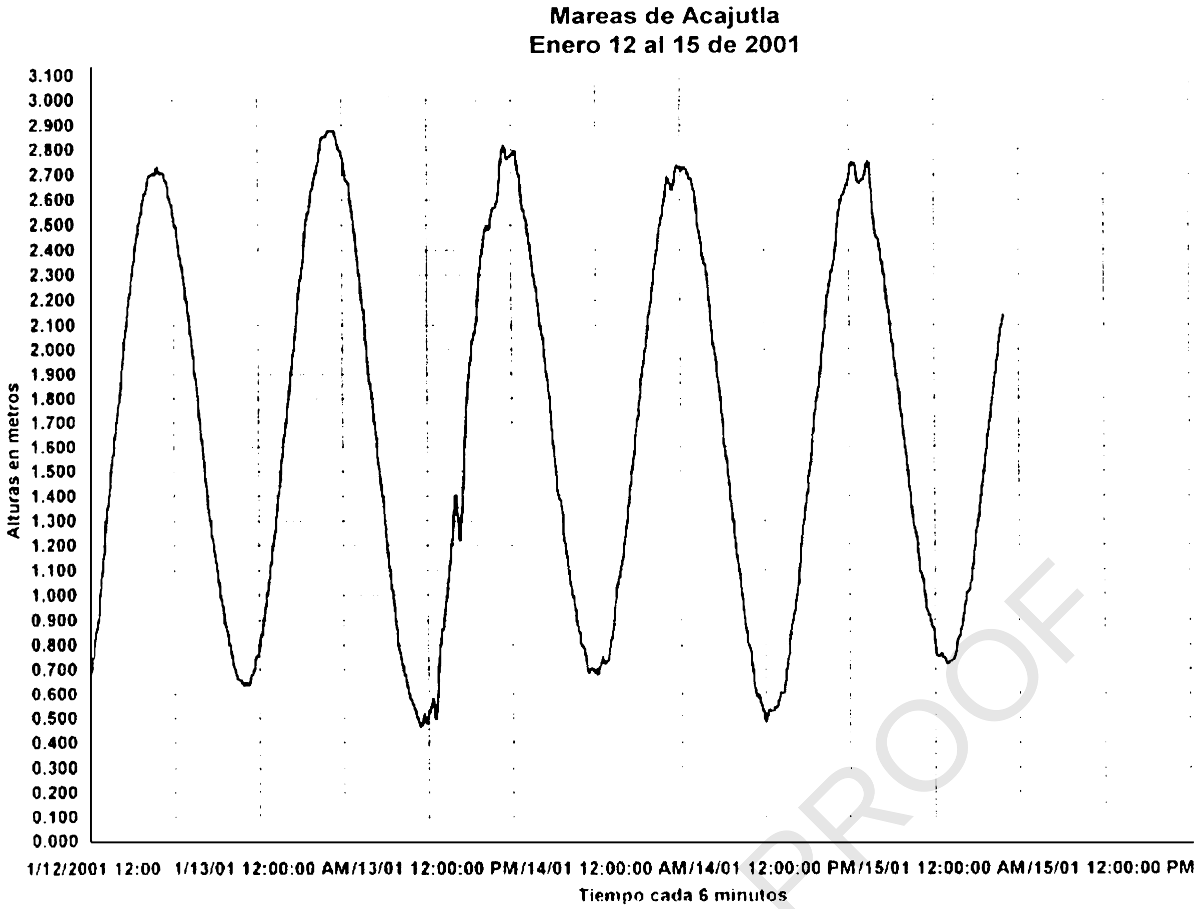

Fig. 5. Tide gauge record from the port of La Libertad showing height above mean sea level (metres) from 12 to 15 January 2001.

3.2. The 13 February 2001 earthquake

Aftershocks from the 13 January earthquake decayed approximately according to Omori's law in the period up to 13 February and were gradually dying out when a second earthquake occurred. The parameters for Omori's equation for the aftershocks prior to the second major event were obtained as follows:

$$\log[N(t)] = 2.7 - 0.7\log(t) \qquad R^2 = 0.9 \tag{1}$$

The source parameters for the second earthquake are listed in Table 2. Wave-form modelling was also carried out for this second event. Fig. 6 shows displacement seismograms filtered between the same corner frequencies as the 13 January event. Signals were noisier but we managed to constrain the mechanism using the envelope of the signal. The depth was 14 km and the seismic moment was 6.05×10^{18} N m. The total source time function duration was 12 s. P and SH waves were very well fit even if at some stations P waves were very noisy (PAS, KDAK). In spite of these problems, the two fault planes were well determined. The event of 13 February 2001 was totally different from that of 13 January: it was a strike–slip event that took place inside the upper continental plate, in the zone of weakness of the volcanic axis. The fault plane must be the one sub-parallel to the volcanic axis, i.e. sub-parallel to the subduction trench, which is confirmed by the distribution of aftershocks located by CIG.

Table 2
Source parameters for 13 February 2001 earthquake

Time (UTC)	Epicentre		Depth (km)	Magnitudes	Agency
	N°	W°			
14:22:06	13.671	88.938	10	M_w 6.5, M_s 6.5, m_b 5.5	NEIC
14:22:16	13.98	88.97	15	M_w 6.6, M_s 6.5, m_b 5.5	HRV
14:22:07	13.927	88.743	9.5	M_C 5.9, M_L 5.7	CASC

The 13 February earthquake, despite its size and relatively shallow focus, did not produce surface rupture, although there are mapped faults to the east of Chichontepec volcano whose rupture would be compatible with the fault plane solution [45]. An important issue in the interpretation of these earthquakes is the focal depth of the 13 February earthquake, which appears to be of the order of 15 km from our well-determined solution. Focal depth is the most difficult seismic source parameter to determine reliably and seismograph coverage in Central America, although improved by recent regional collaborations [46], is still limited, hence reported focal depths

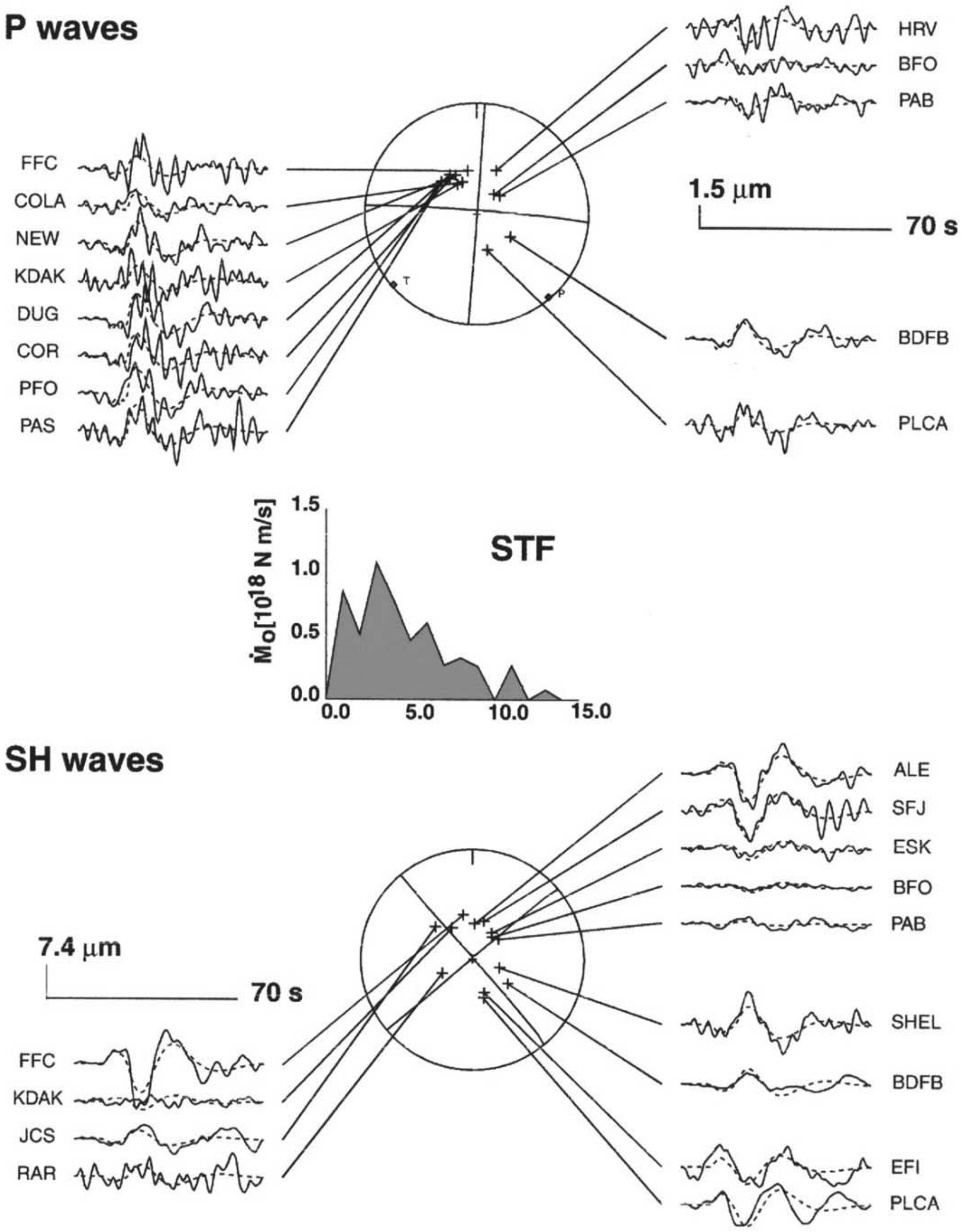

Fig. 6. Analysis of body waves for the 13 February 2001 earthquake. As for Fig. 4 except that only P-waves are considered.

carry a considerable degree of uncertainty. A clear example of this is the earthquake sequence of Jucuapa–Chinameca on 6–7 May 1951; contemporary catalogues list the earthquakes with focal depths between 80 and 100 km, and re-determinations using teleseismic data by Ambraseys and Adams [4] confirms the intermediate focus of the events. However, wave-form modelling, the presence of well-developed surface waves on a seismogram from Guatemala City, and the distribution on damage and intensity, all point compellingly towards very shallow focal depths, probably less than 10 km [10]. On the basis of the very limited evidence available, there does appear to be some correlation between magnitude and focal depth for crustal earthquakes in the Central America region, with events of this size occurring below the upper crust. Ambrasyes and Adams [4] report that the 20 December 1936 earthquake in the region of San Vicente, one of the towns most heavily affected by the 13 February event, was of sub-crustal origin. The empirical relationship of Wells and Coppersmith [47] for strike–slip faults yields a mean value of 10.5 km for the rupture width of an earthquake of this size; if the rupture did not advance more than 5–8 km from the surface, this may at least partly explain why the 13 February earthquake was less destructive than may have been expected from an event of this size occurring so close to population centres.

A preliminary isoseismal for the 13 February 2001 earthquake published by CIG reported a maximum MM intensity of VII–VIII in the area from Lake Ilopango to San Vicente and VI in San Salvador. Our field observations suggest that these are overestimates and that the maximum intensity generally did not exceed VII.

An obvious question to be addressed is whether the 13 February earthquake was in some way triggered by the subduction event a month earlier. Stress transfer due to relaxation of one crustal area leading to heightened tectonic stresses in an adjacent area has been clearly observed, for example, in the sequence of earthquakes from 1939 to 1999 along the North Anatolian fault in Turkey [48]. However, the situation in Central America is much less clear because the two earthquakes are of entirely different tectonic origin, even though they are both ultimately the result of the same general tectonic process. Lomnitz and Rodríguez Elizarrarás [44] report that normal faulting subduction earthquakes in Mexico tend to be followed by either large thrust events or shallow intraplate events four or five years later. A similar pattern may possibly exist in El Salvador, whereby large magnitude subduction earthquakes in some way trigger crustal events within the Caribbean plate within similar, or in some cases much smaller, intervals. The large subduction earthquake of 1915 in western El Salvador was followed by crustal earthquakes in San Salvador and to the west in 1917 and 1919; the subduction earthquake of 1932 offshore of central El Salvador was followed by the crustal earthquake in San Vicente in 1936; the 1982 subduction earthquake was followed in 1986 by the San Salvador upper-crustal earthquake. Therefore, the events of January and February 2001 may be simply a highly accelerated case of a process that is characteristic of the region. Earlier studies have alluded to relationships between Quaternary faulting in the Caribbean plate and the nature of the subducted Cocos plate [49] but the highly complex system of stress transfer and the exact nature of the plate interactions are not sufficiently well known to infer any definitive model at this stage.

4. Strong ground-motion

Both the 13 January and 13 February 2001 earthquakes were well recorded by three accelerograph networks in operation in El Salvador: a network of SMA-1 analogue instruments operated by the CIG, a network of digital and analogue instruments operated at geothermal and hydroelectric plants by GESAL, and the TALULIN network of digital SSA-2 instruments operated by the Universidad Centroamericana (UCA) ‘José Simeón Cañas’ [50]. Records were also obtained from the network of INETER in Nicaragua. The records from the CIG network were digitised and processed by the USGS.

4.1. Characteristics of accelerograms

Tables 3 and 4 list the main characteristics of the accelerograph recordings of the 13 January and 13 February earthquakes; the station locations are shown in Fig. 7. A major difficulty in performing detailed analysis and interpretation of the recorded accelerograms is the lack of information about soil profiles at recording sites other than the CIG stations in San Salvador for which investigations were carried out as part of a microzonation study following the 1986 earthquake [51]. Nearly all of the stations that recorded the two earthquakes are located on pyroclastic deposits such as *tierra blanca* and the older *tobas color café*. Exceptions to this are the Presa 15 de Septiembre hydroelectric dam site (alluvium), La Libertad (alluvium) and Panchimaclo (volcanic rocks). It is very likely that the ground motions at several of the recording sites are also affected by topographical features: the Panchimalco station of the UCA network is located within a N–S trending valley, whereas the San Pedro Nonualco station sits atop an E–W trending narrow ridge. Recordings of distant subduction events off the coast of Nicaragua have consistently produced relatively strong recordings at the latter site, whereas at Panchimalco recordings have generally been weak, frequently below the instrument trigger level [50].

Regrettably several potential records were lost due to malfunction of instruments. The CIG station at Santiago de María in eastern El Salvador did not trigger during the 13 January event; the instruments in the north-western towns of Santa Ana and Metapán also failed to produce records, although it is not clear whether this was due to malfunction or due to accelerations not reaching the triggering level, which may have been the case at Metapán at least. It is clear from comparison of Tables 3 and 4 that the functioning of the CIG instruments was not consistent. More important cases of malfunction concerned the San Vicente instrument of the UCA network, which did not record either of the earthquakes, and the San Pedro Nonualco station that would have produced the most important recording of the 13 February earthquake. The station operated by GESAL at the Berlín geothermal energy plant also failed to yield an accelerogram of the 13 February earthquake.

4.2. Comparisons of strong-motion parameters with predictions

For earthquakes of magnitude greater than about 6, for which the source dimensions are of the order of more than a few kilometres, the use of epicentral distance can seriously overestimate the separation of the site and the source of energy release. For the 13 January earthquake, distances have been measured from the assumed fault rupture, since this is the distance measure proposed by Youngs et al. [52] for subduction zone earthquakes. The actual location of the fault rupture has been fixed by the angle of dip of the fault, which coincides with the angle of dip of Cocos plate as

Table 3
Strong-motion records of 13 January 2001 earthquake

Network	Station	Location		d_{rup}[a] (km)	PGA (g)			PGV (cm/s)		
		N°	W°		N–S	E–W	V	N–S	E–W	V
GESAL	Berlín Geoth.	13.50	88.53	54	0.459	0.370	0.235	21.3	24.0	12.3
UCA	Armenia	13.744	89.501	93	0.601	0.454	0.223	28.8	29.4	19.6
UCA	La Libertad	13.468	89.327	60	1.113	0.575	0.617	53.2	35.5	16.0
UCA	Panchimalco	13.614	89.179	75	0.177	0.154	0.089	9.2	9.4	7.3
UCA	San Bartolo	13.705	89.106	85	0.157	0.199	0.166	25.2	31.2	15.2
UCA	S Pedro Nonualco	13.602	88.927	50	0.580	0.488	0.439	37.5	26.4	18.2
UCA	San Salvador ESJ[b]	13.707	89.201	85	0.301	0.278	0.154	25.4	17.4	11.9
UCA	Santa Tecla	13.671	89.279	83	0.496	0.243	0.487	57.0	34.2	18.5
UCA	Tonacatepeque	13.778	89.114	93	0.234	0.205	0.263	23.1	23.2	9.8
UCA	Zacatecoluca	13.517	88.869	47	0.260	0.314	0.253	12.3	21.9	10.4
CIG	Ahuachapán	13.925	89.805	123	0.146	0.214	0.124	14.9	16.6	10.8
CIG	Acajutla	13.567	89.833	95	0.098	0.108	0.050	14.6	18.6	4.2
CIG	Cutuco	13.333	87.817	125	0.078	0.079	0.063	13.8	8.6	4.0
CIG	Presa 15 de Sept.[c]	13.616	88.550	66	0.152	0.187	0.122	23.5	16.0	10.2
CIG	San Salvador DB[d]	13.733	89.150	84	0.225	0.250	0.160	23.2	19.2	11.3
CIG	San Salvador RE[e]	13.692	89.250	83	0.304	0.323	0.329	22.9	27.6	15.3
CIG	San Miguel	13.475	88.183	107	0.136	0.120	0.089	12.8	12.1	6.0
CIG	Sensuntepeque	13.867	88.663	81	0.082	0.061	0.058	8.5	9.1	6.2
INETER	Boaco	12.473	85.658	336	0.004	0.003	0.002	0.5	0.5	0.4
INETER	Chinandega	12.632	87.133	175	0.090	0.070	0.042	6.3	4.6	2.1
INETER	DEC	12.124	86.267	276	0.045	0.044	0.028	3.1	3.3	1.7
INETER	Estelí	13.092	86.355	263	0.014	0.011	0.009	2.3	2.5	0.9
INETER	Granada	11.937	85.976	312	0.009	0.009	0.006	1.7	1.3	0.9
INETER	Jinotega	13.086	85.995	302	0.006	0.005	0.004	0.7	0.9	0.5
INETER	Juigalpa	12.107	85.372	371	0.003	0.003	0.002	0.6	0.6	0.5
INETER	León	12.117	86.266	276	0.040	0.037	0.026	2.3	2.6	1.4
INETER	Managua (ESSO)[f]	12.144	86.320	270	0.057	0.045	0.022	3.8	3.9	1.5
INETER	Managua (INET)[g]	12.149	86.248	277	0.034	0.041	0.014	2.6	2.7	1.1

[a] Distance from fault rupture as defined by Youngs et al. [52].
[b] Externado de San José.
[c] Ground level instrument adjacent to dam.
[d] Ciudadela Don Bosco.
[e] Ministerio de Relaciones Exteriores; there are two accelerographs at the this site, the reported values are from the instrument at ground level, the other is at the base of a well.
[f] ESSO Refinery.
[g] INETER.

proposed by Burbach et al. [43]. Taking account of the focal depth of the main shock, the seismic moment and the spatial distribution of aftershocks, the fault plane is modelled as a fault plane with a strike of 300° dipping 55° to the NE, which corresponds to a plane sub-parallel to the subduction trench. The dimensions of the rupture plane were constrained by the distribution of aftershock hypocentres from 13 January until the end of August, concentrated at focal depths between 20 and 40 km. The dimensions of the inferred fault rupture plane are 65 km in length and 55 km in width. The uppermost part of the rupture is assumed to extend to a depth of 20 km and extends from (12.95°N, 89.25°W) in the west to (12.67°N, 88.74°W) in the east. The distances from this assumed rupture are given in Table 3.

For the crustal earthquake of 13 February, a more appropriate measure of the source-to-site distance is that proposed originally by Joyner and Boore [53], namely the shortest distance from the surface projection of the fault rupture. The distances from the fault rupture for the 13 February earthquake were determined by modelling the fault as a line striking N94°E, extending from (13.66°N, 89.0°W) to (13.63°N, 88.61°W). This places the fault rupture as extending eastwards from the western shore of Lake Ilopango for about 42 km; this is longer than would be expected from the relationships of Wells and Coppersmith [47], which may indicate a narrow rupture and hence the effective depth of the source that may explain the relatively low amplitudes recorded. This rupture plane was constrained from aftershock distributions from 13 February until the end of August with depths up to 15 km. Seismic activity west of Ilopango has been reported after the 13 February earthquake but it is probably related to the 17 February event near San Salvador. The calculated distances from this assumed source are presented in Table 4; since it is possible that the length of the fault rupture has been overestimated, there is the possibility that some of the distances are underestimated. The uncertainty, however, lies mainly in the eastward extension of the fault rupture, which

Table 4
Strong-motion records of 13 February 2001 earthquake

Network	Station	Location		d_{rup}[a] (km)	PGA (g)			PGV (cm/s)		
		N°	W°		N–S	E–W	V	N–S	E–W	V
GESAL	Berlín (town)	13.50	88.53	17	0.032	0.070	0.031	4.1	6.0	2.9
UCA	Armenia	13.744	89.501	55	0.029	0.037	0.026	4.0	2.3	1.3
UCA	La Libertad	13.468	89.327	41	0.091	0.093	0.037	4.7	4.5	3.1
UCA	Panchimalco	13.614	89.179	20	0.185	0.106	0.045	9.4	4.6	2.0
UCA	San Bartolo	13.705	89.106	13	0.106	0.141	0.123	25.6	22.3	6.9
UCA	San Salvador ESJ[b]	13.707	89.201	22	0.124	0.099	0.052	18.3	6.6	2.7
UCA	Santa Tecla	13.671	89.279	30	0.047	0.040	0.023	6.4	4.8	2.0
UCA	Tonacatepeque	13.778	89.114	18	0.345	0.251	0.240	30.0	24.7	10.5
UCA	Zacatecoluca	13.517	88.869	18	0.408	0.305	0.262	20.1	20.4	9.6
CIG	Presa 15 de Sept.[c]	13.616	88.550	7	0.020	0.026	0.017	6.4	5.0	2.4
CIG	S. Salvador CIG[d]	13.698	89.173	19	0.138	0.071	0.059	19.9	8.4	3.8
CIG	San Salvador DB[e]	13.733	89.150	18	0.100	0.094	0.055	14.8	12.2	4.6
CIG	S. Salvador DUA[f]	13.737	89.209	24	0.077	0.059	0.046	8.2	8.7	3.5
CIG	S. Salvador OBS[g]	13.681	89.198	22	0.107	0.104	0.068	6.7	13.9	3.3
CIG	San Salvador RE[h]	13.692	89.250	27	0.058	0.063	0.034	3.9	8.1	2.2
CIG	S. Salvador SEM[i]	13.705	89.225	25	0.065	0.071	0.044	5.7	10.8	2.6
CIG	S. Salvador UCA[j]	13.677	89.236	26	-	0.058	0.040	-	8.5	2.1
CIG	Santa Tecla	13.675	89.300	32	0.039	0.042	0.019	6.4	7.4	2.2

[a] Distance from fault rupture as defined by Joyner and Boore [53].
[b] Externado de San José.
[c] Ground level site adjacent to dam.
[d] Centro de Investigaciones Geotécnicas.
[e] Ciudadela Don Bosco.
[f] Viveros, Dirección de Urbanismo y Arquitectura; there are two accelerographs at the this site, the reported values are from the instrument at ground level, the other is at the base of a well.
[g] Observatorio Sismológico.
[h] Ministerio de Relaciones Exteriores, ground-level instrument.
[i] San José de la Montaña Seminary, ground-level instrument.
[j] Universidad Centroamericana.

would only affect the distances to the stations at Berlín and the 15 de Septiembre dam.

Algermissen et al. [18] derived an attenuation relationship from 82 recordings of strong-motion obtained in the vicinity of San Salvador, without distinguishing between subduction and crustal earthquakes. Taylor Castillo et al. [54] derived an equation from 89 records from Costa Rica, El Salvador and Nicaragua, again combining crustal and subduction earthquakes. Dahle et al. [55] subsequently produced attenuation equations for response spectral ordinates, using a database of 280 records, including 157 from Costa Rica and more than 60 from Mexico, and making no distinction between different sources of seismicity. Some other studies have separated subduction zone and crustal earthquakes: Alfaro et al. [17] derived two separate equations for PGA, but used only 20 records for each. Schmidt et al. [56] have derived equations for spectral ordinates from a database of 200 accelerograms recorded in Costa Rica, presenting coefficients for the entire dataset and for subduction and crustal sub-sets. Climent et al. [57] derived spectral acceleration equations for Central America using 280 records from Costa Rica, Mexico, Nicaragua and El Salvador; these relationships also did not separate crustal and subduction events.

There are shortcomings in all of the above attenuation relationships in terms of applicability to El Salvador, either because they do not discriminate between subduction and crustal earthquakes, or because they are based on insufficient datasets. The equations of Schmidt et al. [56] are the only exceptions, but there are important tectonic and geologic differences between Costa Rica and El Salvador, on the one hand, and on the other they make use of epicentral and hypocentral distance, which are unsuitable for large events as was noted previously. For these reasons, comparisons have been made with predictions from relationships derived for other regions. For the subduction earthquake of 13 January, the most appropriate attenuation relationships are those of Youngs et al. [52] derived from regressions on almost 500 accelerograms from Alaska, Chile, Cascadia, Japan, Mexico, Peru and the Solomon Islands. These equations have been proposed for intra-slab and interface subduction earthquakes, for events larger than M_w 5 and distances from the fault rupture between 10 and 500 km, making them ideally suited to this situation. The recorded PGA values are compared with those predicted by the intra-slab equation of Youngs et al. [52] in Fig. 8; ground conditions corresponding to more than 20 m of soil overlying rock have been assumed. The equation appears to

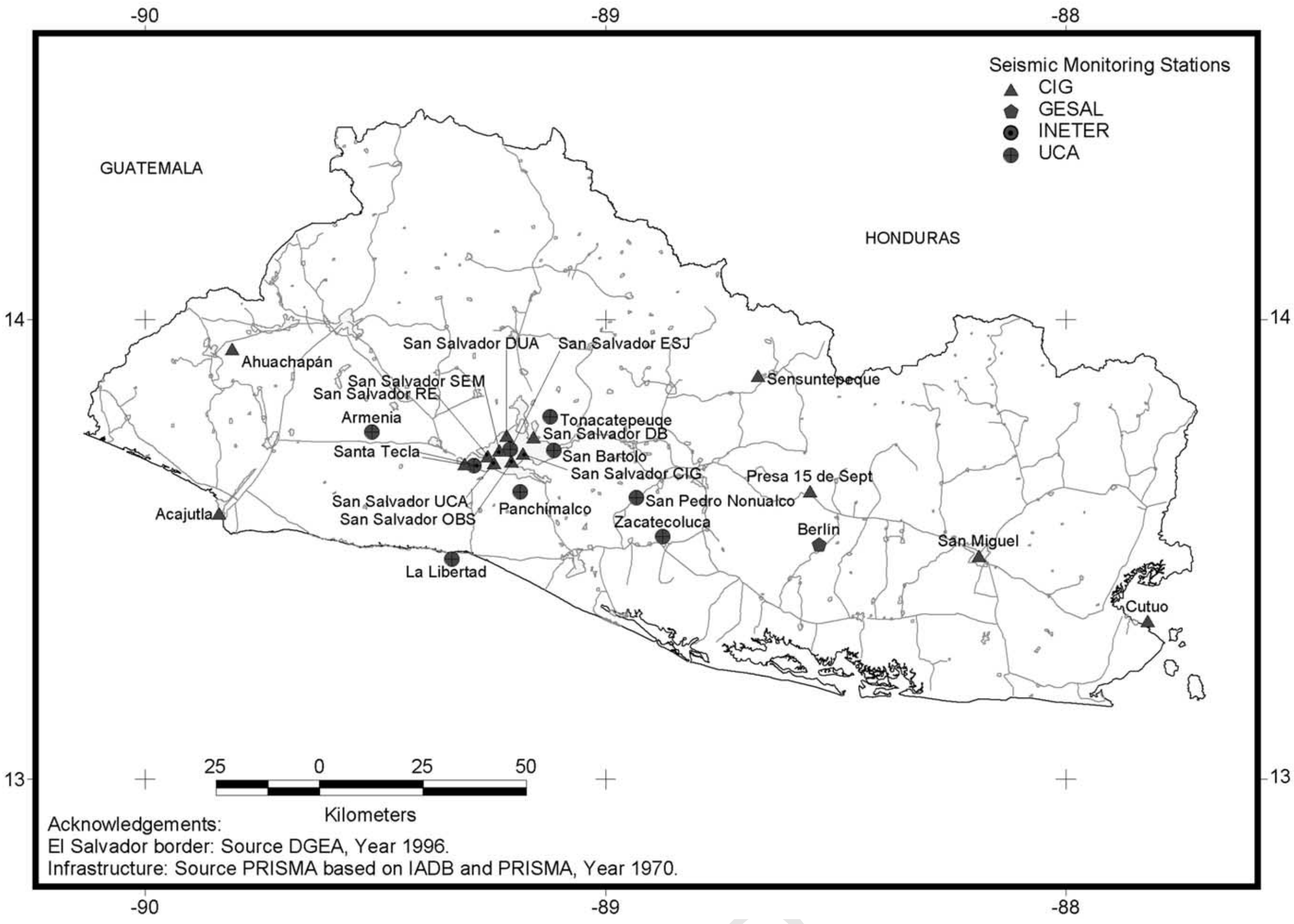

Fig. 7. Location of strong-motion recording stations in El Salvador.

fit the data well at distances of less than 300 km, with values from greater distances being overestimated. It is worth noting that in the distance range from 50 to 130 km, the values obtained from the CIG network are consistently lower than those from the UCA network.

One particularly interesting feature of the motions recorded during the 13 January earthquake is the fact that the response spectra are rich in high frequencies whereas for such a large magnitude event greater energy at intermediate and long periods would have been expected. Similar features have been observed in accelerograms from large subduction zone earthquakes in Japan and also in Peru [58, 59]. Since high-frequency ground motions were recorded in both the 1966 and 1970 Peruvian earthquakes, which were, respectively, associated with thrust and normal ruptures [42], it would appear that this feature may not be exclusively a function of source mechanism. Nonetheless, Prvance and Anderson [60] identify normal faulting earthquakes in the Mexican subduction zone as producing consistently more high-frequency radiation than thrusting events. There is evidence that the recording from La Libertad (Fig. 9), where PGA exceeds 1 g, displays strong site effects at a period of about 0.2 s (Fig. 10). This is visible on many recordings from this station from previous smaller or more distant earthquakes and would be consistent with a relatively thin layer (~10 m) of alluvium overlying bedrock (lavas).

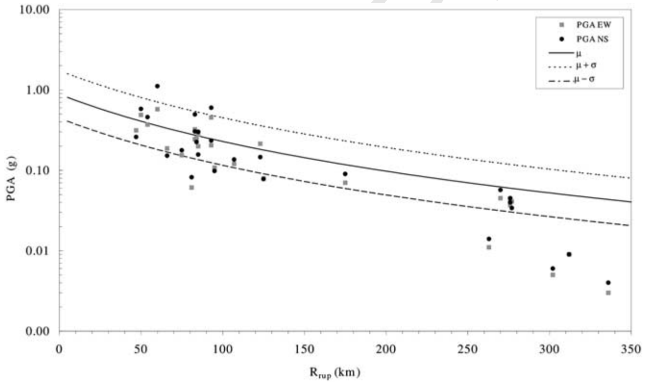

Fig. 8. Recorded PGA values from the 13 January earthquake compared with predictions from the attenuation relationships of Youngs et al. [52].

For the crustal earthquake of 13 February, one possibility would be to use the relationships derived by Spudich et al. [61] for zones of extensional tectonics, but the two recordings from the 1986 San Salvador earthquake used in that study were found to be outliers whose amplitudes were significantly underestimated by the median predictions. Other candidate equations derived from crustal recordings

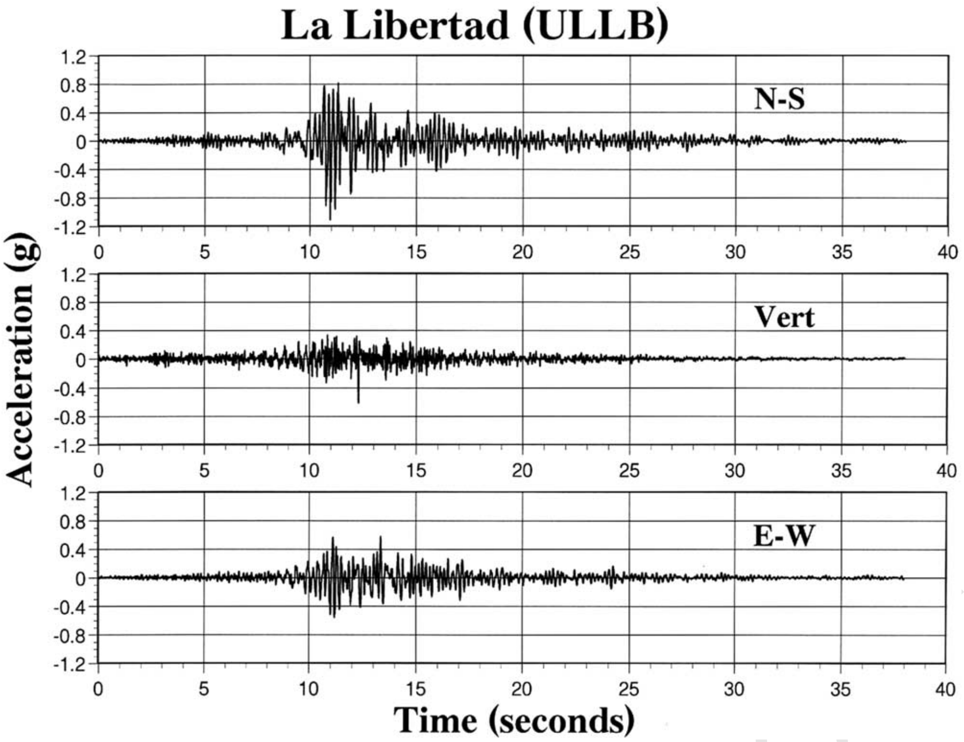

Fig. 9. Accelerogram recorded at La Libertad during 13 January 2001 earthquake.

elsewhere in the world would include the western USA relationships of Boore et al. [62], the global relationships of Abrahamson and Silva [63], the European relationships of Ambraseys et al. [64] and the Italian relationships of Sabetta and Pugliese [65]; the latter may be particularly suitable since large areas of Italy are also volcanic. Fig. 11a compares the recorded PGA values with the median values from these relationships, in which the equations seem to consistently overestimate the observed values beyond about 20 km. Fig. 11b confirms that most of the recorded PGA values are within the $\pm\sigma$ values predicted by Ambraseys et al. [64]. Worthy of particular note in this figure are the low PGA values obtained at Berlín in this event, which raises questions about the reliability of this particular recording: GESAL operates digital accelerographs in the

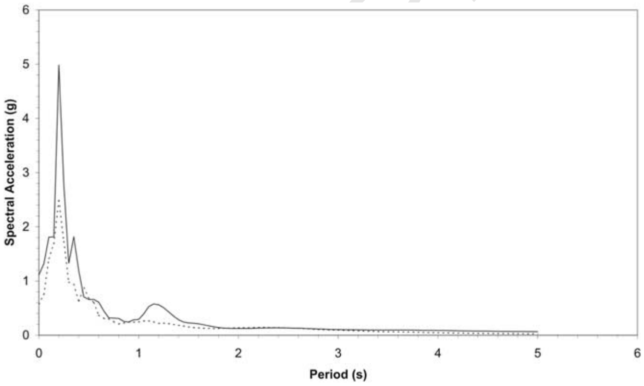

Fig. 10. Absolute acceleration response spectrum (5% damping) of record in Fig. 9.

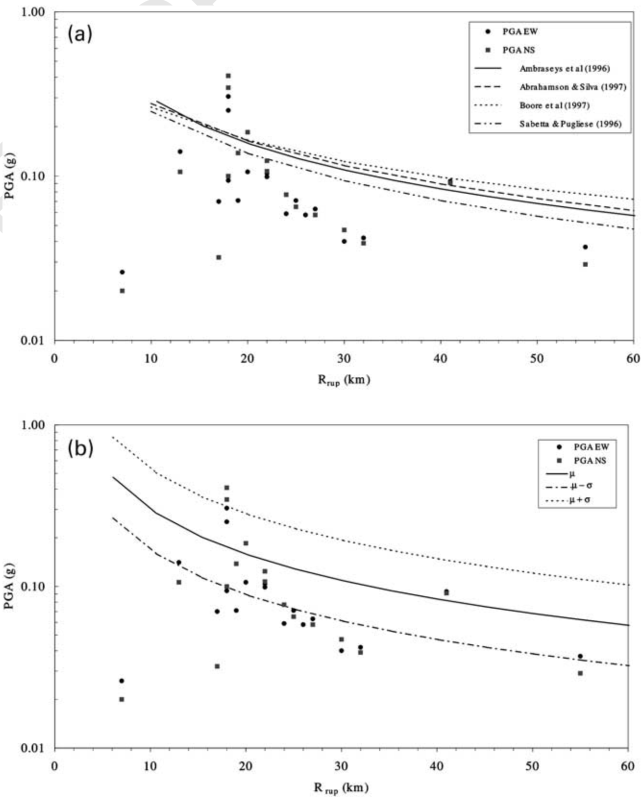

Fig. 11. (a) Recorded PGA values from the 13 February earthquake compared with median values predicted by the equations of Abrahamson and Silva [63], Boore et al. [62], Ambraseys et al. [64] and Sabetta and Pugliese [65]. (b) Recorded values of PGA compared with the 16, 50 and 84% predictions from Ambraseys et al. [64].

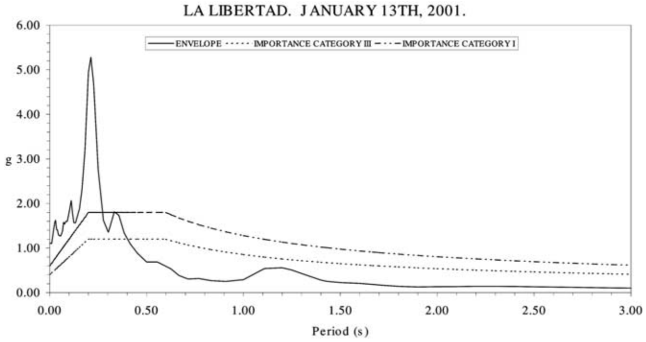

Fig. 12. Envelope of horizontal acceleration spectra from the 13 January recording at La Libertad compared with the elastic spectra from the 1994 design code for soil class S3 and importance categories I and III.

town of Berlin and at the nearby geothermal energy plant, with records having been obtained only from the latter instrument on 13 January and reportedly from the former on 13 February. The even lower amplitudes recorded at the 15 de Septiembre dam may point to the fault rupture being shorter than 42 km and not extending so far east as has been assumed.

4.3. Implications of recorded motions for seismic design code

The first seismic design code in El Salvador was introduced in 1966 following the San Salvador earthquake of the previous year; this code was adapted for El Salvador from the code from Acapulco, Mexico [23]. A revised code was drafted by the Salvadorian Association of Engineers and Architects (ASIA) in 1989, issued as an emergency regulation following the 1986 San Salvador; the design spectra in this code took account of the nature of the ground motions recorded in the earthquake. The current seismic code, published in 1994, forms part of a comprehensive set of regulations for building and civil works produced by the Ministry of Public Works. The current code has several merits, including the fact that it is the first to have involved a probabilistic assessment of seismic hazard in El Salvador [19]. Furthermore, the regulations cover a wide range of practices, including geotechnical works, and also provides guidance on construction using *adobe* despite initial opposition from contractors who were concerned that promotion of vernacular building techniques would be detrimental to their business.

The elastic spectra in the current code appear to be sufficient for most of the ground motions recorded in these earthquakes. The somewhat exceptional record of 13 January at La Libertad exceeds the code spectrum (Fig. 12), but it would not seem reasonable to increase the code spectrum to a maximum level of 5*g* just to accommodate the narrow-band amplification due to specific site effects at this location. The strongest recording from the 13 February earthquake, obtained at Zacatecoluca, is covered by the spectral ordinates specified in the code, as shown in Fig. 13a. Fig. 13b shows the spectrum at the same station from the 13 January earthquake, which is also adequately covered by the code spectrum. In passing it can be noticed that as at other stations [66], the shape of the spectra from the two earthquakes are generally similar, confirming the importance of site effects in determining the nature of the ground motion.

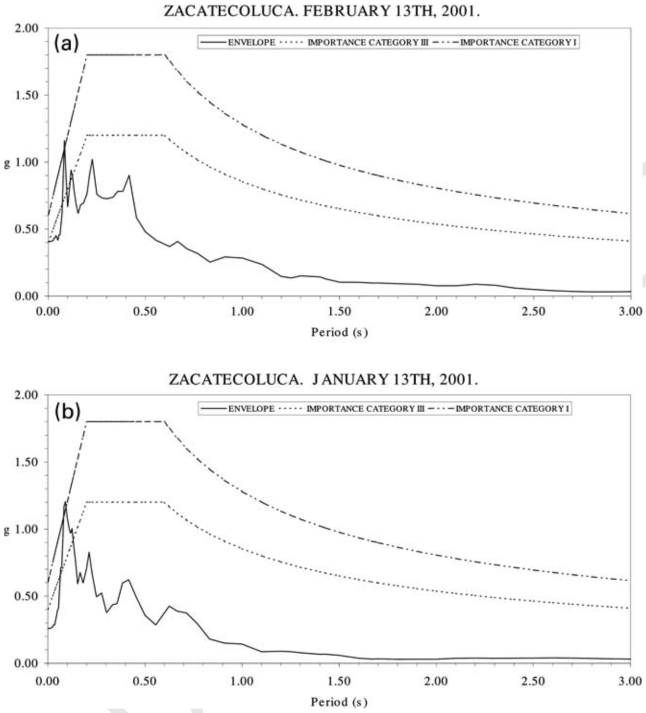

Fig. 13. (a) Envelope of horizontal acceleration spectra from the 13 February recording at Zacatecoluca compared with the elastic spectra from the 1994 design code for soil class S3 and importance categories I and III. (b) Envelope of horizontal acceleration spectra from the 13 January recording at Zacatecoluca compared with the elastic spectra from the 1994 design code for soil class S3 and importance categories I and III.

5. Effects of the earthquakes

The impact of the January and February 2001 earthquakes was strong in many parts of the south of the country, particularly the coastal cordilleras and locations around the volcanic centres. The area around the San Vicente volcano, where buildings had been weakened by the 1999 swarms, and where both the 13 January and 13 February earthquakes caused strong shaking, was particularly affected. The patterns of damage, however, were very uneven and the capital city, San Salvador, was largely unaffected. Nonetheless, the overall impact was devastating to the fabric of the country, with an estimated 40% of the health service and 30% of schools severely damaged.

The death tolls due to the two earthquakes have been reported as 844 and 315, respectively, with the majority of the casualties, particularly in the 13 January event, being due to landslides. It is worth highlighting here that the loss

Fig. 14. Single block fall, triggered by an aftershock of the 13 January earthquake, on the coastal motorway near La Libertad.

of life in these earthquakes underestimates their impact; more people were killed by the M_w 5.7 San Salvador earthquake of October 1986. The death toll is also small compared with the 75,000 lives lost in the fratricidal war from 1980 to 1992, and indeed when compared with the numbers of victims of violent crime, which has grown to epidemic proportions in recent years. The true impact of the earthquakes is more accurately represented by the fact, mentioned previously, that a significant proportion of the population was either made homeless or suffered substantial damage to their housing. Even before the earthquakes it had been estimated that El Salvador had a housing deficit of more than half a million dwellings.

5.1. Landslides and liquefaction

The 13 January earthquake triggered more than 500 landslides across in El Salvador and a further 70 occurred as a result of the 13 February earthquake. Landslides were an extensive secondary effect of the earthquake of 13 January 2001. The landslides could be divided into three broad types according to the classification scheme proposed by Dikau et al. [67]. These were rock and debris falls, slides and debris flows. Many of the landslides occurred on the slopes of volcanoes that are used for coffee cultivation; coinciding with the time of the coffee harvest, many coffee pickers were killed by these slides.

Rockfalls and debris falls were common throughout the area and ranged from single block falls (some of which were up to 3 m in diameter, Fig. 14) to the collapse of slopes cut in pyroclastic ashfall deposits, which exist as a result of weak cementation and high negative pore pressure [28,68]. Such failures were largely independent of lithology, but occurred only on steep slopes. Individual block falls were more common in the rocks of the Bálsamo Formation because of the prevalence of persistent discontinuities in the form of bedding and cooling joints. Highly altered layers of volcanic rock also acted as aquitards.

The occurrence of rock and debris falls in the *tierra blanca* affected an extensive area around the Comasagua Road on the Bálsamo Ridge. Here the steep slopes which were formed as part of the road construction and also by quarrying failed in spectacular manner giving rise to an extensive area of slope instability which extended from the landslide at Las Barrioleras to the Jayaque–Comasagua Junction (Fig. 15) and in Comasagua itself (Fig. 16). This formed a classic shattered ridge. In many cases, it was impossible to tell where one landslide ended and another began.

Large landslides were observed along roads to Comasagua, Talnique, Jayaque, Tepecoyo and Sacacoyo. The principal cases were reported along the road between Nueva San Salvador and Comasagua on slopes of volcanic ashes mainly *tierra blanca*. The Pan-American Highway was blocked between Los Chorros and Colón by landslides to the west of San Salvador. At the Las Leonas location, to

Fig. 15. Debris fall from the Tierra Blanca near Comasagua.

the east of San Salvador, this road was blocked by a large slide of approximately 500,000 to 700,000 m^3 of rock and soil debris. Roads to San Agustín, Santiago de María and Berlín were also blocked. Several landslides were also observed along the road between Cojutepeque and Santiago Texacuangos, and around Lake Ilopango.

The most important group of landslides, which were triggered by the earthquake, were the debris flows. These landslides were responsible for more than half the deaths during the 13 of January earthquake. The two most important of these slides were at Las Colinas (Fig. 17) and Las Barioleras. These landslides, which occurred in the Tierra Blanca showed significant travel distances of 735 m and c. 1140 m, respectively. The former of these two slides destroyed part of the residential area at Las Colinas, while the latter killed many people who were working on the coffee plantations and travelled onto the Pan-American Highway. The long travel distances of these landslides indicate low coefficients of internal friction of between 6 and 9°, inferred from the ratio of slope height to run-out length of the slide [69]. This indicates a significant drop in frictional strength from the undisturbed state, which may be as high as 38°. Debris flows were common throughout the Cordillera del Balsamo resulting from the steep terrain mantled with weak volcanic debris and the presence of aquitards in the underlying Bálsamo Formation.

The Las Colinas landslide in Santa Tecla was the most notorious slide triggered by the earthquakes due to its devastating impact on population. This slope failure buried as many as 500 people. This slide was approximately 790 m long, 150 m wide and left a scarp 50 m high. The total volume of the slide was approximately 200,000 m^3. The slide affected a part of the northern flank of the Bálsamo Ridge composed of the Bálsamo Formation. This formation is formed mainly of andesitic cinders and some interbedded tephra. Extensive cracking was observed on the ridge crest in areas that did not slide, which was cause for additional concern. Some authors attributed this slide to liquefaction of saturated *tierra blanca* deposits [70–72], however, a rotational slope failure of the upper part of the slope has also been attributed as initial failure mechanism [73]. Failure has been found to be related to high water content of the lower part of the slope, which has been attributed to natural drainage blockage by a retaining wall observed on the bottom of the slope [72], although a perched aquifer on the slope due to the impermeable nature of the Bálsamo Formation has also been proposed as the cause of this high water content. Soil saturation was observed only locally, due mainly to the earthquake occurring after 5 months of dry season. The destructiveness of the landslide may have been due to its high mobility, which may have been the result of an unfavourable combination of high water content and material brittleness.

Harp and Wilson [74] have identified Arias intensity (sum of the two horizontal components) as a useful indicator of the capacity of the ground shaking to trigger landslides.

Fig. 16. Landslide damage in Comasagua.

Fig. 17. The Las Colinas landslide, Santa Tecla.

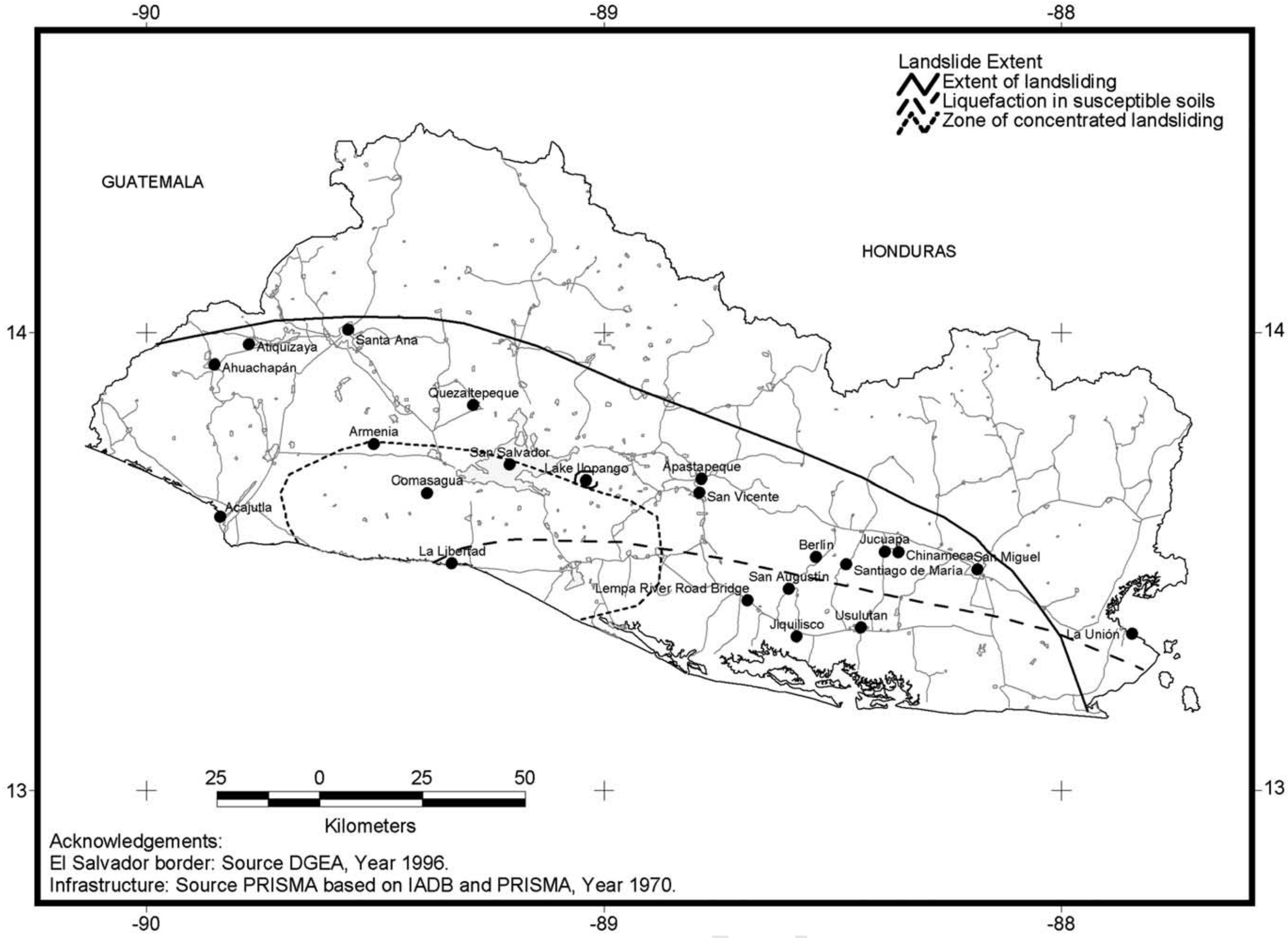

Fig. 18. Distribution of areas affected by landslides (solid line), by concentrated landslides (small dashes) and by liquefaction (large dashes).

From studies of the 1987 Superstition Hills and Whittier Narrows earthquakes in California, Harp and Wilson [74] proposed thresholds of about 0.25–0.3 m/s for landslide triggering. The values of Arias intensity for the records of the 13 January earthquake are as high as 14 m/s and in all cases (excluding the Nicaraguan records), exceed this threshold [75].

In terms of geographical distribution, landslides were triggered across most of the southern half of El Salvador, with a particular high concentration in the Cordillera del Bálsamo to the southwest of San Salvador, between Nueva San Salvador and Armenia (Fig. 18), affecting a much larger area than in previous earthquakes [29]. In a general way, the geographical distribution of landslides roughly corresponds to the distribution of young ash, tuff, and tephra deposits on steep slopes, incised valley walls and river channels. Landslides were also reported to occur in Guatemala [76]. Slides blocked roads between Quesada and Monte Verde and between Moyuta and El Obraje in the Jutiapa District. Landslides were also reported along the Guatemala-Mexico and Quetzaltenango–Retalhuleu roads, and along the road to Ixtahuacan, Solola.

The 13 February earthquake triggered additional landslides to those reported by the 13 January event. Along the Pan-American Highway new landslides were observed at Las Leonas and adjacent locations. A large landslide was reported in the water head part of the Rio Jiboa; it was estimated that volume of sediments yielded in this area reaches between 10 and 15×10^6 m^3 of debris, mainly *tierra blanca* [77]. This landslide blocked the river course for 600–700 m causing an artificial lake to be formed. Another large landslide blocked the course of Rio El Desagüe; in this case a volume between 1 and 2×10^6 m^3 was mobilised, consisting of andesitic breccia blocks of around 0.5–2 m in diameter embedded into a *tierra blanca* matrix [77].

On the slopes of the San Vicente volcano landslides were reported along the El Muerto and El Blanco creeks. The El Muerto landslide was estimated to have mobilised around 700,000–800,000 m^3 of andesitic rock blocks, whereas the El Blanco landslide mobilised silty and sandy gravels and blocks coming from pyroclastic flows. This slide becomes a latent hazard against the Tepetitan town, which was flooded in 1930 by a mudflow resulting in four deaths. New landslides were also reported around the Lake Ilopango [77].

Table 5
Annual average rainfalls (mm) at selected meteorological stations

Year	Ilopango	Santiago de María	La Unión	San Miguel	Ahuachapán	Acajutla	Puente Cuscutlán
1998	1958	2338	2123	1648	1623	2280	2037
1999	1504	1902	1859	1470	1554	1953	1303
2000	1454	1890	1783	1543	1052	1761	1637

Analysis of SPOT image data after the earthquake of 13 of January 2001 with 10 m ground resolution, reveals many flowslides in the Balsamo Cordillera. A similar scene collected after the earthquake of 13 February shows that many of these landslides have expanded in size either as a result of aftershocks from the first earthquake, or from the effects of the second, much closer, event.

The susceptibility of slopes to earthquake-induced instability has been shown to be strongly dependent on the rainfall in the months and weeks prior to the seismic event [33]. Although ACPC [37] reports that the 2000/2001 coffee harvest was delayed due to wet weather, average annual precipitations reported by the Meteorlogy Department of the Salvadorian Ministry of Agriculture (MAG) indicate that rainfalls for the year 2000 were in fact slightly low in many parts of the country, at least compared to the previous 2 years (Table 5), although it should be noted that 1998 was an exceptional year because of Hurricane Mitch.

The hazard of rainfall-induced landslides in the rainy season (normally starting in April or May) following the earthquakes became a major concern. On 19 September 1982, after a rainfall of 223 mm in less than 2 days, a landslide began to move on the slopes of San Salvador Volcano (El Picacho) and then descended rapidly into the densely populated neighbourhood of Montebello. The slide had an estimated volume of 200,000 m^3 and killed an estimated 500 people, leaving another 2400 homeless (CEPRODE, 1994). This slide happened exactly three months after an M_w 7.3 subduction earthquake, which is reported to have caused extensive cracking on slopes. Extensive cracking along ridges, especially along the road to Comasagua in the Cordillera del Bálsamo, caused by the 13 January earthquake led to concerns that a similar sequence of events might follow in the 2001 rainy season. However, the hazard did not materialise during the first months of the rainy season since rainfall levels were exceptionally low, to the point of creating drought and consequently severe problems with water supply and agriculture. Nonetheless, heavy rainfalls have occurred since the earthquakes and a large mud and debris flow was triggered on the lower slopes of the San Vicente (Chichontepec) volcano on 15 September 2001.

Liquefaction was observed at various locations along the coast in central and eastern El Salvador, accompanied by lateral spreading and consequent damage to some houses. Similar observations were made on the shores of Lake Ilopango, where lateral spreading was significant and some houses were rendered uninhabitable due to foundation damage. The most serious effects of lateral spreading occurred on the banks of the Lempa River at San Nicolas Lempa that resulted in collapse of a railway bridge (Figs. 19 and 20).

5.2. Damage to housing

The initial estimates by the Committee for National Emergency (COEN) of the Salvadorian government of the number of homes destroyed by the earthquake was about 150,000, with another 185,000 damaged. There has been some debate regarding the damage statistics, with reports that the COEN figures are overestimated [2], but all sources agree that more than one million people were made homeless by the earthquakes. The overwhelming majority of the damaged houses were of *adobe* and *bahareque*, with the former being the most susceptible type of housing. Timber frames and reinforced masonry houses performed significantly better and it was not uncommon to visit locations where most *adobe* houses were in a state of at least partial collapse whereas reinforced masonry houses were practically unscathed.

In the rural area of El Salvador the dwelling construction types mostly used are *adobe*, *bahareque*, reinforced brick masonry (*mixto*), wood frames cover by thin metal sheets (*lamina*), and wood frames cover by palm fronds (*ranchos*). Other building practices, which are less widely used, include concrete and soil-cement block masonry using soil-cement blocks, and steel frames cover by precast walls (Fig. 21).

Roofs of *adobe* houses may be of metal sheets and/or clay tiles supported by wood trusses or thatched roof supported on wood timber purlins. Load transfer between the roof and walls, or between walls, is often not effective. This building system has high mass and stiffness but low strength.

Bahareque consists of timber vertical elements and horizontal timber, cane or bamboo elements, infilled with mud and finished with plaster. The seismic resistance of *bahareque* depends primarily on the condition of the timber and cane elements, having low vulnerability when carefully maintained. *Bahareque* is a more expensive building system than *adobe*. Roofs are similar to those for *adobe* and show the same problems. *Mixto* is composed of fired clay bricks with mortar and slender elements of concrete with thin steel reinforcement, or the same thickness as the wall, which are not properly reinforced concrete and are known as *nervios* (nerves or tendons). This system, in which the load bearing system is

Fig. 19. Lateral spreading on river bank at San Nicolas Lempa.

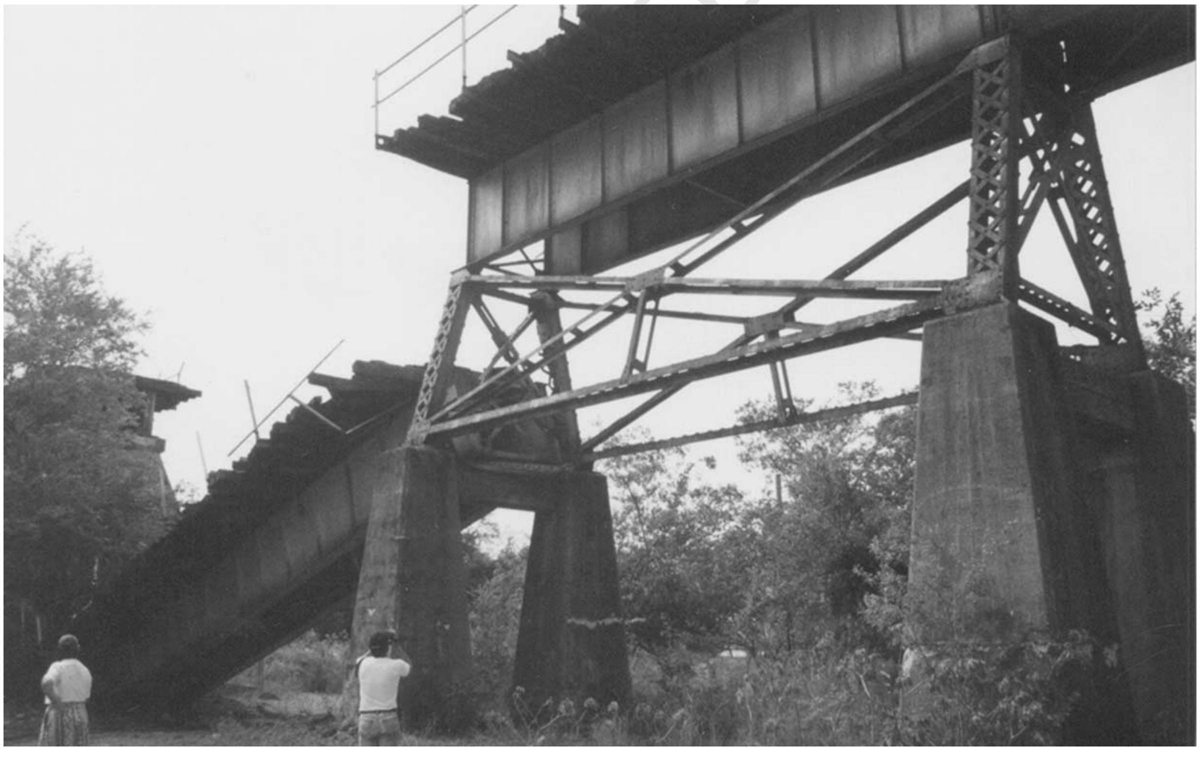

Fig. 20. Collapse of railway bridge due to lateral spreading on banks of the Lempa River.

Fig. 21. Collapsed *adobe* house in San Agustín, of which only the door remains standing after the 13 January earthquake; behind are houses of *mixto* and *lamina*, which have survived the earthquake.

provided by the masonry walls, has relatively good seismic resistance but is considerably more expensive than both *adobe* and *bahareque*. *Lamina* is the name given to buildings of timber or metal frames covered by thin metal sheets, usually founded on a 50 cm high block wall. *Lamina* has good seismic resistance due to its low weight and mass. Wood frames covered by palm fronds have excellent seismic response characteristics but this building system is rapidly disappearing due to scarcity of materials. The construction systems most severely affected by both the January and February earthquakes were *adobe* and *bahareque*.

The damage patterns clearly revealed the social vulnerability of poor forced to live in susceptible locations and vulnerable houses. Small towns such as San Agustín (Fig. 20), where 80% of the houses were made from *adobe*, were particularly hard hit. The same pattern was visible in small hamlets and villages, where *adobe* was even more dominant and where the quality of construction was generally poor. Even in San Salvador, where damage to engineered structures was very limited, extensive damage was observed in shanty dwellings such as in the José Cecilio del Valle area adjacent to the exclusive Escalón neighbourhood, due to both shaking and to movements on slopes.

5.3. Damage to engineered structures

The majority of engineered structures in El Salvador are located in the metropolitan area of San Salvador, and mainly in the cities of San Salvador and Nueva San Salvador (Santa Tecla). When seismic design has been considered at all, the approach has generally been focused on the ultimate limit state. Most damage in engineered structures due to the 13 January earthquake was non-structural, with damage to partition walls, ceilings, A/C ducts and windows. Many major hospitals were put out of service because they lost their functionality and non-structural damage needed to be repaired before they could be used again. Several buildings that suffered light damage in the 1986 earthquake and were not adequately repaired suffered some damage due to the 2001 earthquakes. One structure that had been badly damaged in 1986, a building housing a hair salon next to the Externado de San José High School (itself destroyed in the 1986 earthquake and subsequently rebuilt), withstood the shock without collapse, although the owners have since taken the decision to demolish.

There are only a few buildings in San Salvador that stand more than 70 m height, most of which behaved very well during the earthquakes. One of these, the Torre Cuscutlán (formlerly known as Torre de Democracia), located in the south west of San Salvador, is an irregular tower with external glass walls; none of these were broken. One high-rise structure did suffer some internal damage, the Ministerio del Interior building in the centre of San Salvador, which was also damaged by the 1986 earthquake.

Fig. 22. Guadelupe following the 13 February earthquake, contrasting total collapse of *adobe* houses with the almost undamaged state of the reinforced masonry building to the right.

There are a few other examples of structures having suffered severe damage, such the Regis Condominium in the San Jacinto area of south San Salvador. Most structures that suffered some damage are of reinforced concrete; steel structures behaved well.

Outside the capital there are few engineered structures compared to San Salvador. The hospitals in Usulután and San Miguel were left non-operational due to non-structure damage. Public buildings erected in the 1960's were severely damaged in Santiago de María. Another case of damage outside of the capital city was El Salvador's International Airport located near Comalapa on the coastal plain. The airport suffered important non-structural damage including cracking of infill walls, breakage of windows and collapse of ceilings, as well as some minor cracking in columns and beams in the older sections of the airport buildings.

The 13 February earthquake damaged some engineered structures mainly in the central area of El Salvador. The city that shows most of this kind of destruction is San Vicente, where at least two schools, one of them built in the early 1970s, have suffered severed damage; one branch of the Universidad de El Salvador suffered non-structural damage that limited its function. In addition, this earthquake damaged the Zacatecoluca hospital, which is a twin structure of the Usulutan Hospital. However, in general damage levels were low for the size and location of the earthquake. In the towns of Guadalupe (Fig. 22), Verapaz and Santa Cruz Analquito, which are located very close to the assumed fault rupture, there was total collapse of many houses built from *adobe* and *bahareque*, but *mixto* (reinforced masonry) constructions generally survived intact. Even structures that had been weakened by both the 1999 seismic swarm and the 13 January earthquake, such as the church in the town of San Estebán Catarina, did not suffer as much damage as might have been expected. In the town of Apastepeque, close to the source of the 13 February earthquake and badly affected by the 1999 swarm, residents reported that the most severe effect of the earthquake was to dislodge roof tiles. That a crustal earthquake of M_w 6.6 did not cause greater levels of damage in reinforced masonry nor in some cases in weakened adobe buildings, suggests that the earthquake was less superficial than is typical of volcanic chain earthquakes such as those in Jucuapa–Chinameca in 1951 and in San Salvador in 1986.

In terms of the cultural heritage of El Salvador, there are relatively few examples of colonial architecture surviving in many parts of the country, indeed in San Salvador all buildings from the colonial period have been destroyed by fire or earthquake. The earthquakes caused damage to more than 400 churches in El Salvador.

An important question that immediately presents itself is why the damage to engineered structures, particularly during the 13 January earthquake, was so limited? Even at the Health Centre in La Libertad, where the maximum 5% damped spectral acceleration exceeded 4.5*g*, damage was limited to the fall of part of the ceiling (non-structural) and minor cracks in an external wall. Comparison of accelerograms obtained in San Salvador during the 1982 subduction-zone and 1986 upper-crustal earthquakes provides insight into possible reasons, since the latter event caused significantly higher levels of damage in engineered structures, despite the fact that the response spectral shapes were not very dissimilar, hence the frequency content of the motions is unlikely to provide the explanation. The 1982 and 1986 accelerograms were found, however, to contain almost identical levels of energy, as measured by the Arias intensity but with very different durations, so that the rate of energy input was an order of magnitude greater in the 1986 earthquake [50]. The total energy input, which was actually higher in the January 2001 earthquake than for the 1982 and 1986 records, is a good indicator of the damage potential in brittle and degrading materials such as *adobe* and volcanic soils. It would appear that for damage to be inflicted on engineered structures it is necessary that the motion has both a high energy content and a high rate of energy input, as indicated by the root-mean-square acceleration.

5.4. Performance of lifelines

The performance of lifelines in the two earthquakes has been reported in detail by Lund [79] and EERI [80]. Telecommunications were not seriously affected and service was fully restored in the capital within one day of the first event. Electricity generation was not seriously affected but the distribution system was affected by a large number of transmission lines broken by landslides. There are no gas distribution lines in El Salvador since all household use imported propane distributed in canisters. The diesel and petrol refinery in the port of Acajutla was not damaged and production was not interrupted by the earthquakes.

The distribution of potable and waste water in El Salvador is managed by the state-owned company ANDA. The earthquakes caused disruption to the water distribution system but breakage of pipes was limited; for example, only three repairs in the northern area supply line in San Salvador were reported by ANDA. The most serious disruption to the water distribution system was the damage caused by the 13 February earthquake to the treatment plant at Cacahuatal that supplies the San Vicente area. Although the disruption to the water distribution system by the earthquakes was limited, it is worth noting that even under normal conditions there are problems with water distribution in El Salvador, with chronic shortages and few households, even in urban areas, have uninterrupted water supply 24 h a day.

The most seriously affected lifelines were transport lines. There are three railway lines in El Salvador, connecting the ports of Acajutla and Cutuco (La Unión) and the cement production plants in Metapán in the northwest of the country, used predominantly for transportation of cargo rather than passengers. The eastern line connecting Cutuco has not been operational for many years. The only damage to the railway system was the collapse of the steel arch truss bridge at San Nicolas Lempa due to lateral spreading.

The two main highways in El Salvador run across the country from east to west. The Panamerican Highway (CA-1) runs along the Great Interior Valley; it was originally constructed to serve the coffee industry. The second major artery is the coast road (CA-2) whose original purpose was to serve the cotton plantations that previously occupied the coastal plains. Transport on both roads was severely disrupted by landslides. The coast road between the ports of La Libertad and Acajutla in the west was partially blocked by a number of rock falls and relatively small landslides; the five tunnels on this section of motorway were undamaged apart from minor cracks in their lining. The Panamerican Highway was completely blocked by major landslides both east and west of San Salvador for several weeks. To the west, major slides at Los Chorros blocked the road and even after several weeks traffic was only able to circulate in one direction, with vehicles entering the capital in the morning and leaving in the afternoon. East of San Salvador the highway was completely blocked in both directions by the huge slide, re-activated by the 13 February earthquake, at Las Leonas, obliging traffic to use the old and practically abandoned road running approximately parallel to the north.

The motorway joining San Salvador and the international airport at Comalapa on the coastal plain was damaged by cracks at several locations and during several weeks traffic was reduced to a single lane in each direction over part of the road. The airport was closed for one day following the 13 January earthquake to allow clearing up of debris and inspections of buildings and runways.

6. Implications for seismic risk: physical, social and institutional vulnerability

The 2001 earthquakes have revealed the extreme levels of vulnerability to natural hazards that exist in El Salvador. Moreover, the failure to mitigate earthquake risk in El Salvador is a reflection of institutional vulnerabilities that have not been addressed; chief among these are the capacities for emergency response, monitoring of natural hazards, land-use planning, and seismic design and its enforcement.

6.1. Emergency response

Some observers have claimed that the government response to the disaster in El Salvador has been poorly organised and in particular that the lessons from Hurricane Mitch were clearly not learnt [81]. Although this study is not primarily concerned with emergency aid following the earthquakes, there were some obvious shortcomings, at least in the initial phases of the response. For example, most aid arriving at Comalapa International Airport, located on the coastal plain, was transported almost 30 km to the Feria Internacional in San Salvador for centralised logging and thence distributed to affected areas, several of which were within 1 hour's drive of the airport. Our visits to badly affected rural areas generally indicated that government assistance, in the first few weeks of the crisis, was not getting through to many of the earthquake victims, particularly in more remote rural areas.

The main response to the emergency seems to have been provided by the affected people themselves, although important contributions by NGOs and others, including contingents of the Venezuelan Armed Forces and, changing their historical role, the Salvadorian Armed Forces as well, should not be overlooked. Despite the huge numbers of people made homeless by the earthquakes, there were very few examples of victims living in temporary shelters in the streets of the cities, as there were after the 1986 earthquake. Most rural communities, except where affected by landslides, appear to have remained to rebuild their homes and continue with their lives. Middle class people made homeless, such as those from Las Colinas and adjacent neighbourhoods, were either absorbed by relatives or added to the exodus to the USA. May 2001 saw the highest ever influx of *remesas* into El Salvador, with a monthly total of US$ 197.1 millions.

6.2. Seismic design of buildings

Although damage to engineered structures was limited, at least in terms of structural collapse, there is still a significant danger of many large engineered structures having been weakened by the earthquakes and therefore urgently requiring intervention. This is, in the majority of cases, which may be unlikely to happen given that seismic design requirements are not imposed even for new buildings. Lara [82] reports that prior to the 1986 earthquake in San Salvador, the seismic design code was rarely applied, and there is little evidence to suggest that the codes of 1989 and 1994 have been more widely implemented. Indeed, although it has many technical merits, there is no effective mechanism for the imposition of the current code for earthquake-resistant design in El Salvador [83].

The current seismic design code in El Salvador has many technical merits but the lack of a credible system for its enforcement severely limits its effectiveness in mitigating seismic risk. There are almost many aspects of seismic risk in buildings that fall outside the remit of the code, one being repair and strengthening. As noted previously, the code does include an appendix of guidelines for the improved earthquake-resistant construction of *adobe* although this, logically, does not form part of the actual regulations. These guidelines, and other publications [84], affirm that adobe buildings can be constructed with a degree of earthquake resistance, with minimal requirements in terms of additional costs and building skills. There is clearly a need, however, for a transfer of this knowledge to the most isolated and vulnerable rural communities where these forms of housing are most abundant and also where they are built with the highest levels of susceptibility. Amongst the many obstacles to this effective mitigation are the relatively high rate of illiteracy in rural areas and the lack of confidence in adobe construction following its poor performance in the 2001 earthquakes.

6.3. Land use planning

The high level of landslide hazard in El Salvador makes land-use planning an issue of great importance. The high population density of El Salvador and the housing deficit also makes it a sensitive and controversial issue. There is currently almost no effective control over land development. It is interesting to note that the landslide hazard map shown in Fig. 2 clearly indicates that the area affected by the catastrophic landslide at Las Colinas was identified as being of high hazard. The hazard map was prepared some years after Las Colinas was developed in 1985, but nonetheless no remedial action was taken to stabilise the slopes or to protect the area from landslides. The irrelevance of geohazards in planning decisions is very clearly demonstrated by a recent housing development to the north of San Salvador, called Santísima Trinidad (Fig. 23). The development consists of several rows of four-storey apartment blocks built on terraces on a natural slope with an inclination of about 35°, above which three huge water tanks have been constructed. The constructors apparently did not face any serious obstacles in obtaining permission to build.

Despite the apparent lack of control and accountability in land use planning, the earthquakes may lead to important changes in this area. Following the earthquakes, 200 survivors from Las Colinas, supported by the Salvadorian Foundation for the Application of Law (FESPAD) brought a case against the State to the Supreme Court of Justice for their failure to prevent or mitigate the risk of landslides on the slopes of Cerro La Gloria, which were well known and identified in the PLAMADUR hazard map (Fig. 3). The case was unsuccessful, being dismissed by the Supreme Court; similarly, the attempt by the Santa Tecla municipality to prosecute the developers also failed [81].

More generally, after the earthquake there was a renewed interest in addressing hazard-related land use issues, not only in urban areas but in the country as a whole. However, it is not yet clear how this process will evolve. Certainly, both public and private sectors in El Salvador will need to make rapid advances in their risk management and evaluation practices if large-scale losses are to be avoided in future due to earthquakes or other natural hazards.

6.4. Seismic monitoring

The monitoring of earthquakes, volcanoes and landslides

Fig. 23. Santísima Trinidad residential area north of San Salvador built on terraces along a steep slope (a) above which are three large water tanks (b).

has traditionally been the responsibility of the Centre for Geotechnical Investigations (CIG), which is part of the Ministry of Public Works. Monitoring capacities for natural hazards were severely weakened in the 1980s due to the war and efforts to re-build and re-generate these activities since have been limited. Some responses to this situation have taken the form of independent initiatives by private institutions, a clear example of which is the digital accelerograph network established in 1996 by the UCA. The government of El Salvador has now responded to this situation by forming, in October 2001, SNET (National Service for Territorial Studies), which will unify and strengthen current natural hazards monitoring capacities. The structure of SNET includes four different national services: Geological Service (including earthquake, volcanoes and landslides); Meteorological Service; Hydrological Service; and Risk Management Service. The United States and Japan are expected to provide equipment and technical assistance for SNET. The Spanish government has approved a project to expand and upgrade the existing strong-motion network previously managed by CIG and a convention has been agreed for collaboration amongst the three strong-motion networks in El Salvador.

7. Discussion and conclusions

The El Salvador earthquake of 13 January 2001 was the first major earthquake disaster of the new millennium and serves perhaps as a warning that in many countries of the Third World seismic risk is growing. The combination of population expansion and increasing urbanisation, in the case of El Salvador with cities expanding in the zones of highest seismic hazard, together with the increasing susceptibility of the terrain to landslides, has led to increased levels of risk both to lives and to the livelihood of the country.

The impact of the earthquake of 13 January was compounded by the second event on 13 February, which came as the aftershocks of the former event were beginning to diminish in frequency and intensity. The 13 February event was followed by many aftershocks, both around the crustal source of this earthquake but also offshore in the subduction zone. This would tend to indicate interaction between the two earthquakes, a topic that will be the focus of future research. Interactions between earthquakes are well recognised, with stress release in one location causing, by transfer, stress increase in adjacent zones and hence inducing or accelerating rupture on adjacent faults or fault segments. The clearest example of such interaction is the progression of earthquakes from 1939 to 1999 along the North Anatolian fault in Turkey [48,85,86]. Interactions between different earthquakes has also been identified within subduction zones, as for example in the 1997–1998 sequence in central Chile [87]. That there is interaction between subduction and crustal earthquakes in Central America seems probable: it has been noted that the subduction zone from central El Salvador to the northern Nicaragua has a far lower rate of moment release than the zones offshore from Guatemala and Nicaragua either side [88]. There is also evidence that destructive shallow-focus earthquakes along the volcanic chain opposite the El Salvadorian section of the Middle America Trench are more frequent than in Guatemala and Nicaragua. The exact nature of the interaction and the mechanism of stress transfer between the two seismogenic sources is, however, far from clear at this stage.

The large numbers of accelerograms recorded during the two earthquakes provide a very useful basis for the characterisation of strong ground-motion in Central America, although the lack of any near-source recordings of the 13 February earthquake—due to malfunction of the San Vicente and San Pedro Nonualco stations of the TALULIN network—is an unfortunate gap in the data set. This is particularly the case because the indications from the recorded motions of the second earthquake, and the observed levels of damage, are that the ground motions generated were less intense than would be expected from a shallow earthquake of magnitude M_w 6.6, indicating either very high attenuation with distance or a focus within the lower part of the crust. Macroseismic observations and the limited strong-motion recordings from other earthquakes point towards high rates of attenuation in the volcanic chain zone, as has been found elsewhere including the volcanic region of the North Island of New Zealand [89]. Notwithstanding this observation, the 13 February earthquakes appears not to have been as shallow as other slightly smaller but more destructive events along the volcanic chain in El Salvador and neighbouring countries. There are several features of the ground motion that warrant further research:

- The differences between ground motions from crustal and subduction events in Central America, and the development of separate predictive relationships for the two sources of seismicity.
- The influence of site effects due to both surface geology and topographical features; the apparent predominance of these influences suggests that microzonation is a potentially very useful tool in El Salvador.
- The specification of earthquake loads for seismic design, taking account of both the different geographical distributions of the hazard from crustal and subduction earthquakes and the different natures of the resulting ground motions.
- The relationship between the nature of the recorded motion and its capacity to produce damage: it is abundantly clear that PGA is of very little significance in this respect, and to some extent this is also true for spectral accelerations (whence the current trend towards displacement-based approaches to assessment and design).

The lack of extensive structural damage in reinforced concrete buildings due to these earthquakes should not be interpreted as a vindication of the success of the current seismic design code in El Salvador nor its predecessors, since regardless of their technical merits these codes have generally been applied only sporadically. The lack of major structural damages and collapse of large buildings appears to be more closely related to the nature of the ground motions generated than the quality of engineering design or construction. Particularly in San Salvador there is now a real danger of complacency regarding the capacity of existing buildings, despite the fact that it is widely known that many buildings have been left damaged by the 10 October 1986 earthquake and these may have been further weakened by the 2001 earthquakes. Destructive moderate magnitude earthquakes occur in San Salvador on average every 20–25 years [14] and the next event could cause terrible damage and loss of life in the overcrowded and expanding capital.

The most devastating impact of the 2001 earthquakes has been the triggering of hundreds of landslides in volcanic soils, which have buried houses and blocked roads, causing most of the deaths in these earthquakes and bringing massive disruption: the Pan-American Highway remained closed for more than 10 months due to the landslide at Las Leonas. The number of landslides triggered by these earthquakes, the size of the slides and their geographical distribution, all indicate increasing susceptibility of the terrain when compared to patterns in previous earthquakes, with no indication that this was due to precedent rainfall. The hazard of earthquake- and rainfall-induced landslides in the volcanic soils that dominate much of El Salvador, and particularly the most densely populated areas, urgently requires attention. The identification of zones of high landslide hazard is an important component of any programme of mitigation, but relocation to lower hazard zones will often not be an option in this densely populated country with a long history of conflicts over land ownership. Stabilisation measures cannot necessarily be imported from regions of the world with entirely different soil characteristics, since one of the distinguishing features of volcanic soils such as *tierra blanca* is the complete loss of cementation at small strains, followed by the collapse of its matrix structure and a drastic loss of strength [68]. One of the most important fields of research in El Salvador is the engineering characterisation of the *tierra blanca*, in order to model its behaviour in slopes subjected to rainfall and due to earthquake shaking, and similarly to model its modified behaviour after the application of different stabilisation techniques.

Seismic risk in El Salvador clearly cannot be viewed in complete isolation from other risks, including those due to other natural hazards such as floods and volcanic eruption but also anthropogenic risks such as pollution, deforestation, crime, poverty, disease and social conflict. The failure to tackle the challenges of seismic risk, or even to hold back its increasing levels, is not due to any lack of awareness amongst Salvadorians of the very high earthquake hazard that affects their country. Rather the lack of effective measures against earthquake risk reflects the fact that there are many urgently pressing needs on limited resources, exacerbated by the weakness of central and local government. A pessimistic view of the situation may conclude that earthquake risk mitigation will only be possible following the solution of other major social problems in El Salvador. An alternative view holds that recognition of the interaction of seismic vulnerability with other features of vulnerability, including institutional vulnerability, means that concerted programmes of seismic risk mitigation could provide a vehicle and a stimulus to the solution of many other issues, including the current concentration of more than half of the population in one-third of the national territory. El Salvador will need external assistance, both in terms of material resources and technology transfer, to make this vision a reality.

8. Uncited reference

[78].

Acknowledgments

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