THE SAN SALVADOR EARTHQUAKE OF 10 OCTOBER 1986

A FIELD REPORT BY EEFIT

Rendel Palmer & Tritton

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This report was made possible by the generous funding which EEFIT records with gratitude from the following:

Rendel Palmer & Tritton, Consulting Engineers, London.

The British Government, through the Science and Engineering Research Council.

The University of Bath.

EEFIT's work would also have been impossible without the help of many individuals and organisations, particularly Dr. Jon de Cortina of the Catholic University, San Salvador. The helpfulness shown to the team by many Salvadoreans during their time of national crisis is also recorded with gratitude.

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EEFIT September 1987

LIST OF CONTENTS

5.0 ENGINEERED STRUCTURES

LIST OF FIGURES

LIST OF TABLES

LIST OF PLATES

1.0 INTRODUCTION

1.1 **Background to the EFFIT mission**

The San Salvador earthquake of 10th October 1986 was of moderate magnitude. However it caused considerable damage in the city of San Salvador. In particular it was damaging to engineered buildings and caused more damage than would normally be expected for earthquakes of equivalent magnitude. For these reasons EEFIT believed there were lessons to be learnt for earthquake engineers.

EEFIT is a group of engineers, architects and scientists with an interest in earthquakes. It was founded in 1983 with the aim of reporting to the UK and the international community the lessons to be learnt from damaging earthquakes.

It was decided that even if other international teams were to study the earthquake a two man EEFIT team could make a useful contribution to the field investigation work and that this was the best means of reporting the work to the UK.

1.2 **EEFIT mission**

The EEFIT team consisted of Julian Bommer (Civil Engineer) of Rendel Palmer & Tritton and Stephen Ledbetter (Structural Engineer) of Bath University. Bommer's expenses were met by Rendel Palmer & Tritton and Ledbetter's expenses were paid by the Science and Engineering Research Council. The team spent 15 days in San Salvador beginning on 20th October, 10 days after the earthquake. It was not practical to travel far from San Salvador, however the team travelled to Santa Tecla and to Soyapango (see Fig. 4) and were able to establish that all of the significant damage was in or near to San Salvador.

The field methods of the team were very simple. Most of the interesting damage buildings were visited. They were inspected and photographed externally and where access was possible, internally. Where possible the team spoke to local engineers working on the buildings. In addition to seeking information from engineers, the team spoke to eye witnesses who were often able to describe the mode of failure.

The buildings studied could be divided into three categories for the purpose of inspection;

a) Some of the buildings had collapsed completely and in these cases the team could often deduce very little about the original structure and its mode of failure. The failed buildings were photographed and local people were asked about the building as it was before the earthquake and its behaviour during the earthquake.

b) Some buildings were damaged but the team had no access inside the buildings. This arose because the buildings were locked and closed, because the owners believed that a study might prejudice their future compensation, because the owners were genuinely too busy in the crisis following the earthquake, or because of bureaucratic delays.

c) At a number of sites the team had full access to damaged buildings and the help of owners and engineers. For these buildings the team were able to make detailed studies, photograph inside buildings and discuss the nature of the damage, the emergency repairs carried out and the long term repairs that were planned.

In the early stages of the mission the team were helped to locate sites of engineering interest by Dr. Cortina of the Catholic University and by a team of insurance assessors from Thomas Howell Kiewit of London.

The team visited the National Seismological Institute where they were able to discuss the strong motion records of the earthquake and the geology of the San Salvador area. Some samples of soil were brought back by the team and tested at Imperial College.

Engineers and seismologists from the USA and Venezuela also visited the San Salvador earthquake. Other reports on the earthquake are listed in the references at the end of this report.

2.0 SEISMICITY OF THE SAN SALVADOR AREA

2.1 Regional Tectonics and Volcanism

The Republic of El Salvador, occupying an area of about 22,000 square kilometres, lies on the Pacific Coast of the Central American isthmus, bordered by Guatemala and Honduras, (Fig.1).

El Salvador is situated on the so-called 'ring of fire', the belt of volcanic and earthquake activity that encircles the Pacific Ocean. The tectonics of the Central American and Caribbean region are fairly complex, with five tectonic plates interacting, these being the North and South American, the Nazca, Cocos and Caribbean Plates (Fig. 2). The zone of tectonic activity that primarily affects El Salvador is the Middle American Trench, where the Cocos Plate is subducted below the Caribbean Plate at a rate of a few centimetres a year. This subduction zone is illustrated schematically in Fig. 3a.

Four distinct zones of seismic activity have been identified by the location of earthquake foci in the region. Three of these are Benioff zones, zones of earthquake sources within the subducted Cocos Plate. These zones are the source of the vast majority of the earthquakes that are felt in El Salvador, (Fig.3b). However, it is a fourth, quite separate, zone which gives rise to the most destructive earthquakes; this is associated with the chain of volcanoes that runs almost parallel to the coast through El Salvador, Nicaragua and Costa Rica. Earthquakes in this zone are generally of shallow focal depth and intermediate magnitude, as was the case with the San Salvador earthquakes of May 1965 and October 1986, and the earthquake in Managua, Nicaragua on 23 December 1972.

2.2 Geology of the San Salvador Area

San Salvador, El Salvador's capital city, lies about 26 km from the coast (Fig. 5) on an erosion surface known locally as the 'Valley of the Hammocks', presumably because of its high level of earthquake activity. The erosion surface slopes from west to east in the metropolitan area of San Salvador, varying in elevation between 750 and 650 m above sea level. The surface continues to slope to the east as far as Lake Ilopango, which is 438 m above sea level. To the north are the relatively subdued Cerros de Mariona, with a maximum elevation of 798 m, to the west is the San Salvador Volcano, known as El Boqueron, whose elevation is 1967 m, and to the south is the coastal cordillera (maximum elevation 1100 m) and the extinct volcano, Cerro de San Jacinto, which stands at 1154 m above sea level, (Fig.4).

All the rocks out cropping in the area are volcanic in origin, the oldest formations dating from the Upper Tertiary period. There is extensive faulting throughout the area, as shown in Fig. 4. These faults were identified by a German geological team working in conjunction with El Salvador's National Geographic Institute, which published a geological map of the country in 1978, on a scale of 1:100,000. It is known that the faults generally dip steeply, between vertical and 65 degrees, but little is known about their actual mechanism.

Almost the entire metropolitan area is overlain by 'tierra blanca', a yellow-white volcanic ash, reworked by surface waters. This fluviatile pumice is thought to have its origin in the volcano that is now submerged within Lake Ilopango. This volcano was last active in 1880, (see section 2.3.1). Near the Lake, the tierra blanca has been found to extend to depths of 100 m, thinning out westwards where it gives way to the slopes of El Boqueron. In the metropolitan area, the deposits of fluviatile pumitic ash generally vary between 5 and 20 m in depth.

San Salvador is crossed by a large number of steep narrow gullies, called 'arenales', cut into the tierra blanca by heavy rains. Largely as a result of pumping for the city's supply, the ground water table is now situated at depths greater than 80 m, although near to Lake Ilopango the phreatic level is just below the ground surface.

2.3 Historical Seimicity

Historical records of earthquakes in El Salvador and neighbouring countries exist from as far back as the Spanish Conquest at the beginning of the fifteenth century. The major task of collating all this data and converting it into a numerical model of long-term seismic behaviour in El Salvador has yet to be carried out, although several studies have been carried out on the subject, and some of the more important references on the historical seismicity are given in the bibliography at the end of this report.

Here a summary of some of the reports of major earthquake occcurrences in and around San Salvador is given, with some indication of the certainty that can be attached to the event.

2.3.1 Major Historical Earthquakes

The first recorded earthquake damage to San Salvador occurred in 1524, before it was established as the country's capital city. The original capital of Bermuda, founded by the Spanish in 1526, was transferred to San Salvador in 1538-9, after itself being destroyed by earthquakes.

San Salvador is reported to have suffered from numerous shocks in 1556, and also in 1576, when even the 'well-built' houses were destroyed. The epicentre for the latter event was placed between San Marcos and Santo Tomas, (Fig. 4).

Complete destruction of the city is also recorded in 1594, although there is less certainty about this event. Strong shocks in San Salvador are reported for 1625.

Some sources describe the destruction of San Salvador by an earthquake in 1656, but this is most probably a confusion with the event of 30 September 1659, when a very destructive earthquake occurred simultaneously with the eruption of El Boqueron.

Two further cases of earthquake destruction in San Salvador are reported for 1707 and 1719, although there is some doubt about both of these, particularly the former.

A strong shock in San Salvador is reported in 1773, resulting in damage in San Marcos.

A reliably documented case of earthquake destruction of the city occurred on 2nd February 1798. The heaviest damage occured in Cuscatlan, southwest of San Salvador, but a strong aftershock hit the capital on 9th February.

Destruction of the city in 1806 is described in one source.

Reports, both with some degree of uncertainty, are given of damaging earthquakes in San Salvador in August 1815 and February 1831.

A very damaging earthquake did hit the capital on 22 March 1839, with strong aftershocks continuing into 1840, the strongest being on 31 April and 1 October 1839, the second causing considerable additional damage.

A strong shock on 4 April 1853 is reported to have resulted in moderate damage in San Salvador.

A very destructive earthquake struck San Salvador on 16 April 1854, following strong foreshocks. The area of highest inensity was around Cerro San Jacinto, and the area of highest damage occurred in a band about a kilometre wide, running NW-SE across the city. The earthquake resulted in about 100 deaths, and led to the relocation of the capital at Nueva San Salvador a few kilometres to the west. The capital was returned to its original location in 1895, and Nueva San Salvador exists today as Santa Tecla, (Fig. 4).

Strong shocks felt in San Salvador are reported on 17 October, 24 and 26 November 1854. Some houses were destroyed by an earthquake in early December 1856.

A strong earthquake to the south of Lake Ilopango on 6 November 1857 caused panic in San Salvador. Strong shocks are also reported in the city on 28 May 1859, but apparently these did not cause damage.

A very large earthquake, with a duration of almost two minutes, occurred on 19 December 1862, and was felt from Chinandega in Nicaragua to Belize; moderate damage resulted in San Salvador. The wide distribution of damage suggests that this was a large event of deep focus, rather than a volcanic chain earthquake.

A number of strong shocks are reported in San Salvador on 27 June, 12 and 19-20 October 1865, and 21 March and 13 August 1866, 2 April and 30 June 1867, and 1 March 1869. On 19 March in 1873, a very large shock in San Salvador, following a series of foreshocks, left only 15 houses standing. The epicentre was presumed to be near Santo Tomas.

Some activity of El Boqueron in April and May 1876 is reported in one source.

In 1879, on 20 December, a swarm of earthquakes began, one causing heavy damage at Ilopango on 27 December and another, on 31 December, was felt throughout El Salvador. The swarm culminated with an eruption of the volcano within Lake Ilopango, which was preceded by a rise in the level of the lake, resulting in flooding of certain areas.

Strong shocks were felt in San Salvador on 8 July 1883 and in March 1884, the latter felling old walls at the British Consulate.

Some reports exist of a destructive earthquake on 19 June 1906.

Another major disaster occurred on 7 June 1917, when an earthquake was accompanied by the eruption of El Boqueron, as in 1659. A damaging aftershock occurred on 19 June.

A violent earthquake also occurred on 28 April 1919, killing more than 100 people, most of them in houses that had been damaged by the 1917 earthquake.

Another major earthquake disaster, which has been fairly well documented, occurred in 1965, and this is discussed in the next section.

In conclusion, it is clear that San Salvador is situated in an area of high seismic activity and has suffered damage from earthquakes on numerous occasions. According to White (1986) the return period for earthquakes that damage the city of San Salvador varies between 2 and 65 years, with an average of 24 years. The susceptibility of San Salvador to earthquake destruction is corroborated by the almost complete absence of any buildings dating back further than the middle of the last century.

2.3.2 1965 Earthquake

This earthquake occurred on 3 May 1965 shortly after 4 a.m. local time. The epicentre was located to the south-east of San Salvador, between San Marcos and Santo Tomas (Figs. 4 and 7). The focal depth was of the order of 10 km. The body wave magnitude (as given by the U.S. Coast and Geodetic Survey) was mb=5.1 and the surface wave magnitude (as given by the Pasadena seismic station) was Ms=6.25.

The maximum observed intensity was VII-VIII on the Modified Mercalli Scale (Lomnitz and Schulz, 1966). Heavy damage resulted in the North and East of San Salvador, including the National University, Mejicanos, San Jacinto and the area adjacent to Lake Ilopango. The shaking was reported to be felt in Guatemala, some 200 km away.

The earthquake had been preceded by a seismic swarm which began on 2 February 1965, reaching a peak of more than 600 earthquakes a day on 7-8 February. The activity died down significantly in March and April, picking up again prior to the main shock. Heavy aftershock activity was also observed. The earthquake resulted in 120 deaths, and left about 10,000 people homeless.

The earthquake was investigated by a UNESCO reconnaisance team, which produced a detailed report on the disaster, (Lomnitz and Schulz, 1966; Rosenblueth, 1965; Fiedler, 1965).

Amongst the interesting features that were observed was liquefaction of the saturated soils in the vicinity of Lake Ilopango, shown by cracks in the ground, from which mud and water were ejected. There were also numerous slides in the steep cuttings in the tierra blanca, as well as in the arenales.

There were no strong motion accelerographs in San Salvador in 1965, but Rosenblueth reported that there was no evidence of significant vertical ground accelerations, and that subjective reports on the nature of the shaking made no reference to vertical motions, even though the human body is more sensitive to vertical than to horizontal motions. The absence of significant vertical accelerations was confirmed for Rosenblueth by the three aftershocks he experienced while in San Salvador.

Using a seismogram, recorded about 15 km from the epicentre, Rosenblueth estimated a peak horizonal ground acceleration of 0.44g, and from observed displacements of machinery at the Industrias Unidas factory, closer the epicentre, he estimated peak values of between 0.5 and 0.78g.

On the basis of his observations, Rosenblueth proposed a new aseismic construction code for El Salvador, which was adopted in 1966.

3.0 ASEISMIC BUILDING REGULATIONS

3.1 1946 Code

Ulrich (1946) reported to the U.S. Coast and Geodetic Survey that a building code for earthquake resistant design in El Salvador was about to be adopted in May 1946, requiring design for a horizontal ground acceleration of 0.2g. According to Rosenblueth (1965), the code was adopted shortly afterwards, but was never enforced.

3.2 1966 Code

The 1966 code for earthquake resistant design in El Salvador was adopted as a result of the 1965 earthquake. The code was based on the recommendations in Rosenblueth's report to UNESCO, in which he proposed a code based on the building regulations for Acapulco, Mexico. Rosenblueth stated that it would have been equally applicable to adopt the Chilean code, or even the code from New Zealand, although the latter would have required extensive modification.

In terms of seismic zoning, the 1966 code simply divides El Salvador into two zones, by a straight line running parallel to the coast; Zone I, which includes San Salvador, is on the coastal side and is of higher seismic hazard, with a design intensity of 8 to 9 on the Modified Mercalli Scale, whereas the design intensity in Zone II is 7 to 8, (Fig. 5). The code converts these intensities into design spectra for engineering purposes. In his report, Rosenblueth points out that these intensities correspond to firm ground (conglomerates, hard clays and dense granular material) and that higher intensities should be expected in areas of loose or compressible soil, although this is not clearly stated in the code, which prescribes the same design parameters irrespective of local ground conditions.

The code defines three Use Groups, reflecting the importance of the structure and the consequences of its failure: Group A includes public buildings, hospitals and telephone exchanges, and Group B includes office buildings and dwellings; Group C buildings are those whose failure due to earthquake effects would not normally damage humans or costly goods and equipment, and for which aseismic design is not required.

The code also classifies structures into three different types, according to the way in which they carry lateral loads, with definitions similar to those that appear in the Chilean (1963) and Cuban (1964) codes; these classifications are really a measure of a structure's ductility. Type 1 structures are those with at least two members capable of resisting horizontal loads and whose deformations under lateral loads are essentially due to flexure. Type 2 structures are those whose deformations under lateral loads are essentially due to shear stresses or axial forces in members. Type 3 structures include elevated water tanks, chimney stacks and structures supported on a single column or row of columns in the direction analyzed, or whose columns are not sufficiently tied to roofs and floors to distribute the horizontal forces amongst columns of different flexibilities.

For structures in Zone I the base shear force for design is V=C.W, where W is the weight of the structure and C is the base shear coefficient as given in Table 1.

The value of C may be reduced by a factor D, defined as $D = (C/x)^{\frac{1}{2}}$, where x is the displacement (in centimetres) of the centre of gravity of the building under the action of the lateral forces corresponding to the seimic coefficient C; this actually represents the spectral response and the approximate relation between D and the natural period of vibration of the building is shown in Fig. 6.

The code permits psuedo-static analysis, which for certain structures can be simplified by neglecting lateral displacements, torques and overturning moments, and for larger structures the design shear at different storeys are calculated according to the following formula:

$$Fi = C.D.W. \frac{Wi.Hi.}{W.H.}$$

where Fi is the horizontal design force at the 'ith' storey, Wi is the weight of the storey under consideration, Hi the height of the storey and H the overall height of the building.

Dynamic analysis is not mandatory for any structures, but it is permitted. For modal analysis, the contributions for each mode are determined using a base shear coefficient a.C, where a represents the spectral response; the relation between a and natural period is shown in Fig. 6. The technique specified for superimposing the effects of the various modes is that of the square root of the sum of the squares.

The code gives no guidance on non-linear analysis, although this is also true of all other current codes, nor on detailing of reinforcement; thus while the structural type classification assumes a certain level of ductility, no guidance is given on how to ensure the structure's ductility.

The code limits the maximum relative displacement between consecutive floors to 0.002 times the corresponding difference in elevations, or 0.004 if this will not result in damage to any integral part of the structure. No drift limitations are imposed for floors and roofs which do not usually support live loads.

One interesting omission from the code is design considerations for vertical ground accelerations. As pointed out before, Rosenblueth (1965) reported no significant vertical accelerations associated with the earthquake of 3 May 1965, which he attributed to the shallow focus of the earthquake, and the result was that all column failures were in flexure, eccentric compression or diagonal tension, and there was no evidence of pronounced oscillation of horizontal structural elements. However, Rosenblueth stated that this observation should not be extrapolated to all future earthquakes, since important vertical accelerations could be present under other conditions. (It is interesting to note that Rosenblueth suggested that significant vertical ground accelerations would be produced by earthquakes of deeper foci, whereas the 1986 earthquake, which did produce very strong vertical accelerations, was of slightly shallower focal depth than the earthquake of 1965). Accordingly, Rosenblueth recommended that concrete columns be designed so that their vertical reinforcement be capable of resisting a tension not smaller than 25% of the static load on the column. This recommendation did not find its way into the code which makes no reference at all to the vertical effects of earthquakes, although this is also the case in most earthquake resistant codes, except the UBC (1988) and Eurocode 8, which only consider vertical effects in a few special cases.

3.3 Application of Aseismic Building Codes in El Salvador

As mentioned earlier, the 1946 building code in El Salvador was never enforced. Prior to the 1965 earthquake, engineers, when they applied aseismic design considerations at all, employed various codes from around the world, including the 1956 San Francisco building code, the US Uniform Building Code, the German (DIN) code and the code of the American Concrete Institute, (Rosenblueth, 1965).

In assessing the application of the 1966 code it is worthwhile looking at Article 32 which deals with the enforcement of the code, and states:

> "Each project of new building or repair of earthquake-damaged structures presented for approval shall comply with these regulations and requires authorization from the General Direction of Architecture and Urbanism. This Direction is free to inspect the works at all times to check the correct fulfilment of requirements.
>
> Drawings and computations shall be authorized by an architect or engineer legally recognized in his profession who will be responsible of the work executed." (IAEE, 1984).

The team's observations in San Salvador and their discussions with engineers in the city suggest that the 1966 code has not been enforced, and as before 1965, engineers have used a variety of aseismic design criteria, such as those mentioned previously, and more recent codes such as the one from Colombia (1980).

In terms of demolition and repair, the lack of enforcement of the 1966 code was quite apparent, as is discussed in a later section, (10.3).

In discussing the enforcement and application of aseismic design codes in El Salavador, it is important to point out the severe shortage of qualified professionals and technicians, which, along with the other factors, has contributed to the situation described above. Nationally, illiteracy in El Salvador stands at 43%, and both of the capital's seats of learning, the National and Catholic Universities, suffer from grave financial difficulties and other disruptions; the National University was occupied by the army between 1981 and 1985, during which time large numbers of books and much important equipment was lost. The National University also suffered severe damage in both the 1965 and 1986 earthquakes.

4.0 SEISMOLOGY OF THE EARTHQUAKE

In seismological terms the 10th October 1986 earthquake was fairly small (worldwide there are about 600 earthquakes of the same size or larger every year) and it occurred in an area of very complex local tectonics and volcanism, which are not fully understood. As a result, the mechanism of the earthquake was not unambiguously defined either by field evidence or teleseismic data, and it would be misleading to attempt to summarize the seismological aspects of the earthquake in a few short lines; instead, the available information, both from field observations and teleseismic readings are presented, with indications of their reliabilities, to assist future research work.

4.1 Characteristics of the Earthquake

4.1.1 Origin time, Epicentre and Depth

The origin time of the earthquake, that is the instant in Greenwich Mean Time at which the energy release began, was first determined by the National Earthquake Information Service (NEIS) to be 17:49:23.7, which was just before midday local time (this is confirmed by personal reports of the event as well by the fact that a large number of clocks stopped at that moment). This value was determined by NEIS using data from 94 seismic stations, and the standard deviation of the results was 1.1 seconds, which, with P-wave velocities of, say, 8km/sec represents a standard deviation in the epicentral location of several kilometres. The epicentre given was at 13.829^{o} N, 89.126^{o} W, which is several kilometres to the north-east of San Salvador. From the same teleseismic readings, the depth of the earthquake focus was estimated at 5 km. Subsequently, the NEIS recalculated these values using data from 131 stations. The origin time was then determined as 17:49:24.1, with a standard devation of 1.2 seconds, and the epicentre was given as 13.827 N, 89.118 W, just to the south-east of the original estimate. The depth was then constrained at 7km.

Another determination of the epicentral co-ordinates was carried out by Dave Harlow of the USGS and Roberto Linares of the Geotechnical Investigation Centre (CIG) in San Salvador; they used data from the seismograph network of the Seismology Department of CIG, and arrived at values of 13.673 N, 89.203 W, which places the epicentre a couple of kilometers south of the city centre,

(Fig. 7). This location differs from that of the NEIS by almost 20 km, and is certainly more consistent with the observed distribution of strong shaking and damage. The exact location of the epicentre is of secondary importance since earthquakes do not generate from a single point but from a source area, usually associated with a geological fault; it is clear from macroseismic evidence that this source area was almost directly below the city of San Salvador.

4.1.2 **Size of the Earthquake**

The original value of the earthquake's magnitude was given by the Seismology Department of CIG as 7.5; this was the value given by the Salvadorean government and the value that was reported by the media in Britain. The magnitude of the earthquake was still being quoted as 7.5 by some sources in San Salvador some months after the earthquake.

The NEIS calculated the surface wave magnitude, Ms=5.4 from 9 stations, and the body wave magnitude mb=5.0 from 46 observations. The seismograph station at Pasadena gave Ms=5.5. As with the epicentral location, the ISC determination of the magnitudes will not be published until October 1988.

Some time after the earthquake the NEIS carried out a moment tensor solution (see section 4.1.4) which gave a seismic moment for the event of 4.7×10^{24} dyn-cm. This gives a value of the Kanamori-, or moment-, magnitude, of Mw=5.7, (Kanamori, 1978).

It is clear that the earthquake was a fairly small event in seismological terms, and the disproportionate amount of damage that it caused was the result of its proximity to a major population centre and its shallow focus.

4.1.3 **Damage Distribution**

The earthquake caused very strong shaking over a fairly small area, although it was actually felt in Guatemala and Honduras, and in the Honduran capital of Tegucigalpa, some 320km from San Salvador, the shaking caused damage to the old building of the National Museum, and felled paintings and other objects in a number of places.

The maximum intensity in San Salvador was VIII-IX on the Modified Mercalli Scale. The team did not attempt to draw up an isoseismal map since their observations were concentrated on engineering damage within a relatively small area, but an isoseismal map produced by other investigators is given in Fig. 7. This distribution of intensity is generally consistent with the teams observations within the city, but it is not possible to confirm the extent of the isoseismals outside the metropolitan area.

The damaged area was generally similar to that in 1965, although it did not extend so far to the east. Damage to engineered structures was greatest in the city centre and to the north where buildings like the Benjamin Bloom Hospital, the U.S. Embassy and the National University are situated; heavy damage to poor housing occured in southern and eastern parts of the city.

4.1.4 **Earthquake Source**

Whilst the damaged engineered structures were mainly concentrated over a relatively small area, the spread does not clearly define a causative fault; similarly, the location of damage to houses represents the distribution of quality of construction as much as the distribution of intensity. In this way, the field observations do not clearly define the earthquake source.

Ground cracks were observed in a number of places and generally with a north-west to south-east trend. Two significant ground fissures observed by the team were located to the south of the city centre, and in the football pitch in the grounds of the Externado de San Jose. This second fissure extended the entire length of the football pitch, and had an orientation north-west to south-east, very close to the location of one of the main known faults. However, it is unlikely that the fissure is a direct surface manifestation of fault, but rather a secondary effect, since it disappears at either end of the football pitch. Nonetheless, the displacements on the crack may reflect the movements on the fault below it; the maximum displacement on the crack was a right-lateral horizontal displacement of about 30mm, and a vertical movement of about 100 mm, with the west side downthrown relative to the east. Reports suggest that these, and other ground fissures with the same orientation, did not form with the main shock, but subsequently, with the aftershocks, (Rymer, 1987). Therefore, these cracks, rather than representing the causative fault, represent the redistribution of stresses in the area following the main energy release. It is not suprising that this small earthquake did not produce large surface faulting, and it is possible that the earthquake mechanism involved motion on more than one geological fault.

Teleseimic information was used by the NEIS to carry out a moment tensor solution, which is a method of determing two perpendicular fault locations, slip on either of which would theoretically have produced motion consistent with the seismograph recordings. It is thus an extension of the fault plane solution, but as with the fault plane solution the moment tensor solution does not indicate which of the two possible fault planes did produce the earthquake.

The moment tensor solution is fairly complex, so here only a brief summary of the results is given; 23 records from 10 seismogaph stations were used to define a centroid, which is the centre of energy release, which is not necessarily coincident with the hypocentre. The centroid had co-ordinates 13.91 N $\pm$ 0.05, 89.40 W $\pm$ 0.05, and was located at a depth of 15 km. This point is actually a considerable distance to the north-west of San Salvador, beyond El Boqueron. The two fault planes that the solution defined had the following properties:

	Strike	Dip	Slip
	(All in degrees)		
Plane 1	272	79	179
Plane 2	2	89	11

The strike is the orientation of the fault line measured positive clockwise from north; the dip is the angle the fault plane makes to the horizontal, dipping down to the right of the fault line. The slip is the direction of motion of the hanging wall (the side above the inclined fault plane) relative to the foot wall (below the fault plane); it is measured positive upwards relative to the strike direction in the plane of the fault. Clearly, neither of the fault planes defined coincide with the known faults in the area, and the location of the centroid is clearly not consistent with the observations. However, the dip of the faults is consistent with what is known about the faults in the area, and it is possible that the movements on the faults that the moment tensor solution suggests are not dissimilar to the actual movement on the causative fault.

The slip direction on plane 1 is almost pure strike-slip with a right-lateral motion; the slip on plane 2 is left-lateral strike-slip, with a small component of thrust.

It is possible that the seismograms recorded by the Seismology Department of CIG in El Salvador could provide more useful information in defining the causative mechanism.

The possible mechanism of the earthquake is discussed further in section 4.2.2.

4.1.5 Foreshocks and Aftershocks

Unlike for the earthquake of 3 May 1965, there were no reports of significant foreshock activity preceding the 10th October 1986 earthquake. There was however, a great deal of aftershock activity, the first appreciable aftershock coming about 14 minutes after the main shock. Another shock, three hours after the main shock, caused additional damage in the city, and in the afternoon of 13th October a magnitude Ms=4.7 event took place. A strong tremor on 15th January 1987 caused widespread panic in San Salvador but little additional damage.

The location of the larger aftershocks (Ms $>$ 2.5) during October and November 1986 are plotted in Fig. 8. These events were all of shallow focus, mostly less than 10km. These locations are all subject to some degree of inaccuracy (as with the location of the main shock). Nonetheless, the general grouping of the shocks does not seem to associate them with any one particular fault but rather they seem to represent the readjustment of tectonic stresses in the area.

4.2 Strong Motion

The San Salvador earthquake produced several recordings of strong ground motion within the source area, which provide very useful information in terms of seismology and engineering, both with relation to this particular event and to these two disciplines in general. No attempt is made here to give a full analysis of the strong motion records, but rather to present the information available and some interpretation of that information.

4.2.1 Strong Motion Network

The El Salvador Geotechnical Investigation Centre Strong Motion Network (ESCIGSMN) was set up following the 1965 earthquake with funds made available by the U.S. Aid for International Development.

The network in San Salvador consists of nine stations comprising eleven 3-component strong motion instruments (there are three instruments at different levels of the Camino Real Hotel). Two of the instruments did not trigger in the earthquake, at the Ministry of Education in the city centre, and at the Industrias Unidas factory to the east. The other seven stations, where records were obtained, are shown in Fig. 9.

Only one of the instruments, at the National Seismological Observatory (OBS), is housed in a purpose built structure, all the others being located within reinforced concrete buildings of between 1 and 10 storeys. The OBS station is also the only one that is not situated on level ground, being on the top of a steep hill. All of the stations are founded on the fluviatile pumice, except the Sheraton Hotel (HSH) which is founded on recent lavas overlying tierra blanca. The characteristics of the stations and the corrected strong motion records are given in Table 2.

With the exception of the instrument at the Institute of Urban Housing (IVU), which is an AR-240, all the others are the popular SMA-1 model.

The records were digitized and processed in the United States by the Division of Mines and Geology of the California Department of Conservation, using an automatic digitizing technique. A number of problems were encounted in digitizing the records: the vertical component at the IVU station did not function and the horizontal components, recorded on photographic paper rather than the film used in the SMA-1, were of very low contrast. At the roof of the Camino Real Hotel (HCR), the lower two traces were intertwined to such an extent that it was not possible to digitize them. The records from the OBS station, which may have recorded very strong motion, were of little use since part of the film between 2 and 5 seconds was covered by an opaque strip.

The maximum values of acceleration on the uncorrected records were 0.72g horizontally (IVU) and 0.46g vertically (IGN). The correction procedure that was applied to the records included a correction for instrument characteristics and the application of an Ormsby filter, (Shakal et al, 1986).

4.2.2 **Nature of the Strong Motion**

The uncorrected records from four stations are shown in Figs. 10-13. The motion can generally be described as beginning with a high frequency vertical acceleration with several peaks having amplitudes close to the maximum. The horizontal acceleration begins about 1 second later, having a lower frequency than the vertical motion, but larger amplitude. The horizontal shaking is very strong for about 3 seconds, then gradually decays over several seconds.

The peak values of acceleration, both horizontal and vertical, are very high, perhaps suprisingly so for an earthquake of such small magnitude, although in part this is due to the proximity of the recording stations to the source. These values serve as a confirmation of the unpredictability of peak ground accelerations in the near field. The usual attenuation relaws, relating peak acceleration to magnitude and distance, do not hold in the near field.

The nature of the strong motion records is influenced by the fault location and mechanism, the ground conditions and the structural characteristics of the building where the instrument is housed, and it is almost impossible to decouple their individual effects.

The strong vertical shaking is not necessarily indicative of vertical movement on the causative fault, but could in large part be due to the location of the stations at epicentral distances of the order of the focal depth, thus recording waves propagating upwards from the source.

It would be expected that the layer of pumitic ash would filter out some of the higher frequency motion, and this can be seen by comparison of the records from the Sheraton Hotel (HSH), founded on rock, with the other records, and similarly by comparison of the response spectra in Figs. 14-16, particularly the sharp peaks at low periods on the E-W component of the Hotel Sheraton record, (Fig. 14b). It can be seen that many of the spectra have two peaks, one between 0.2 and 0.4 seconds, the other between 0.5 and 0.7 seconds. One possible explanation of the peak response at the higher periods is the effect of trapped energy in the soil layer, although the peak is also present in one of the components at the Sheraton Hotel. This peak could be the structural response of the Sheraton, or even represent effects in the fluviatile pumice that lies below the lava at the Sheraton site.

The response of the buildings would also provide a feasible explanation for the records from the six-storey IVU and UCA stations, whose spectra show peak response at periods which are probably very close to their natural periods of vibration. However, this reasoning could not be extended to the IGN and CIG stations, whose spectra have similar peaks to the spectra of the IVU and UCA, but which are of one and two storeys respectively. The effect possibly arises from the fact that due to the proximity of the stations to the earthquake source the seismic waves recorded had not propogated through an elastic medium but through a material behaving plastically due to overstressing by tectonic forces. The nature of the records and their spectra is probably due to a combination of all of the effects mentioned above, and others, and as previously stated it would be extremely difficult to separate their individual contributions.

The spectra show a strong similarity to the spectrum from Station No. 2 of the Chalome Shandon array of the Parkfield earthquake of June 1966; studies comparing these two events may shed further light on the interpretation of the recorded strong motion.

The vertical spectra, with dominant periods between 0.1 and 0.4 seconds, are shown in Fig. 17. It can be seen that in some cases the maximum vertical spectral acceleration exceeds 1.0g, at 5 per cent of critical damping.

A study of the digitized strong motion records could shed some more light on the causative fault, by examination of energy flux and duration, (Sarma, 1971), but this is beyond the scope of this report. Some indication can be obtained, however, by looking at the peak values of velocity, which are related to energy; it would be expected therefore that peak velocities would decrease with distance from the causative fault. The stations in order of peak velocities, and the distances of each station from the faults A-A, B-B and C-C, as shown in Fig.9, are given in Table 3.

It should be well noted that the distances given here are quite approximate. This would seem to indicate that of these three faults, A-A is the least likely to have been the source of the earthquake. The fault labelled C-C would appear to be the most likely source of the earthquake by this criterion, which would not be inconsistent with the epicentral location and the observed distribution of intensity. A point that should be borne in mind is that the order in which the stations are arranged in Table 3 could very well represent the order of thickness of the tierra blanca deposits at each station.

A final point worth mentioning is that the earthquake strong motions were of high amplitude but short duration, and it is therefore possible that the large accelerations caused failure in many structures, since the resultant forces stressed the structural elements beyond the elastic limit, although collapse did not ensue because the shaking terminated so rapidly. Consequently, the earthquake may have left many structures appearing to be sound, but in fact significantly weakened them and left them vulnerable in future strong earthquakes.

4.2.3 **Relation of the strong motion to design parameters in the code**

Since the 1966 building code for earthquake resistant design in El Salvador was never enforced, its design criteria cannot be assessed by the performance of engineered structures in San Salvador. However, it is interesting to compare the recorded ground motions with the design parameters specified by the code.

The first, and perhaps most important, point to make in this respect is the shape of the response spectrum. The spectrum in the code (Fig. 6) suggests a decay of spectral response with period above 0.2 seconds, whereas the spectra generated from the corrected strong motion records (Figs. 14-16) show that the decay of response with increasing period begins at periods of around 0.7 seconds. Therefore, in light of this the plateau at the lower period end of the design spectrum, which takes account of the 'shake-down' effect (this is the effect whereby if a structure is damaged by shaking, forming plastic hinges, its stiffness decreases, and hence its period of vibration increases. Thus, if the structure initially had a natural period at the lower period end of the spectrum, it will have a higher spectral response to the shaking which occurs after the initial damage), should perhaps extend to around 0.7 seconds.

As far as the actual values of the base shear coefficients are concerned, Fig. 18 shows the design spectra from the 1966 code for Group A structures (section 3.2) and the envelope of all the horizontal spectra from the 1986 earthquake, except those from the instruments at upper levels of the Camino Real Hotel, which are records of the response of that structure. At first a comparison of these curves would suggest that the design parameters from the code are extremely inadequate, but the fact is that it would be extremely conservative to apply the peak values of this envelope to elastic design. Firstly, the values on the uppermost curve represent the maximum response, which only acts for a fraction of a second; it has been suggested that in psuedo-static design the use of 1/2 or 1/3 of the peak acceleration is equivalent to the dynamic effect of the full value, (Newmark, 1975). The values of the uppermost curve would also need to be further reduced for other effects to become design curves: these include radiation damping in the foundations, the very short duration of the shaking, the low probability of the natural period of the structure coinciding exactly with one of the sharp peaks on the response spectrum and the safety factors that are incorporated into the permissible stress levels that the code specifies. However, this would still leave values of acceleration higher than those specified in the code; for the design values to be adequate it is necessary to achieve the required ductility factor in the structure, which is the ratio of the maximum displacement that the structure can sustain without collapse to the displacement at the elastic limit of the structure. Using standard methods of calculation for design (Newmark and Hall, 1982), the elastic spectral values may be reduced by a factor of $1/u$ in the frequency range 0 to 2 Hz, and by $(2u-1)^{-\frac{1}{2}}$ in the range 8 to 33Hz, where u is the ductility factor. In the frequency range of 2 to 8HZ, the reduction factor is between these two.

The other important lesson to be learnt from the strong motion records is that the earthquake produced very strong vertical shaking, which may very well be repeated in future events, and the code should include design criteria to resist such vertical motions.

4.3 Geotechnical Aspects

The tierra blanca deposit which cover nearly all of the metropolitan area of San Salvador is a fairly competent soil, as is shown by the large number of near vertical cuts around the city's roads, and the steep banks of the arenales. This competence is enhanced by the absence of ground water near the surface, with the phreatic level being at depths of over 80m.

The earthquake triggered a large number of landslides in the steep cuttings, which are generally bare of any vegetation. In general, these landslides were fairly small, and inconvenient rather than damaging, although in a few cases they had very serious consequences (Plate 1). One particularly large slip, extending about 50m, occurred in the southern district of Santa Marta, when the bank of a very deep arenal, cut through the tierra blanca by heavy rain waters flowing down from the Cerro de San Jacinto, slipped, carrying with it into the ravine a row of houses, resulting in about 50 deaths. It is possible that this particular landslip was in part due to the ground in the vicinity being saturated as the result of a blocked or broken drain. Just beyond the end of the slip were a few houses, adjacent to the drain in question, which, although structurally relatively undamaged, had sunk into liquefied ground. This was the only observed case of liquefaction, but it was also one of the few locations where the ground was saturated, (Plate 2).

Two small soil samples were brought back from San Salvador: the team recovered one from a slope failure in the embankment on which the El Dorado plant is situated (see section 5.5.4 and Plate 34), and the other was brought back by an individual working with rescue teams in the city, the sample being recovered from a depth of about 2 feet in Los Planes de Rendero, south of the city. This second sample is tierra blanca, whereas the other is reworked tierra blanca, and has a brown colour, probably being mixed with some other material. Particle size distribution tests were carried out on both samples by V. N. Georgianou of the Department of Civil Engineering at Imperial College. The results of these tests are shown in Fig. 19.

It can be seen that the two samples are very similar, both being well-graded silty sands. Figure 19 also shows the bounds of the most liquefiable soils, as determined from laboratory tests, (Lee and Fitton, 1968). It can be seen that both samples fall within the general range of liquefiable soils, but are less well-graded than the most liquefiable materials. Whilst this lack of uniformity would tend to decrease the liquefaction potential of the soil, the lack of compaction of the tierra blanca tends to increase its susceptibility. In general, the ground water level in San Salvador is too low for liquefaction to be a problem, but the observations at Santa Marta, and the observations near Lake Ilopango in 1965 (section 2.3.2) show that when saturated the tierra blanca is a liquefiable deposit. Should the water level in the San Salvador area ever rise significantly in the future then the possibility of liquefaction could present a major problem.

Apart from the isolated case in Santa Marta, and the buildings damaged by slope instability, there was generally no evidence of foundation failures in San Salvador. However, it is known that large areas on the city's perimeter have been filled and levelled since 1955, when the city began to expand, and that these fills are generally poorly compacted, (Schmidt-Thome, 1975). At the Colegio Guadelupano (section 5.4.6) very large settlements were observed to have been induced by the earthquake in poorly compacted fills, (Plate 20).

The effects of the volcanic ash on the strong motion, resulting from trapping of seismic energy within the soil layer, is discussed in Section 4.2.2. Although it is true that damage on the west side of the city, where the tierra blanca deposits thin out, was less severe than elsewhere, the damage was really too concentrated to indicate to what extent the deposits of fluviatile pumice gave rise to higher intensities; this is certainly an area requiring further study.

5.0 ENGINEERED STRUCTURES

5.1 Construction type

The majority of engineered buildings in San Salvador have a reinforced concrete frame. These may have beams spanning in one direction or in both directions. The team saw no slab and column construction. The frames are clad and divided by masonry infill panels or are clad with glass and concrete curtain walls and divided by light weight partitions. Structural steel has to be imported into El Salvador and its use is largely restricted to the construction of industrial plant. The buildings in San Salvador are generally 10 storeys or less in height. The only exceptions are the ANTEL Tower and the Ministry of the Interior. Plate 3 shows a general view of San Salvador.

Masonry building in San Salvador uses either solid or hollow bricks or concrete blockwork with a concrete mortar in each case. Load bearing concrete blockwork is used extensively to provide one and two storey dwellings in the wealthier areas of San Salvador. In some cases reinforced blockwork has been used but its use is by no means universal. Masonry infill is used extensively in reinforced concrete frames where it is often required to carry shear loads during earthquakes.

Traditional building in El Salvador uses bahareque, (See section 9.1). Today bahereque is principally used to construct single storey housing in the poorer areas of San Salvador. There are however examples of its use in two and three storey structures. Plate 4 shows a two storey bahereque building of elaborate construction which is clearly an engineered structure.

5.2 Damage to engineered structures

The Salvadorean Construction Association (CASALCO) reported that it had registered considerable damage to seventy five buildings of three or more storeys which is consistent with the teams observations. One report states that 40 government buildings suffered major structural damage. Three of the city's major hospitals required extensive repair or reconstruction. A partial survey of the schools in San Salvador showed that 20% of the schools were beyond repair, 25% required major repairs and of the remaining 55% nearly all required repairs to either the building structure or the cladding and fittings. At the National University to the north of the city 50% of the buildings were unusable following the earthquake.

Although a high proportion of engineered structures were damaged there were insufficient number of damaged buildings for a statistical analysis of damage susceptibility to be carried out. The likelihood of failure depends on height, geometry, method of construction, quality of construction and location. Because of the complex interaction between these factors no clear patterns of damage distribution are discernible from the sample. Nor is it possible to correlate the damage sustained to the height of the building. However most damaged buildings had four or more storeys. The method of construction and quality of construction did have an effect on the damage susceptibility of buildings.

5.3 Causes of structural failure

The causes of structural failure in the San Salavador earthquake can be listed under the three headings; inadequate materials, poor geometric forms and buildings that have been inadequately maintained, repaired or modified. In every case the damage was made more severe by the presence of a strong vertical ground motion in addition to the horizontal motion. In some cases buildings were deficient in more than one respect. It is certainly the case that buildings of a poor shape had no reserve of strength in their members to carry any unanticipated loads.

5.3.1 Effect of vertical shaking

The ground motion of the earthquake contained a strong vertical component (the ground motion is described fully in section 4.2 of this report). The vertical component has a high predominant frequency of nearly 10 Hz and a measured peak acceleration of 0.46g. This vertical shaking was seen to be highly damaging to concrete structures. The team observed column failures due to compressive overloading that resembled the effects of a standard cube test on concrete. This was due to the high vertical acceleration and also due to the high frequency of the ground motion which it seems led to resonance of floor slabs and beams. As a result of the high frequency of the vertical acceleration the structures underwent many cycles of reversed loading during the earthquake. It appears that some columns which disintegrated completely were damaged by the high number of load reversals in a failure process which could be called 'low cycle fatigue'.

A further effect of the strong vertical ground motion was its interaction with the horizontal ground motion. The team have not made a theoretical study of the interaction between the three orthogonal components of the ground motion and its effects on structures. However, it must be borne in mind that some of the shear failures of buildings have arisen because of the interaction between simultaneous horizontal and vertical shaking. In some cases it appeared that columns had been weakened by vertical shaking and formed a soft storey that subsequently failed.

5.3.2 **Building material defects**

A 1965 report suggested that the cement available in San Salvador was defective and that it failed to meet the ASTM test for cement paste. This would confirm the team's observation that the more recent concrete was of far higher quality than that used in buildings constructed 30 years ago. Particularly bad concrete was observed at the Externado de San Jose where concrete columns had little more strength than the adjacent brick infill panels (Plate 5).

Aggregates are variable in their quality. The engineers with whom the team spoke were aware of this problem. More recent building and high quality older buildings use an aggregate quarried some distance from San Salvador. This produces a far better concrete than is obtained by using more local aggregates of volcanic origin. Volcanic aggregates are coarse and rounded and they produced a very porous concrete.

Reinforcing steel is imported or milled locally. That which is milled locally is brittle and is generally of smaller diameter than its nominal size. There are a number of examples of brittle failure of both main reinforcement and secondary reinforcement. This has occurred principally in older buildings.

The standard of workmanship in the buildings is good. Where concrete columns had failed exposing the reinforcement, it was clear from the cover to the reinforcement, uniform spacing of the links and consistent lap lengths of the bars that the buildings were put together with reasonable care. Poor quality of buildings is due more to poor design. There was a rule of thumb in San Salvador that shear links should be placed at 150mm centres, which is clearly inadequate. The team found that links were generally at either 150mm or 300mm spacing, frequently with inadequate tying in of the ends. This has provided inadequate confinement in many columns.

The infill panels of reinforced concrete frames are constructed of clay bricks or concrete blocks. These confined panels are stiffer in shear than the surrounding frame and have been called on to carry the shear loads within the building. The hollow clay bricks fail in a very brittle manner in compression and the stronger solid bricks and concrete blocks fail by buckling of the panel which again is a sudden form of collapse. This is dangerous as it causes masonry to fall from the buildings. It also leads to the formation of soft storeys and the subsequent failure of the frame. Infill panels were generally tied to the reinforced concrete frame with dowel bars but there was no reinforcement within the many failed panels that the team observed.

5.3.3 Structural defects

Soft storeys: The most common form of failure was the collapse of the ground floor. In most cases this resulted not only because the shear forces are greater at this level but also because the ground floor was weaker in shear than those above. Often the ground floor was divided into larger rooms with fewer partition walls and shop windows or other openings in the outer walls. This was certainly the case with the Hotel San Salvador (Plate 6) . The Edificio Iztalco (Plate 7) failed at the third floor. This building is a 9 storey tower the lower floors of which have a greater floor area and stiffness.

Shear walls: Reinforced concrete shear walls are not often used in San Salvador. The ten storey tower block at the Hospital Benjamin Bloom is constructed with shear walls at either end and a central core to carry shear. This had performed well in the earthquake. In general buildings rely on unreinforced masonry infill panels to carry shear loads. These were found to be inadequate in many buildings and it appeared that the buildings were designed as flexible moment resisting frames which had then been inadvertently restrained by stiff infill panels.

In many cases masonry panels that may have acted as shear walls were pierced by window and door openings which reduced their effectiveness. In particular there is a practice of building masonry panels to within 300-600mm of a ceiling and glazing the upper part of the wall. This produces very narrow horizontal bands of weakness in the building and failure of the columns in shear at the bands of weakness (Plate 8).

Poor geometry: There were many cases where failure of the building was in part due to the poor geometry of the building. There were two notable examples of buildings containing large open spaces in their structural layout which led to failure. The Freemason's Lodge was a large meeting hall with inadequate structural stability. The roof of the building was supported on a relatively slender structure around its perimeter and the whole building has fallen apart as if torn by an internal explosion (Plate 9). The Almacenes Siman is a large department store of four storeys with a central void piercing all four floors to provide a stair well. Much of the damage to this structure was around the edge of the void where unsymmetric dynamic loads occurred in the columns.

5.3.4 Repairs and modifications

Following the 1965 earthquake some buildings were repaired and a number of those buildings then failed again in the 1986 earthquake. The team were unable to study the repairs to buildings and at the Ruben Dario building were unable to ascertain the reasons for failure. This building had collapsed completely and was reduced to a pile of close stacked floors. Talks with local engineers suggest that the decision to repair rather than demolish the building in 1965 had been a controversial one. Failures at the National University and the Colegio Guadelupano show that repairing the previous failure and removing the original weakness in the structure only exposed a new weakness.

One industrial structure had been damaged by overloading. Large masses of material were stored on the upper floors and the resulting shear loads caused damage to the structure. It appeared that the structure, which was part of an industrial process, was not originally designed as a storage space. The team were told by local engineers that the upper floors of the US Embassy were heavily overloaded with communication equipment. This could explain the large amount of structural damage that occurred to the building.

5.3.5 Foundations

Only one engineered building was seriously affected by a foundation failure during or after the earthquake. The foundations of the Colegio Guadelupano are on very loose, uncompacted fill, which is banked up and this settled during the earthquake. Identical settlement occurred during the 1965 earthquake.

5.4 Case Studies: Building Structures

The team observed some 70 damaged buildings. Case studies of some of these are given below. These were chosen as a typical sample and are generally those to which the team had access. The positions of these buildings are shown in Fig. 20.

5.4.1 National University

The National University is on a campus on the northern fringe of San Salvador. There are some forty buildings on the campus, of which 15 were severely damaged and 5 were moderately damaged. A further 14 buildings had suffered damage but were still in use.

A number of buildings had failed as a result of having a soft storey. The Economics Building and the Engineering Building were heavily damaged. The Economics Building in particular had a very stiff structure above the ground floor. The four storey building which has large lecture theatres with glazed walls on the ground floor has smaller rooms on the floors above and very stiff concrete panels attached to its facade at these levels (Plate 10).

The Architecture & Engineering Building (Plate 11) was damaged in 1965. Rosenbleuth, in his report to UNESCO, comments that it is necessary to stiffen the columns of the building at all four levels. However only the lower columns have been enlarged and these stiff storeys transferred the seismic forces up to where they caused failure to the relatively weak third and fourth floors, in the 1986 earthquake.

The Dental Hospital is formed by two blocks three storeys high joined by a connecting structure containing stairs. The building is a reinforced concrete frame with a lightweight roof of steel lattice girders and asbestos sheets. On the upper floor, masonry partition walls which were curtailed at the level of the false ceilings and not properly tied to the structure had simply fallen over. Many of the false ceilings, air conditioning ducts and light fittings had fallen down and on the upper floor most of the asbestos roof had also fallen (Plate 12). Heavy equipment including dentist's chairs had been thrown over and further damage was caused by the ingress of rainwater.

5.4.2 **Ministry of Agriculture**

This four storey concrete framed building stands astride a ground dislocation. This had damaged adjacent two storey masonry structures, splitting them on the line of dislocation, and had damaged water pipes along its line. The Ministry consists of 3 separate structural frames; a central structure contains the stairs and circulation areas, two orthogonal wings contain office space. The concrete frames each performed well but there was some differential movement between the frames. The major damage occurred on the fourth floor. This is of different construction to the rest of the building and may be a later addition. It is a steel frame with a concrete block cladding and a roof cover of asbestos sheets. The blockwork was not tied to the steel frame and now leans heavily outwards from the building (Plates 13 and 14). Also in this upper floor there was much damage to the false ceiling and roof sheeting. The consequent ingress of water had also caused considerable damage to the fittings of the building. The team was told that the building had been damaged in 1965 but no details of the damage were available.

5.4.3 **Hospital Benjamin Bloom**

The hospital consists of a ten storey tower and a three storey wing, both constructed in 1962. The tower is a reinforced concrete frame with substantial reinforced concrete shear walls forming two opposite faces. The other two faces contain a large amount of glazing but there is a central lift shaft and stairwell capable of carrying shear loads orthogonal to the shear walls. The tower suffered structural damage but appeared to be repairable. The main cause of damage was shear failure of masonry panels which bridge between the shear walls and infill around the lift shaft. The greatest damage occurred in the end walls of the tower block which each consist of two shear walls either side of a masonry and glass infill extending the full height of the building. The shear walls were undamaged but the masonry panels, which were unreinforced, failed at every storey (Plates 15 and 16). Within the tower there was major non-structural damage to water and gas supplies and to the windows. The electricity substation and emergency power supply, both located in the basement, failed at the time of the earthquake.

The wing of the hospital is the Children's Hospital. It consists of three structurally separate units built into sloping ground. One block of the structure was undamaged, one suffered partial collapse and the third collapsed completely. It appears that this has occurred because of the sloping ground as the blocks each had ground floor columns of different height along one facade. The block with the longest columns failed completely (Plates 17 and 18). In this section concrete had spalled from the ground floor columns over as much as 80% of their height. The columns probably contain insufficient links to provide confinement but the extent of the damage to the columns suggests that some other factor has contributed to their failure. The concrete was of reasonable quality and it appears that it has been broken up by the application of many pulses of vertical loading.

5.4.4 **US Embassy**

The Chancery Building of the US Embassy is only one block away from the Hospital Benjamin Bloom. It was erected in 1967 and was extensively modified in 1982. The building was originally a four storey building but in 1982 a mezzanine was added at first floor level to give the building 5 storeys of roughly equal height. The well constructed reinforced concrete frame was severely affected at the first, second and third floor levels where there was damage to the internal shear walls, and by damage to the perimeter columns at first floor level. There was considerable spalling of concrete from all faces of these columns consistent with a vertical overloading. The columns were being repaired by casting larger circular columns around them, but this was only a temporary measure. There was also damage to the services within the building and the building envelope was no longer waterproof. It is understood that the building will be replaced at a cost of U.S.$70M.

5.4.5 **Pete's Bar**

This is typical of an older style of building in San Salvador. The construction is comparatively heavy with solid brick walls in a reinforced concrete frame. The four storey building adjacent to the US Embassy failed at its ground floor. It appears that the masonry of the upper floors had resisted shear producing a very rigid structure supported by a relatively weak ground floor (Plate 19). The diagonal cracking on the face of the building was caused by unidirectional shear when the building fell by some 4m. The ground floor collapsed gradually enabling people to escape from a back entrance as the front settled. This probably occurred because of the heavy construction and the use of substantial masonry walls combined with an asymmetry in the ground floor. The team observed similar failures in four other buildings of this style and size.

5.4.6 **Colegio Guadelupano**

The college is a group of buildings all of which were badly damaged by the earthquake. The largest and most recent building, the Bachillerato, was under construction at the time of the 1965 earthquake and the reinforced concrete frame was damaged at that time. The four storey building originally had ground floor columns that tapered from ceiling to floor and following the damage of 1965 these were reconstructed as prismatic columns 900mm x 600mm containing 25mm high yield bars. The ground floor columns at the east end of the building suffered severe damage during the 1986 earthquake. The damage was clearly made worse by the absence of adequate links which were 8mm bars at 300mm centres. However the columns are on a grid of 6.6m x 5.4m and there was less damage at the other end of the building. It appears that the damage was initiated by settlement of the very loose fill on which the east end of the building is founded. Rosenbleuth reported the same settlement problem in 1965 (Plates 20 and 21).

The Kinder y Clausura wing was constructed in the 1950's. The three storey structure of a reinforced concrete frame with masonry infill panels suffered severe damage and was beyond repair. Many of the infill panels had buckled and most of the concrete columns on the ground floor had formed hinges at their tops and bases. The formation of these hinges led to spalling of concrete and a shortening of the columns by as much as 600mm. Damage in the wing gets progressively worst further from the main building so that the upper floors have settled 600mm at the outer end and there is no settlement at the inner end. The drift at first floor level was 120mm and at second floor level a further 40mm. The building was empty of people at the time of the earthquake but the failure of the heavy internal masonry walls could have caused many injuries (Plate 22).

5.4.7 Colegio Externado de San Jose

This three storey school is square in plan and constructed around an open quadrangle. It was built in 1952. The geometry of the building was ideally suited to resist seismic loading. It was symmetrical in plan, was subdivided into small rooms by masonry walls and had columns regularly spaced throughout. All three storeys were similar and their was no likelihood of a conventional soft storey collapse. The masonry used was solid brick and this provides a good resistance to shear when it is restrained in panels. The school was not damaged by the 1965 earthquake. Plate 23 shows the mode of damage. The masonry infill has prevented the columns from bending and forming hinges at their tops and bases and shear failure has occurred on a plane through the ground floor windows. The concrete is made from a very coarse volcanic aggregate which produces a very weak and porous material. The columns are not markedly stronger than the masonry and all the panels of unreinforced masonry and concrete columns between the windows on the ground floor have failed. All of the walls were damaged to a similar extent indicating that the building was shaken equally in the E-W and N-S directions. There was no damage to the upper storeys of the building.

5.4.8 Almacenes Siman

The Almacenes Siman is a four storey department store and adjacent seven storey car park built in the 1970's. The team were told that construction was in accordance with the ACI codes. A base shear of 10% of the building weight had been taken for the seismic loading. The standard of construction appeared to be good, the steel was imported and the aggregate used in the concrete was a good quality crushed rock.

The building consists of a reinforced concrete frame with brick infill panels. The columns are 700mm x 700mm with 12 No.32mm high yield bars in each and they form an orthogonal grid spanning 8m in each direction. There is an opening of 8m x 16m piercing every floor to provide a central well. The ground floor columns adjacent to this well had failed close to their tops while the columns on the floor above were also cracked at their tops (Plate 24). The lower columns had failed in shear on a plane inclined at 45° and there was considerable spalling of the concrete on the faces indicating an overloading of the columns. The floor had been propped with temporary supports and the engineer planned to cut out and replace the damaged concrete columns. There was also considerable damage to the cladding and internal walls of the building, in particular where an adjacent building had collided with the store.

Damage to the car park was less severe. The columns of the car park are stiffened by infill walls rising to half the height of the columns. There is much spalling of concrete from the faces of the columns above the walls indicating the presence of both horizontal and vertical shaking (Plate 25).

5.4.9 **Edificio Tuzamal**

This modern five storey building is a reinforced concrete frame with a cladding of precast concrete units and glazing. The frame appears to have survived the earthquake with no damage. However large precast elements have fallen from the upper floors into the street and many of the large panes of glass have been shattered. There was considerable internal damage to the buildings services and to the suspended ceilings (Plate 26).

5.4.10 **Edificio Ruben Dario**

The Ruben Dario Building collapsed completely during the earthquake killing an estimated 200 people. The building was a six storey reinforced concrete frame forming a U shape, on plan, around the Almacenes Pacifico. The building was badly damaged by the 1965 earthquake and repaired. The building has now been reduced to a close pack of floor slabs and the extent of damage was such that the team were unable to ascertain the nature of the previous repairs or the mode of failure. However it was clear from talking with engineers in the city that the decision to repair the building in 1965 had been a controversial one. The remains of the building caught fire following the collapse as gas bottles used for heating were split open (Plate 27).

When the Ruben Dario building collapsed it collided with the six storey Almacenes Pacifico causing it to drift up to 600mm at its top (Plate 28). This movement was continuing after 3 weeks and surveyors were monitoring the movement in the hope that they would be able to clear rescue workers from the Ruben Dario site before collapse occurred.

5.4.11 Hotel San Salvador

This eight storey reinforced concrete framed structure had been built as an hotel but was being used as offices at the time of the earthquake. The structure suffered remarkably little visible damage above the third floor when the lower three floors failed causing the building to settle by several metres and lean back at an angle of 10-15^{o} (Plate 6). The building has a basement and failure of the ground floor has caused the building to collapse into its own basement at the rear. The team were unable to gain detailed information about the building but were told that it was damaged by the 1965 earthquake and repaired.

5.4.12 Ministry of Education and National Library

This complex consists of two eight storey towers on adjacent sides of the two storey library building (Plate 29). All three structures were badly damaged by the earthquake. The library building is a very open structure with circular concrete columns, 500mm diameter on a 6m x 7m grid, supporting a concrete slab roof. There are large voids in the floor slab and there are walkways suspended from the concrete roof. The heavy roof has drifted to the east causing distortion of the curtain walling and severe damage to the concrete columns. These columns are braced to the tower blocks at approximately 1m below the roof level; huge shear forces are generated by this restraint and the roof failed completely (Plate 30). The extent of the damage to the columns suggests that they were subjected to large shear loads in two directions and probably to large vertical loads, the combination of which has completely shattered the concrete. The walkways are suspended on 20mm diameter hangers. These have buckled under a temporary compressive load and are curved out of line by 75mm at the midpoint of a 4m long hanger.

The two towers of the Ministry of Education are reinforced concrete frames with hollow brick exterior panels and a rendered finish. These panels and frames which collect load as shear walls are very weak and brittle and have failed in both towers (Plate 31).

5.4.13 Edificio Iztalco

This nine storey office block is a reinforced concrete frame. It is clad with a curtain walling system of glass and corrugated metal. The building has failed at the third floor level where an entire storey has collapsed. The team were unable to gain access to the building or inspect it closely but it appears that this total collapse of an entire storey was possible because of the lack of any substantial walls or partitions (Plate 7).

5.5 Case Studies: industrial complexes

5.5.1 Location of industry in El Salvador

Much of the industry of El Salvador is sited in San Salvador to the south east and east of the city. This area was badly affected by the earthquake and substantial damage was caused to the brewery, flour mill and Unisola plant. This has serious consequences for the economy of El Salvador. The damage was contained within the site in each case but leaks from chemical storage tanks, which would have affected a wider area, were narrowly avoided.

5.5.2 Flour mill

This complex consist of ten reinforced concrete silos in groups of four and six and a reinforced concrete framed building containing the milling process. These three structures are connected by high level footbridges. The team did not gain access to the site but were able to talk with people who had been inside. One of the high level footbridges fell to the ground while the other survived. Apparently, the bridge was 700mm longer than the opening which it spanned and it seems likely that the supports gave a ratcheting action causing the bridge to 'walk' in one direction until it fell from one end (Plate 32). The team were told of considerable damage to machinery in the mill building.

5.5.3 **Unisola Plant**

The Unisola plant produces soap and washing power. It consist of one and two storey offices, warehouses, etc., and a six storey drying tower. A two storey steel frame shed used for storage had recently been completed. There was no visible damage to the cladding or the portals of the shed but these were stayed by 10mm diameter bars tensioned diagonally in the plane of the roof. Nearly all of these bars had failed and had been welded together immediately after the earthquake. A six storey reinforced concrete tower at the plant holds a drying cylinder six storeys high (Plate 33). The tower was not designed to resist seismic loads but the cylinder is supported at each floor by large roller bearings which allow for differential movement. Chemicals were stored at the top before passing down the drying cylinder. The tower was heavily loaded at this level during the earthquake. There is damage to the concrete at every level of the tower but particularly at the level where the floor area reduces. An engineer watching the tower from the ground was able to observe 3 cycles of movement of the tower in an east to west direction with the final movement being eastward. Plans for remedial work in the tower included the cessation of all high level storage, the future resiting of all ancillary plant to the lowest possible level in the tower and the removal of the damaged outer columns to leave a slimmer structure supporting only the drying cylinder.

Also, at the Unisola plant there was a tank containing 150 tonnes of oleum. This tank was supported on made ground behind a 10m high retaining wall. The tank settled slightly at the time of the earthquake and fortunately it was emptied before its connecting pipes sheared off on the following day. At the time the team visited the tank, it had settled a total of 150mm. A leakage of oleum, which is sulphur dioxide dissolved in sulphuric acid, would have seriously affected surrounding sites.

5.5.4 **El Dorado Plant**

This plant processed cotton and soya to produce margarine and edible vegetable oil. The plant is extensive but at one edge of the site industrial plant has been constructed on a 15m bank with a slope of 60 degrees. The team were told that the slope had a factor of safety of 1.0 against sliding, under normal gravity loads. However, it failed during the earthquake and a boiler house directly above the slope had been demolished (Plate 34). A methane plant has been built in a similarly precarious position but it is used only for part of the year and it was not in use at the time of the earthquake. Most of the damage at the El Dorado plant is the failure of the pipework and large storage tanks. The plant was in production at the time of the team's visit but several storage tanks had buckled at their base giving an 'elephant's foot' failure (Plate 35). Each of these tanks held 400-600 tonnes of vegetable oil but there was no evidence of major leaks.

6.0 DAMAGE TO BUILDING SERVICES AND NON-STRUCTURAL ELEMENTS

6.1 Pipework

There were many cases of damage to pipework within buildings. The Hospital Benjamin Bloom was disabled by the failure of water and piped medical gases. The Banco Hipotechnica had suffered no visible structural damage yet it was reported that the whole of its basement was flooded. There was damage to the U.S Embassy caused by water escaping from damaged pipes.

6.2 Light fittings

In many buildings the light fittings were installed as part of a false ceiling. These fared very badly during the earthquake and the team found few instances of suspended ceilings surviving the earthquake. Some light fittings were large yet were suspended by only two or three thin wires (Plate 36).

6.3 Air Conditioning

This also was installed as part of a suspended ceiling with large galvanised steel ducts in the ceiling void. These are again suspended by very few wires that appear to be inadequate for the job. The size of air conditioning ducts is such that they can cause injury when they fall. In buildings such as the Dental Hospital, many of the ducts broke loose.

Older buildings are air conditioned by units fitted into window openings. These heavy units were often only supported by flimsy brackets and many had partially broken loose and were left poorly supported at second and third floor levels. The team had no details of air conditioning units crashing to the ground, but doubtless some fell several storeys to the pavement below. The system of mounting these units offers no resistance to seismic loading.

6.4 Switchgear

The telephone network in San Salvador, ANTEL, was badly affected by the earthquake. The telephone exchange buildings suffered very little structural damage but the switchgear within the exchanges was thrown into chaos when the earthquake accelerations tripped switches and when the racks supporting the switches were toppled over. The ANTEL telephone system was still badly affected four weeks after the earthquake. Local calls were difficult to make and international calls were made from temporary exchanges using the radio dishes available at hotels and other large buildings.

6.5 Suspended ceilings

Many of the buildings damaged by the earthquake were fitted with suspended ceilings. In nearly every case these had partially or totally collapsed. The ceilings consist of very light rails suspended by thin wires, these form a grid that supports the ceiling tiles. At the Colegio Guadelupano the tiles used in the assembly hall were of relatively heavy material, resembling asbestos sheet and fell 7 or 8m to the floor. Fortunately the room was not occupied at the time. Even where the tiles are made of a light fibre board, they must have caused increased panic to the occupants as they fell from the ceiling.

6.6 Glazing

There was surprisingly little damage to glazing during the earthquake. This was due largely to the use of louvred type windows that contain small panes of glass each of which can rotate in its frame (Plate 37). Even buildings that had suffered partial collapse contained unbroken panes of glass. The frames of the windows can undergo large shear displacements and even buckle without the small panes breaking as they move in relation to one another.

Where large panes were used windows still performed better than expected and it appears that a large amount of play is built into the glazing systems, as required by the 1966 earthquake code.

7.0 INFRASTRUCTURE

The damage and disruption caused to San Salvador's infrastructure was fairly extensive, particularly for such a small earthquake, although the city certainly had not been brought to a standstill by the disaster.

7.1 Roads and Bridges

There are no long span bridges in and around San Salvador, the primary function of the bridges being to traverse the steep and narrow 'arenales'. There were no cases of actual collapse of bridge structures, although there was minor damage to many. The bridge on the road between the city and the airport, of about 20m span, suffered damage due to longitudional compression, shown by the buckling in its surface; the bridge was still passable.

One bridge which was actually closed off to traffic by the earthquake is probably the largest in the city with a span of about 25-35m. This bridge, situated in the northern district of Mejicanos, is a solid structure, with masonry walls infilled with soil and rubble, over which the road was constructed; a pipe embedded in the fill served to carry the stream water through. It appeared that the pipe had broken, causing the soil to be washed out along with a part of the masonry wall on the downstream side. The soil above the pipe had then slumped forming a large hole in the road surface (Plate 38).

Damage to roads did cause disruption to traffic but most parts of the city were accessible. (It should be noted that prior to the earthquake the city's roads were already in a very poor state of repair - a popular car bumper sticker reads "Mr Mayor, I'm not drunk, I'm just trying to avoid the potholes."). Damage to roads and disruption of traffic flow resulted from small localised slope failures in the steep cuttings (Plate 39) and from the large number of burst water mains, which left many roads flooded, and the repair work caused further disruption.

7.2 Water Supply

The production of potable water for San Salvador was not affected by the earthquake, but nonetheless many people were left without drinking water as a result of damage to the distribution network. More than 500 water pipes were broken by the effects of the earthquake, 287 of which were primary distribution lines. To remedy the resulting shortage, water was distributed in tankers.

The drainage and sewage systems also both suffered grave damages, which posed a potential health problem.

7.3 Electricity

The situation with the city's electricity was similar to that of the water supply, with the actual production centres unaffected by the earthquake, but severe damage resulting to the distribution system. Two of the four substations that serve the city at Soyapango and San Antonio Abad (see Fig. 4) were damaged - the damage to one of them was the result of a landslide attributed to a plugged drain (Morgan, 1987). There was also extensive damage to poles, cables and transformers. However, rapid provisional repairs restored 80% of the city's electricity within 26 hours of the disaster, with only the areas most heavily affected by the earthquake remaining without electricity.

There is no system of piped gas distribution in San Salvador, but many buildings use butane gas; fires which followed the collapse of the Ruben Dario Building were thought to have been caused by butane cannisters.

7.4 Health

The city's health care infrastructure suffered a great deal of damage in the earthquake. The following centres were the worst affected: the Benjamin Bloom Children's Hospital, the Health Units of the North, San Jacinto and Concepcion and the Military Hospital. As a result, most of the health services were being provided from tents or from buildings temporarily occupied by medical staff (Plate 40). This created numerous difficulties for the health service at a time when it was most greatly needed; as a result of the earthquake the total number of people requiring medical attention had risen to over 10,000.

7.5 Education

Education in San Salvador was severely disrupted by the earthquake, with the loss of some 1,400 classrooms. In one school, the Don Juan Bosco, 43 pupils lost their lives when their classrooms collapsed in the earthquake. As described earlier in the report, the buildings of the National University, and much of the equipment housed therein, suffered a great deal of damage, and classes were suspended, as was the case in most of the city's primary and secondary schools. In some other education centres, such as the Catholic University (which suffered almost no damage in the earthquake) most classes were suspended while the students participated in rescue and relief work.

8.0 HOUSING

As with most earthquakes in developing countries, the majority of deaths and injuries resulting from the San Salvador earthquake were caused by the collapse of houses. The extensive damage to housing was also, quite obviously, the reason for the very large number of families left homeless by the disaster.

Housing in the wealthier parts of the city did not generally suffer great damage, being of one or two storeys and of sound construction. The Ministry of Planning (MINPLAN) reported that 23,000 houses were destroyed by the earthquake, and 30,000 more were badly damaged. The majority of these houses were situated in the poor areas on the city's periphery, in the north, east and south, including districts such as Mejicanos, San Jacinto and Santa Marta amongst many others (Fig 4). These shanty towns have grown rapidly in recent years with the tide of poeple migrating to the capital from the countryside, driven by war, drought and poverty. The population of San Salvador, like many other Latin American capitals, has risen sharply over the last two decades; in 1960 the population stood at 200,000 and in 1969, at 400,000. At the time of the earthquake the population had risen as high as 1,500,000. Arriving in a densely populated city, where land prices are very high, these people have been forced to purchase tiny plots of land on terraces cut into steep hillsides (Plate 41). The houses are often constructed so that the cut forms the back wall and the facade is often flush with the front of the terrace step; it is this type of terrain on which many of San Salvador's poor are obliged to live, as much as the type and quality of construction, that gave rise to the large loss of housing in the earthquake. It is known that such geological ridges as those whose slopes the shanty towns occupy, can amplify earthquake induced ground motions, and the vertical cuts are inherently unstable, particularly under earthquake conditions.

The following sections briefly describe the primary forms of low-cost construction in San Salvador, and their performance in the earthquake.

8.1 Bahareque

Bahareque is the traditional form of construction in El Salvador. It is formed from timber verticals and bamboo horizontals, infilled with mud and plastered with a lime mortar. The roofs are usually made from tiles or corrugated iron on nailed wooden trusses or purlins (Plate 42). Bahareque is very well suited to El Salvador's geography, employing materials that are widely available and at low cost, being easy to construct (some houses had been completely rebuilt within three weeks of the earthquake (Plate 43) and it provides good insulation against the intense tropical heat. Furthermore, when well constructed from good quality materials, bahareque also behaves very well under seismic conditions (Plate 44) much more so than heavier and weaker forms of construction in other parts of Latin America, such as adobe, which is formed from sun-dried clay bricks. The aseismic qualities of bahareque were demonstrated by the large number of houses where the dried mud had simply been shaken out, leaving the flexible frame intact. However, the timber and bamboo are usually used without any sort of preservative treatment being applied, and the action of insects and micro-organisms leads to a complete deterioration within ten to fifteen years, when the houses become very weak.

8.2 Timber

There are few timber houses in San Salvador, probably due its relatively high cost, although timber is often used for the construction of the frames, after which bahareque is used, or corrugated iron or plastic sheeting (called 'lamina') to form the walls of the house (Plate 45). The few houses constructed entirely of timber that were seen had generally performed very well, but again there was much evidence of deterioration of the untreated timber. An obvious hazard with timber construction is the spread of fire, but no large fires followed the earthquake.

8.3 Masonry

Masonry is not very widely used in the poorer districts, but in the few cases where it had been used the results were usually disastrous. The masonry was generally completely unreinforced, and poor quality mortars were used. The vulnerability of the masonry houses was further aggravated by high walls that are built to provide a cooler environment, and the fact that in many cases the walls were not joined at the corners, each one acting independently, with a negligible resistance to horizontal forces perpendicular to its own plane.

9.0 RESPONSE TO THE DISASTER

It is not possible in this report to give a full description and analysis of the social and economic effects of the disaster and the response to them, since the investigation was carried out by a two man team over a period of just two weeks, where the primary concerns were the engineering and seismological aspects of the earthquake. However, a brief description of the team's observations is given to provide a more complete illustration of the disaster.

9.1 Social and Economic Effects of the Earthquake

The death toll from the earthquake, which will probably never be known exactly, was about 1,500, although there can be little doubt that had the earthquake occurred during the night, rather than at midday when most people were outside, this figure would have been several times higher. As stated earlier in this report, the majority of the casualities resulted from the collapse of houses, but there were a few other important causes of fatalities: about 50 people died as a result of the landslide in Santa Marta (section 4.3), 43 children died in the collapse of the Don Juan Bosco School and all of the occupants of the offices housed in the six-storey Ruben Dario lost their lives. The number of injured has been put at 10,000.

The damage to the city's housing left as many as 300,000 people homeless. Some immediately set about repairing or rebuilding their homes, but many were reluctant to rebuild their homes on the same unsuitable terrain. Large numbers of people returned to other parts of the country from whence they had come to San Salvador in recent years. The majority of the homeless simply erected temporary shelters in the streets, on roundabouts, in parks, almost anywhere that they could find a space to occupy (Plate 46). These shelters were constructed from wood, plastic sheeting, canvas, corrugated iron and any other materials that were available to them; very few of the homeless were sheltered in tents. Although the rainy season was coming to an end at the time of the earthquake, there were some very heavy storms in the weeks after the earthquake, causing havoc to these inadequate shelters.

It is reported that many of the homeless were stilling living in these shelters almost a year after the disaster, and that others had begun to occupy private and government land.

The total economic cost of the earthquake, including lost production, has been estimated at US$ 1.5-2.0 billion, about 10% of which was insured. For a poor country like El Salvador, this represents an enormous loss, and it comes on top of crop failures in recent years due to drought, and six years of civil war which has claimed 60,000 lives. The country's economy is in very bad shape: at the beginning of 1986, inflation stood at 22%, which rose to 34% in the first six months of the year, and by the beginning of 1987 it had risen above 40%.

Both the public and private sectors suffered very badly from the earthquake, particularly small businesses and workshops, resulting in a significant increase in the number of unemployed in the city; before the earthquake urban unemployment stood at 19%, with a further 58% chronically underemployed.

9.2 Aid Distribution

To handle the disaster the Salvadorean government established the National Emergency Committee (COEN), headed by the country's President, Jose Napoleon Duarte. COEN delegated the task of handling the aid donated to El Savador to a committee formed by the private enterprise association; after complaints that its powers were limited to just receiving the aid, the government granted this committee the power to actually distribute the aid. There were accusations later on that in the distribution of aid preference was given to employees of those companies that were represented in the committee.

A number of non-governmental organisations were involved in distributing aid to the earthquake victims, most visibly the Church and the trade union confederation, UNTS. A large amount of the aid that was sent to El Salvador after the earthquake was actually addressed to these two bodies. Not all of the aid sent to El Salvador was accepted, for apparently political rather than technical reasons: fifteen plane loads of emergency aid from groups in the US, directed to the Church Emergency Committee (CIE), were refused permission to land by the government; and whilst a large consignment of medical supplies from Cuba was accepted, a team of more than forty specialists offered with the equipment were denied entry to the country. There were reports in the

Salvadorean press of one shipment of aid being held up because Russian-made rucksacks had been found amongst the materials donated.

The actual distribution of aid in the field was generally fairly poorly organized as far as the EEFIT team saw. Trucks would often arrive in the poor areas unannounced, giving out the aid on what appeared to be a 'first come-first served' basis; people living higher up on the slopes rarely managed to get down to the roads in time to receive the aid distributed, which was primarily food. To remedy this, many affected communities, often with the help of the UNTS, had formed their own committees to check the aid distribution. For example, a committee visited in Las Brisas had drawn up several copies of a list of all the affected people in their community, in order of priority, and each person had to sign against their name to acknowledge receipt of their ration from each consignment of aid. This particular committee was working with the church, and reported that much of the food they had received had been donated by friends and relatives in the countryside who had carried out their harvests early for the benefit of the earthquake victims.

9.3 Repair and Demolition

There was no apparent control over repair work and demolition of buildings damaged in the 1986 earthquake. A few days after the earthquake the government announced that it would pass a demolition law allowing an independent body to enforce the demolition of any buildings deemed to be damaged beyond repair; there was strong opposition to the proposal within the National Assembly. The newspapers reported that a list of condemned buildings had been prepared by the government, but there was no evidence that this demolition was being carried out. Four weeks after the earthquake a list of condemned buildings had not been published, and none of the engineers or loss adjusters that the team met had been able to obtain such a list. 10 months after the earthquake, the Edificio Iztalco was still standing in its precarious state. The team has been unable to ascertain whether any of the severely damaged buildings have been demolished.

During the three weeks the team were in San Salvador they observed very few engineered structures being repaired. Repairs were being carried out at the Almacenes Siman and the Unisola Plant, and in both cases there was no independent supervision of the repair work. It seems likely that a similar situation existed after the 1965 earthquake considering the number of repaired buildings that failed in the most recent earthquake.

The team was told by rescue workers at the Ruben Dario that they had requested the demolition of the Edifico Pacifico which was standing precariously over the rubble of the Dario (Plate 28), posing an obvious threat to the rescue workers. The owner of the building had refused to allow demolition of the Pacifico.

10.0 CONCLUSIONS

San Salvador is situated in an area of high seismic hazard. The earthquakes which pose this hazard are associated with the Central American volcanic chain. Due to the fact that most of the geological faults are not much more than 10km in length, although the earthquakes are relatively frequent, they are of moderate magnitude; the earthquakes are also of shallow focal depth, which results in strong shaking over quite a small area, and serious damage is thus confined to the occasions when such an earthquake has its origin close to the works of man.

The task of fully evaluating seismic risk in El Salvador, including a study of the historical seismicity, geology, tectonics and local soil effects, has yet to be carried out, but it is an important and necessary objective.

The most recent earthquake demonstrates that within the near field of a small earthquake in the volcanic chain, large ground accelerations (with a significant vertical component) can be expected, although the strong shaking will be of short duration. The observation made in this last earthquake suggest strongly that the effects of the vertical shaking can be very damaging, increasing the damage done by the horizontal shaking.

A number of general conclusions can be made about engineered construction in San Salvador: the 1966 earthquake resistant design code has not been enforced, and many buildings that were damaged in the 1965 earthquake were not repaired adequately. Reinforcement is often poorly detailed, particularly in columns, where horizontal reinforcement was often observed to be totally inadequate. Furthermore, the small bars used for links and stirrups are milled locally, and tend to be brittle. Masonry infill panels often failed in a brittle manner, forming soft storeys, which lead to collapse.

Glazing systems in San Salvador generally performed very well. However, building services located in the ceiling void are often inadequately attached.

There was generally little evidence of aseismic consideration in the design and installation of machinery and lifelines, as shown by the huge damage suffered by the water and telecommunications systems.

The traditional form of housing is a cheap and efficient method of construction, using timber verticals and bamboo horizontals, filled in with dried mud. It is very appropriate to El Salvador, and not generally a "death trap" like other forms of housing in the Third World. However, it does require preservative treatment to prevent its deterioration in El Salvador's aggressive climate.

A further, and often more serious, problem with respect to the poorer housing and some other buildings is the instability, especially during earthquakes, of the steep natural slopes on which they are located.

There are a number of areas in which further research would be significantly assisted by the records of the strong motion produced by the earthquake, particularly the soil amplification effects and the design parameters that should appear in the country's aseismic building code, including a revision of the shape of the design spectra.

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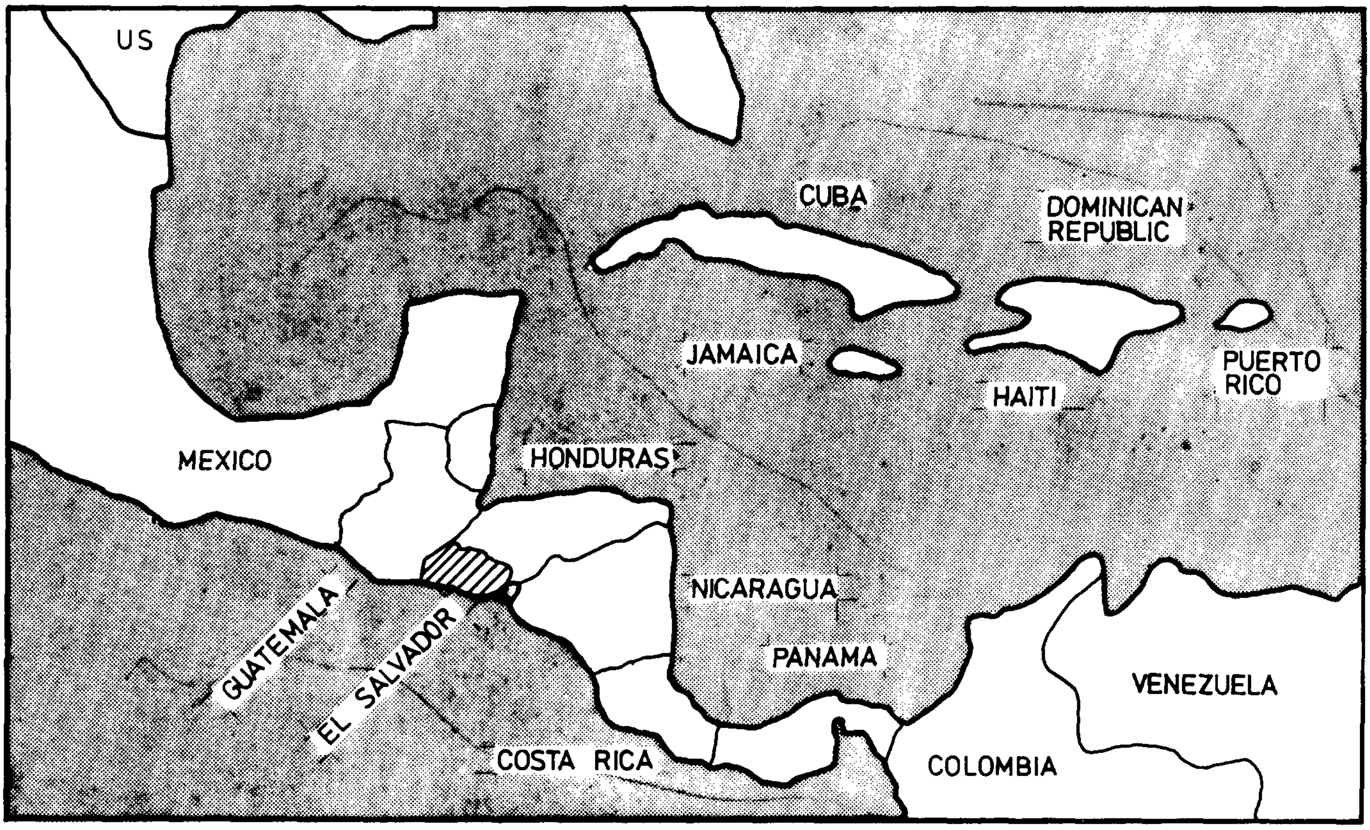


FIGURE 1: LOCATION OF EL SALVADOR IN CENTRAL AMERICA.

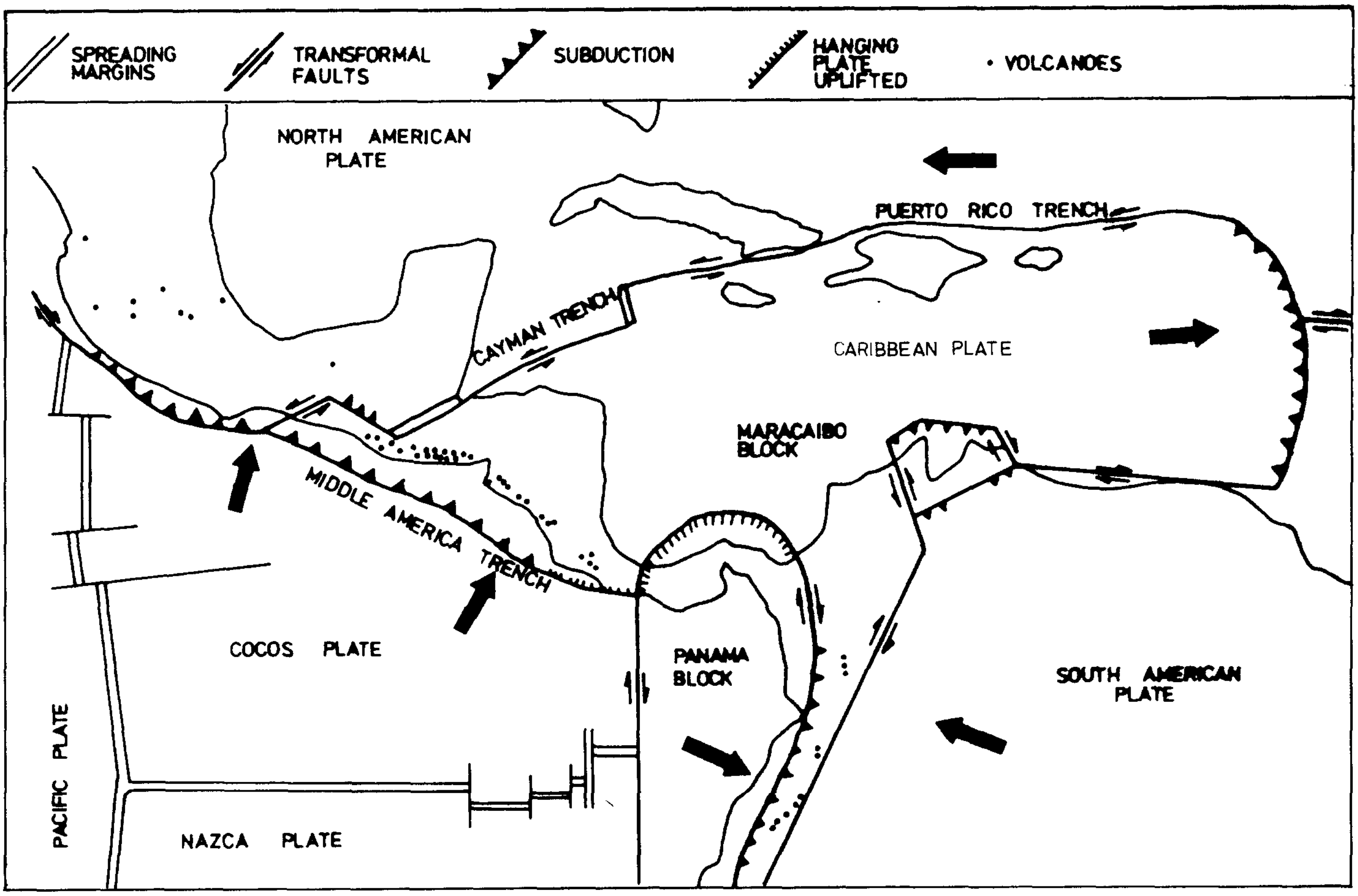
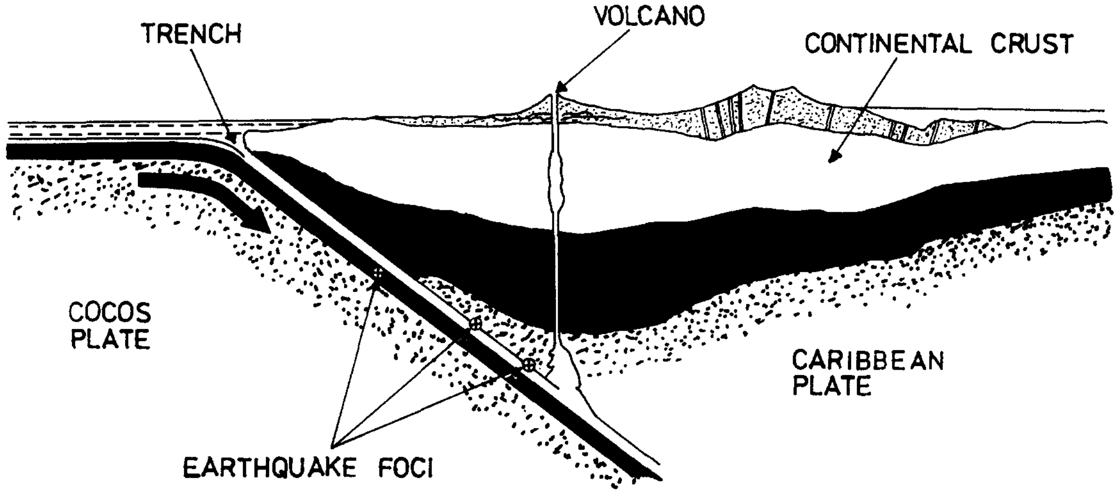
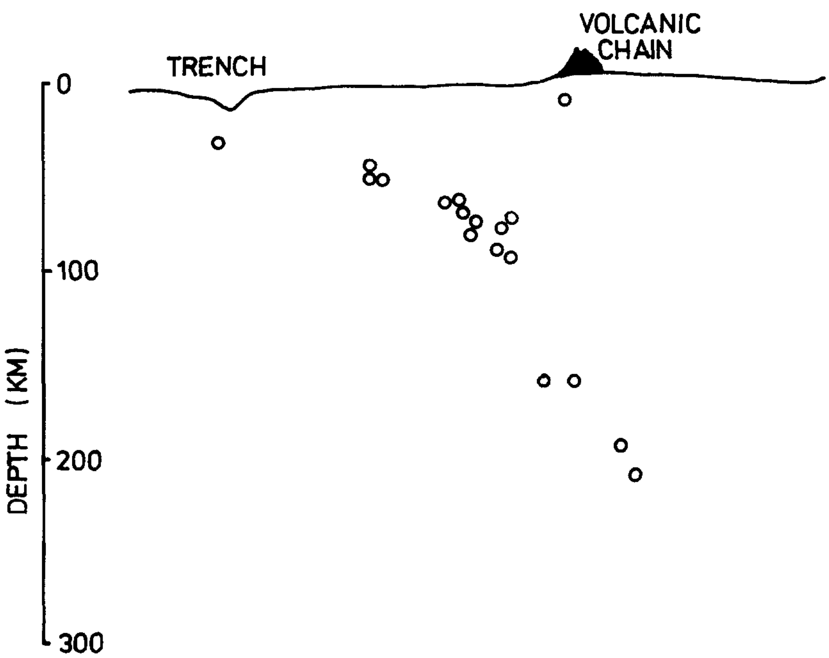


FIGURE 2: TECTONICS OF THE CARIBBEAN REGION.



3A: SCHEMATIC REPRESENTATION OF SUBDUCTION ZONE.



3B: CROSS SECTION OF SUBDUCTION ZONE (N16E) SHOWING EARTHQUAKE FOCI.

FIGURE 3.

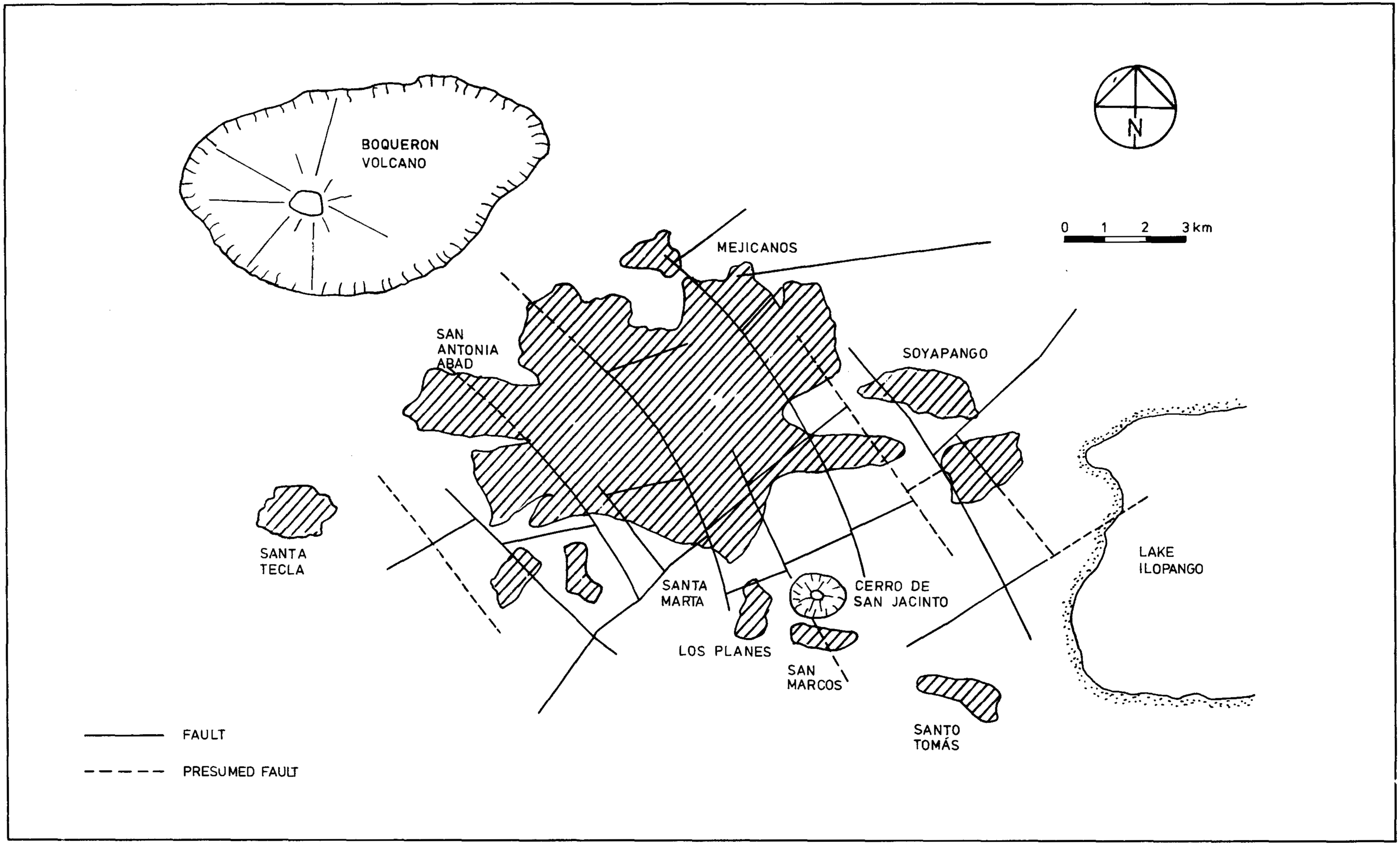


FIGURE 4: MAIN GEOLOGICAL FAULTS IN SAN SALVADOR AREA.

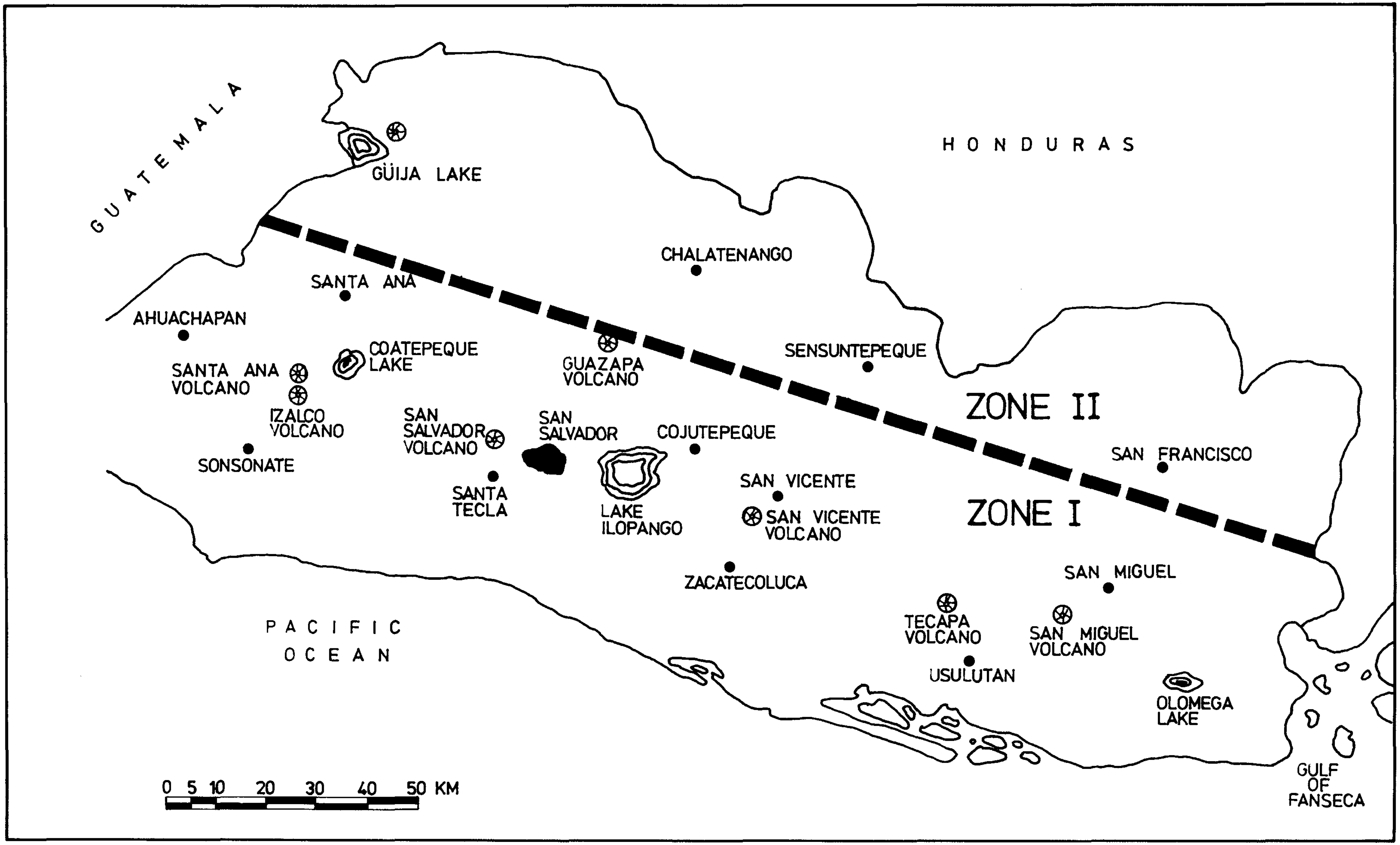


FIGURE 5: REPUBLIC OF EL SALVADOR, SHOWING SEISMIC ZONES AS DEFINED IN THE 1966 CODE.

	GROUP A	GROUP B
TYPE 1	0·16	0·12
TYPE 2	0·31	0·24
TYPE 3	0·39	0·30

TABLE 1: BASE SHEAR COEFFICIENTS C (FROM 1966 BUILDING CODE IN EL SALVADOR) FOR STRUCTURE IN ZONE 1

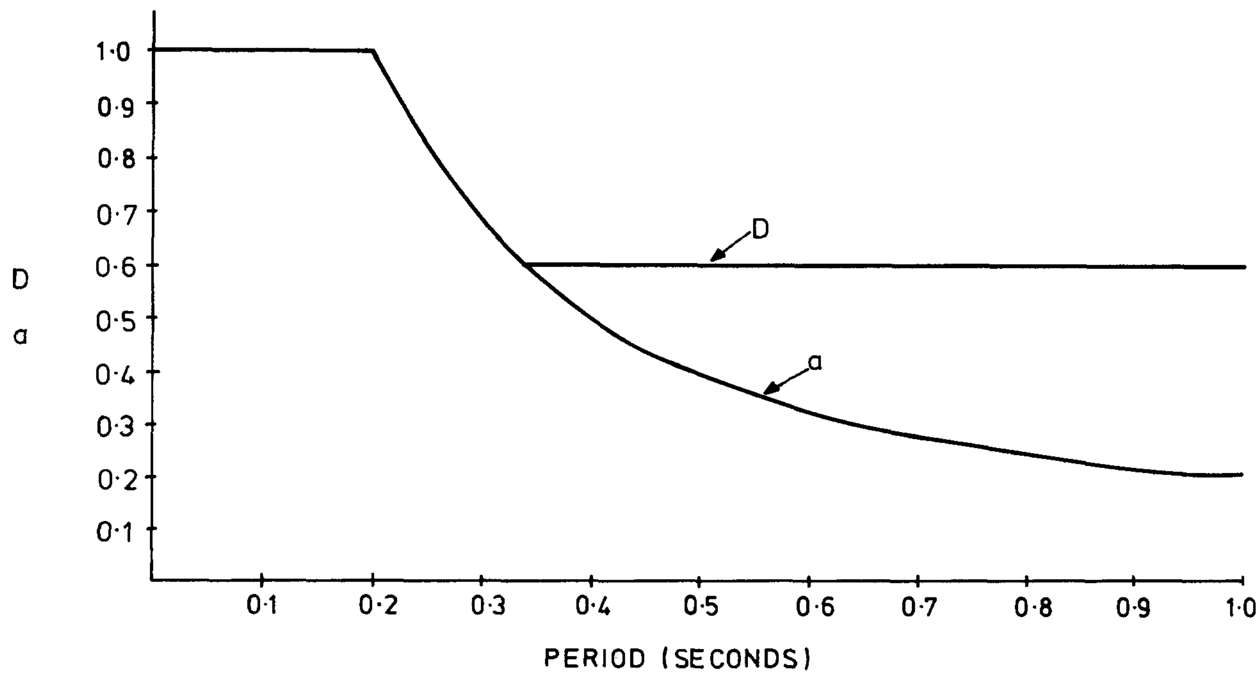


FIGURE 6: COEFFICIENTS D AND a (FROM THE 1966 BUILDING CODE IN EL SALVADOR) AS FUNCTIONS OF THE NATURAL PERIOD OF VIBRATION OF THE STRUCTURE

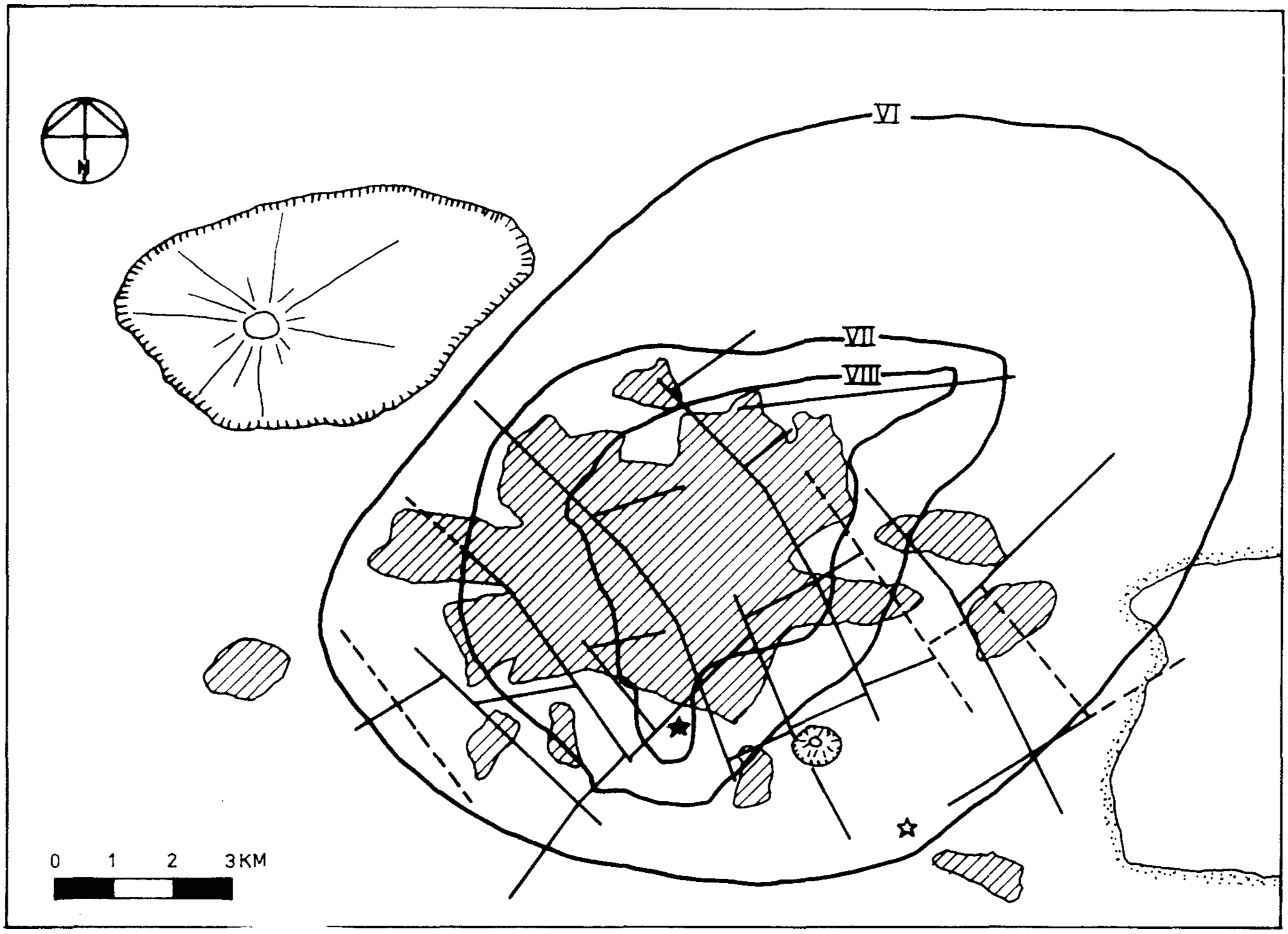


FIGURE 7: ISOSEIRMAL MAP FOR SAN SALVADOR EARTHQUAKE OF 10 OCTOBER 1986 (AFTER HARLOW 1986) ★ EPICENTRE ☆ EPICENTRE 3 MAY 1965 EARTHQUAKE

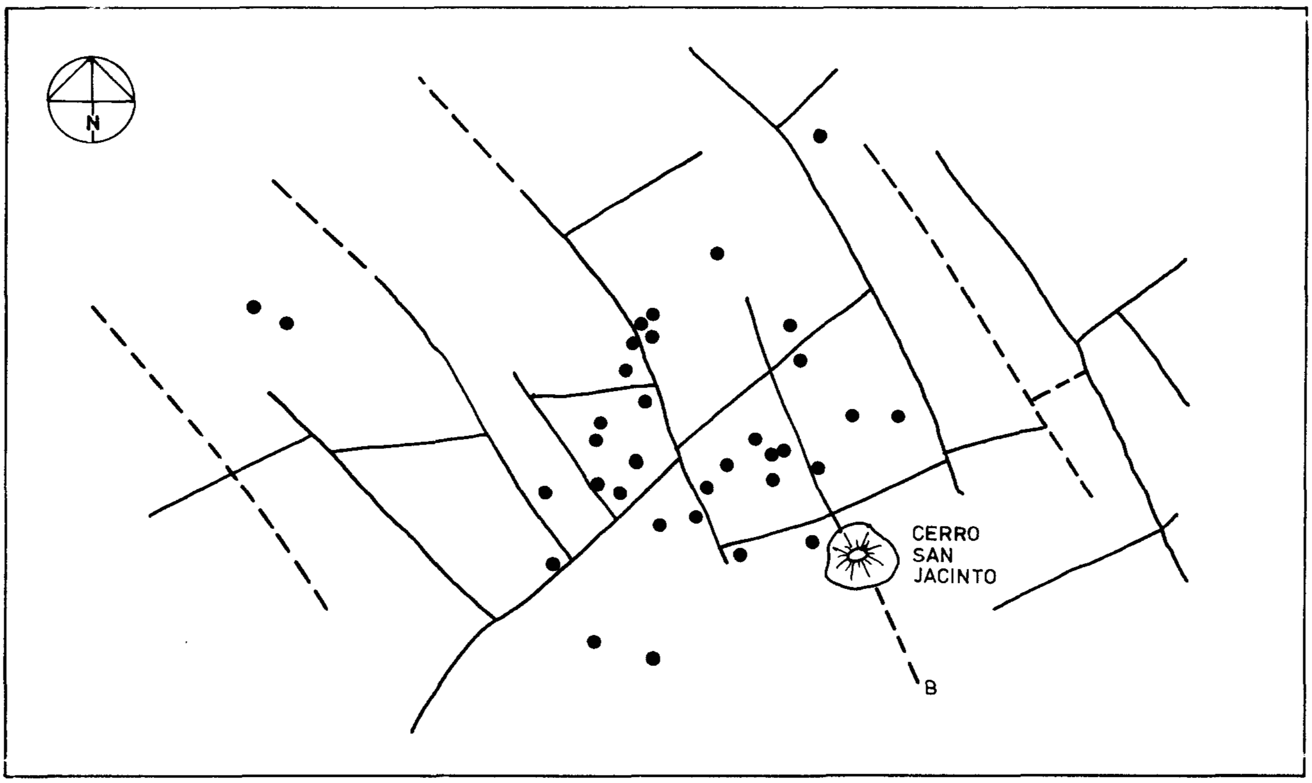


FIGURE 8: AFTERSHOCKS IN SAN SALVADOR AREA WITH MAGNITUDE ≥2.5 DURING OCTOBER AND NOVEMBER 1986.

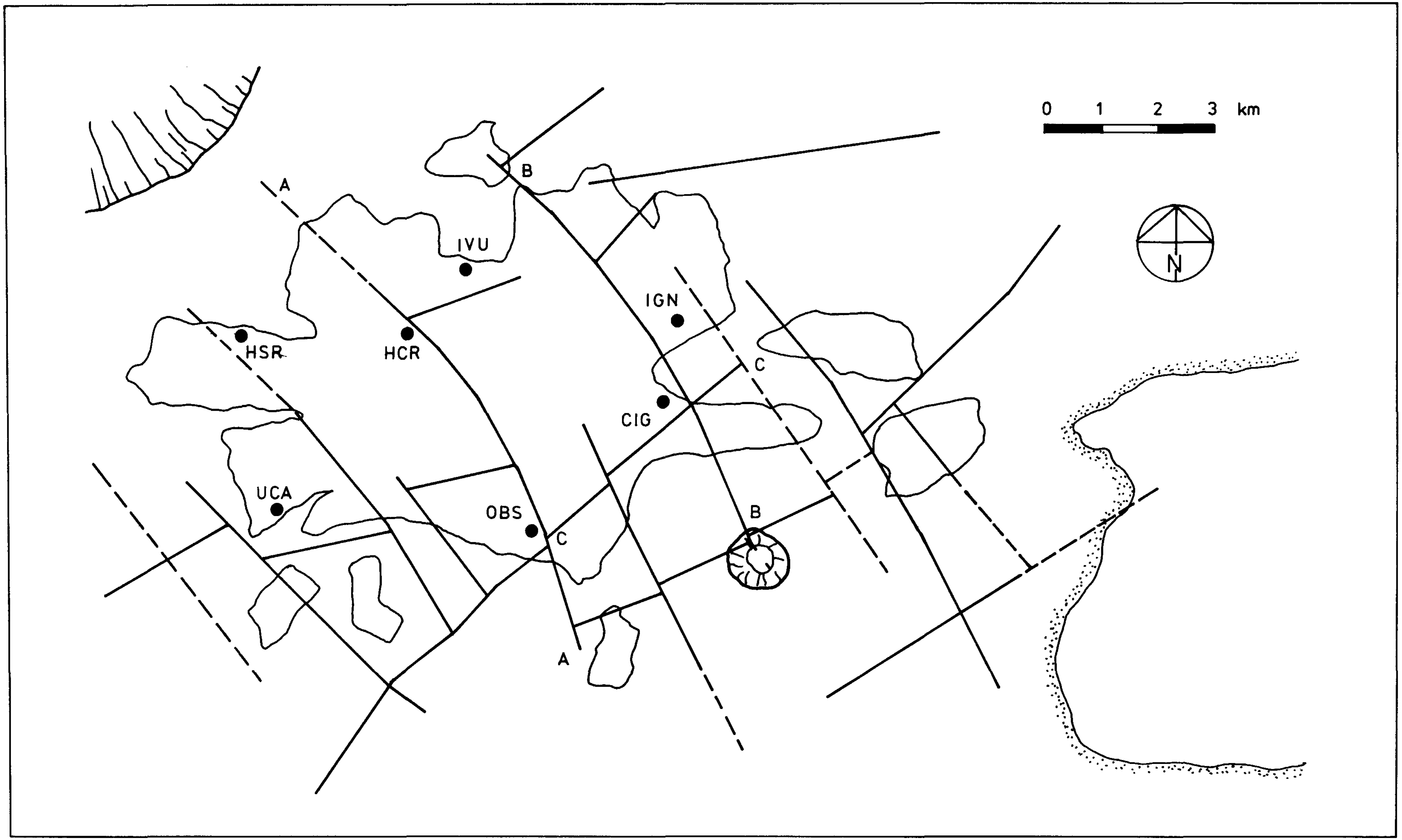


FIGURE 9: STRONG MOTION RECORDING STATIONS IN SAN SALVADOR.
TRIGGERED BY THE 10 OCTOBER 1986 EARTHQUAKE.

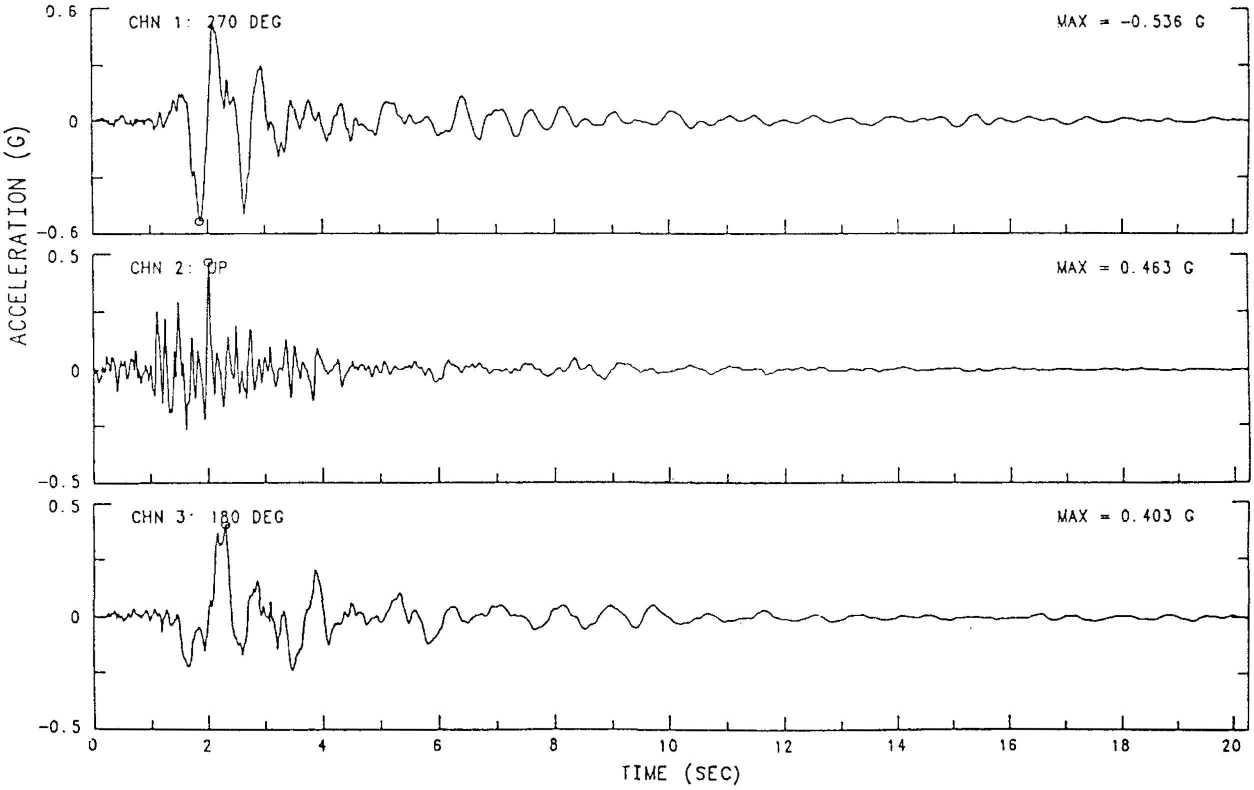


FIGURE 10 : UNCORRECTED STRONG MOTION RECORDS FROM SHERATON HOTEL (HSR).

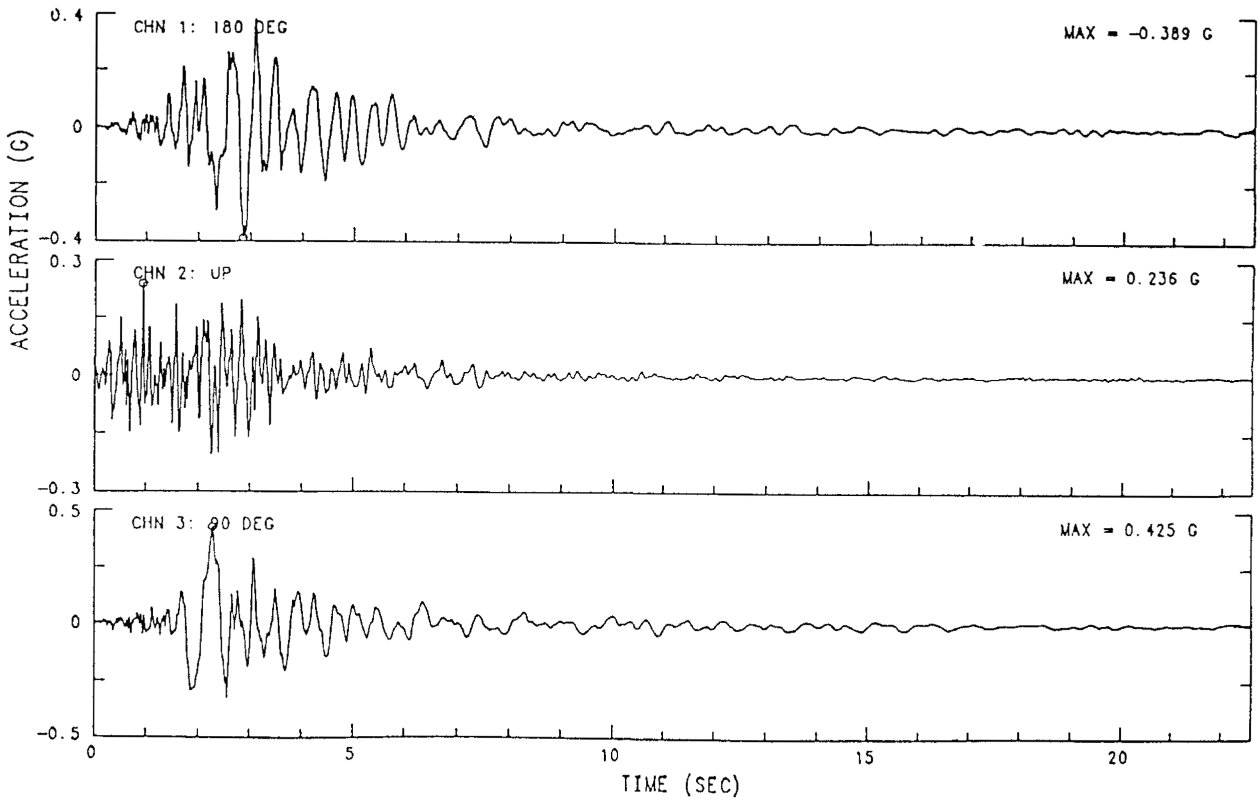


FIGURE 11 : UNCORRECTED STRONG MOTION RECORDS FROM THE BASEMENT OF THE CAMINO REAL HOTEL (HCR).

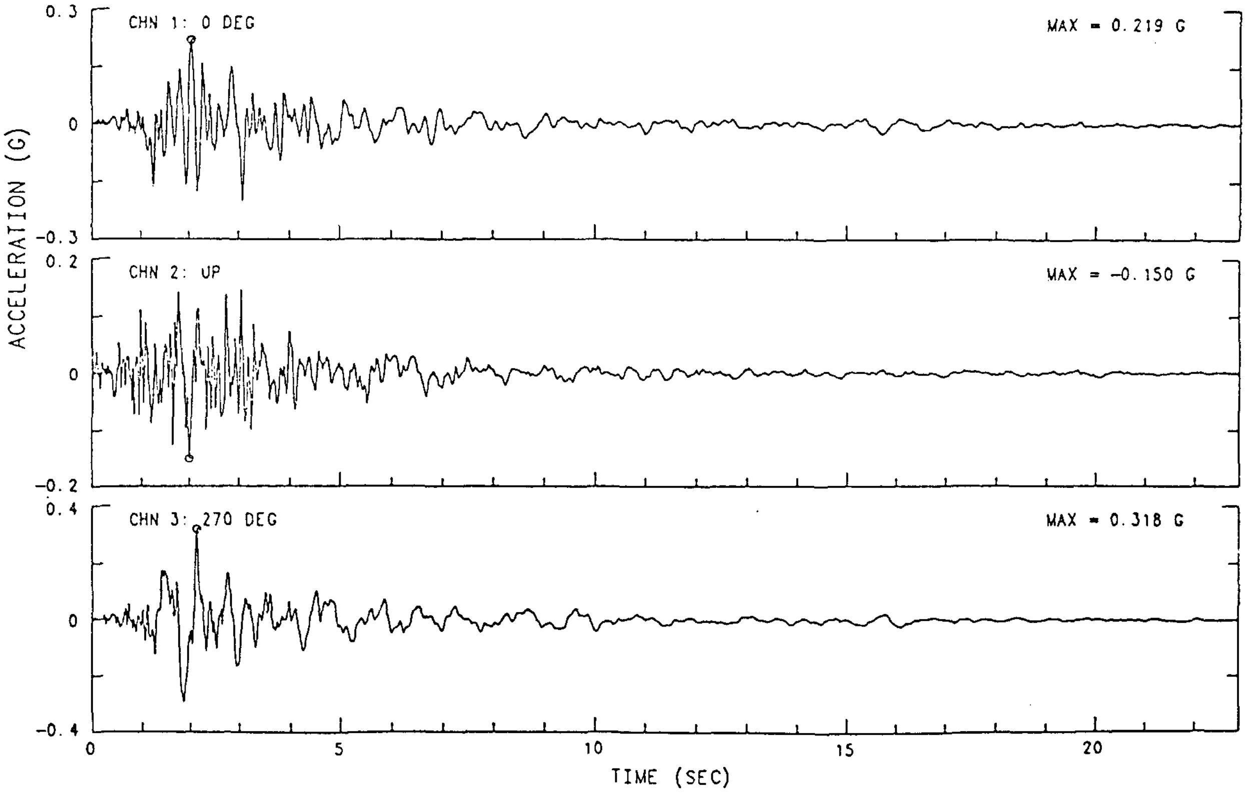


FIGURE 12: UNCORRECTED STRONG MOTION RECORDS FROM THE NATIONAL GEOGRAPHIC INSTITUTE (IGN)

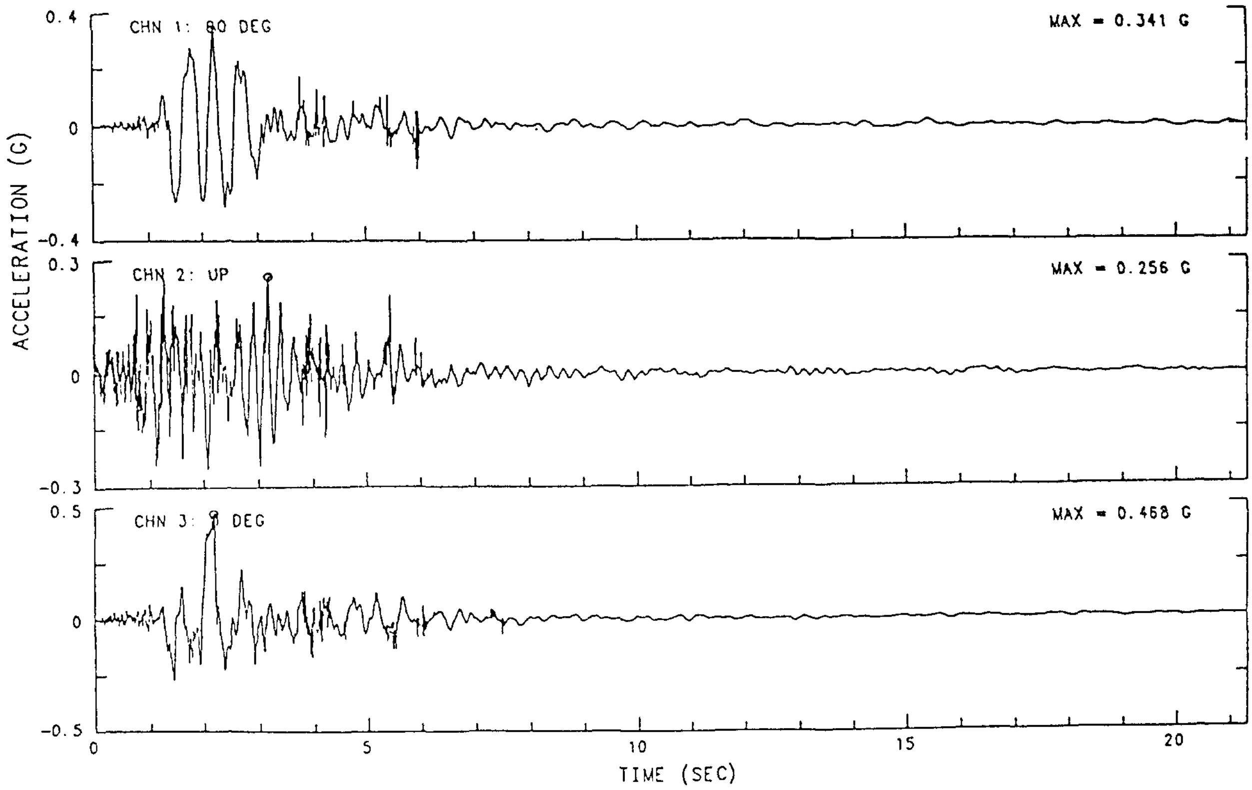


FIGURE 13: UNCORRECTED STRONG MOTION RECORDS FROM THE CENTRO AMERICANA UNIVERSITY (UCA)

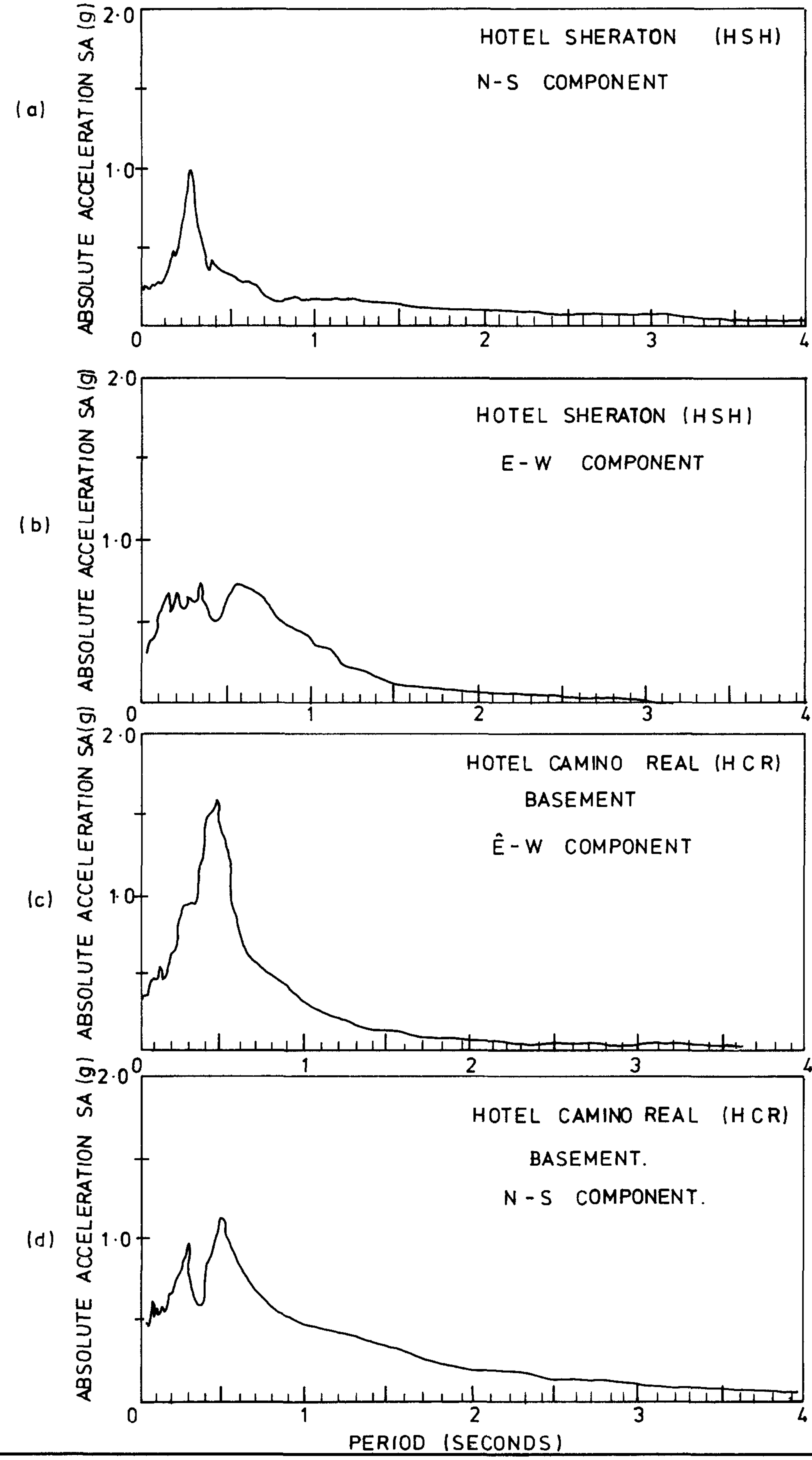


FIGURE 14 : RESPONSE SPECTRA OF ABSOLUTE ACCELERATION FOR 5% DAMPING, FROM HORIZONTAL STRONG MOTION RECORDS AT THE SHERATON AND CAMINO REAL HOTELS.

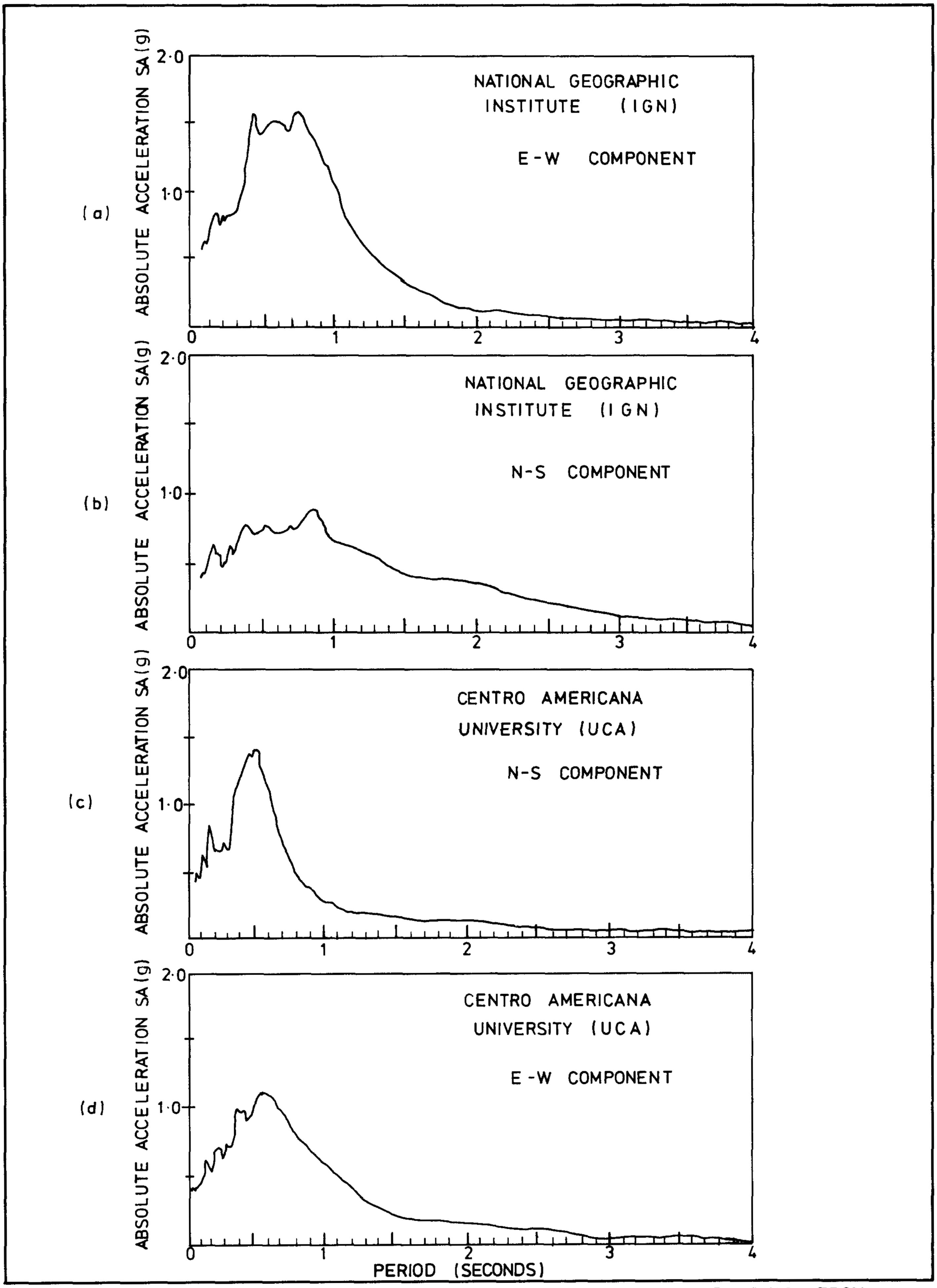


FIGURE 15: RESPONSE SPECTRA OF ABSOLUTE ACCELERATION FOR 5% DAMPING, FROM HORIZONTAL STRONG MOTION RECORDS AT THE NATIONAL GEOGRAPHIC INSTITUTE AND THE CENTRO AMERICANA UNIVERSITY.

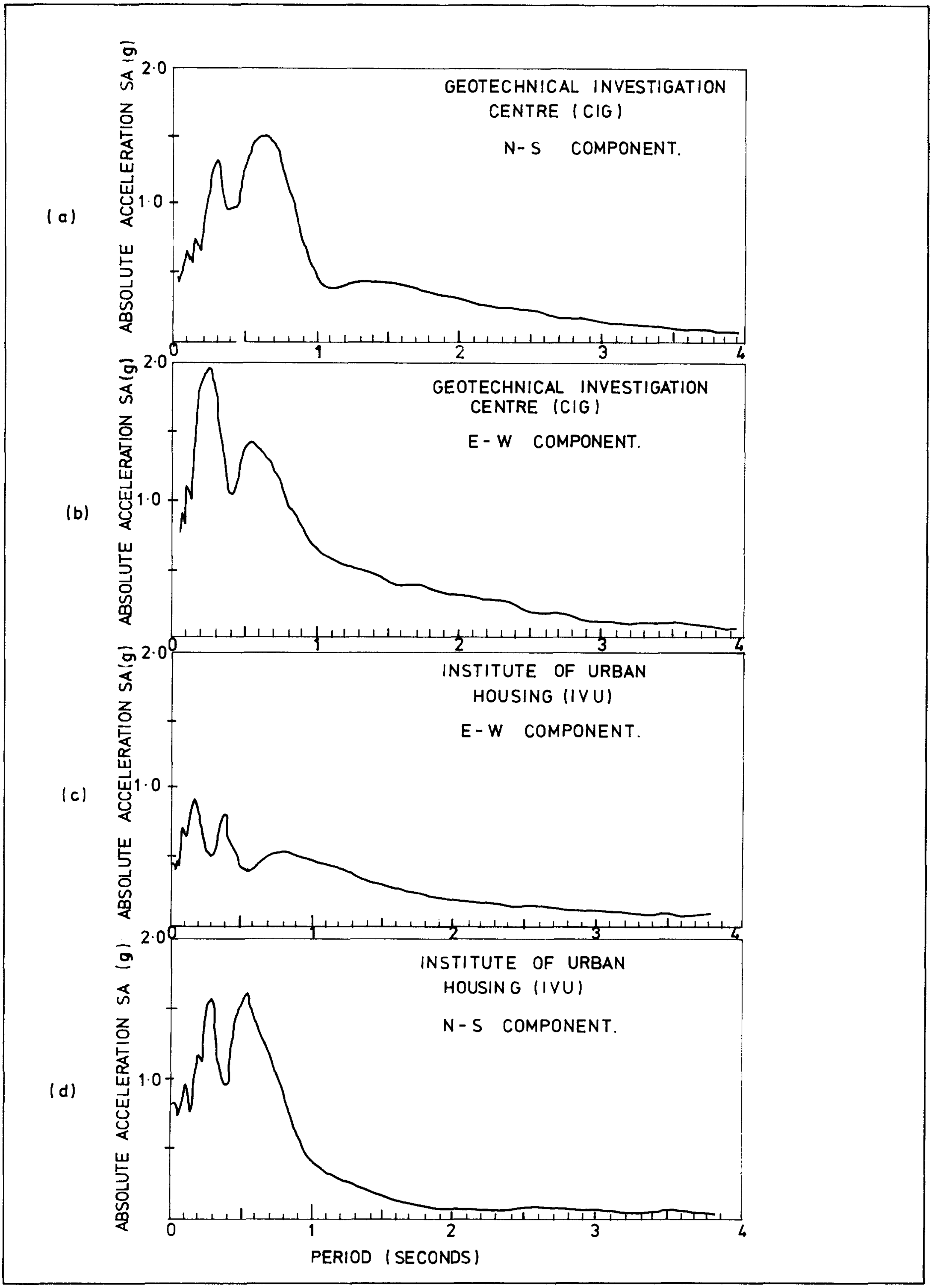


FIGURE 16 : RESPONSE SPECTRA OF ABSOLUTE ACCELERATION FOR 5 % DAMPING FROM HORIZONTAL STRONG MOTION RECORDS AT THE GEOTECHNICAL INVESTIGATION CENTRE AND THE INSTITUTE OF URBAN HOUSING.

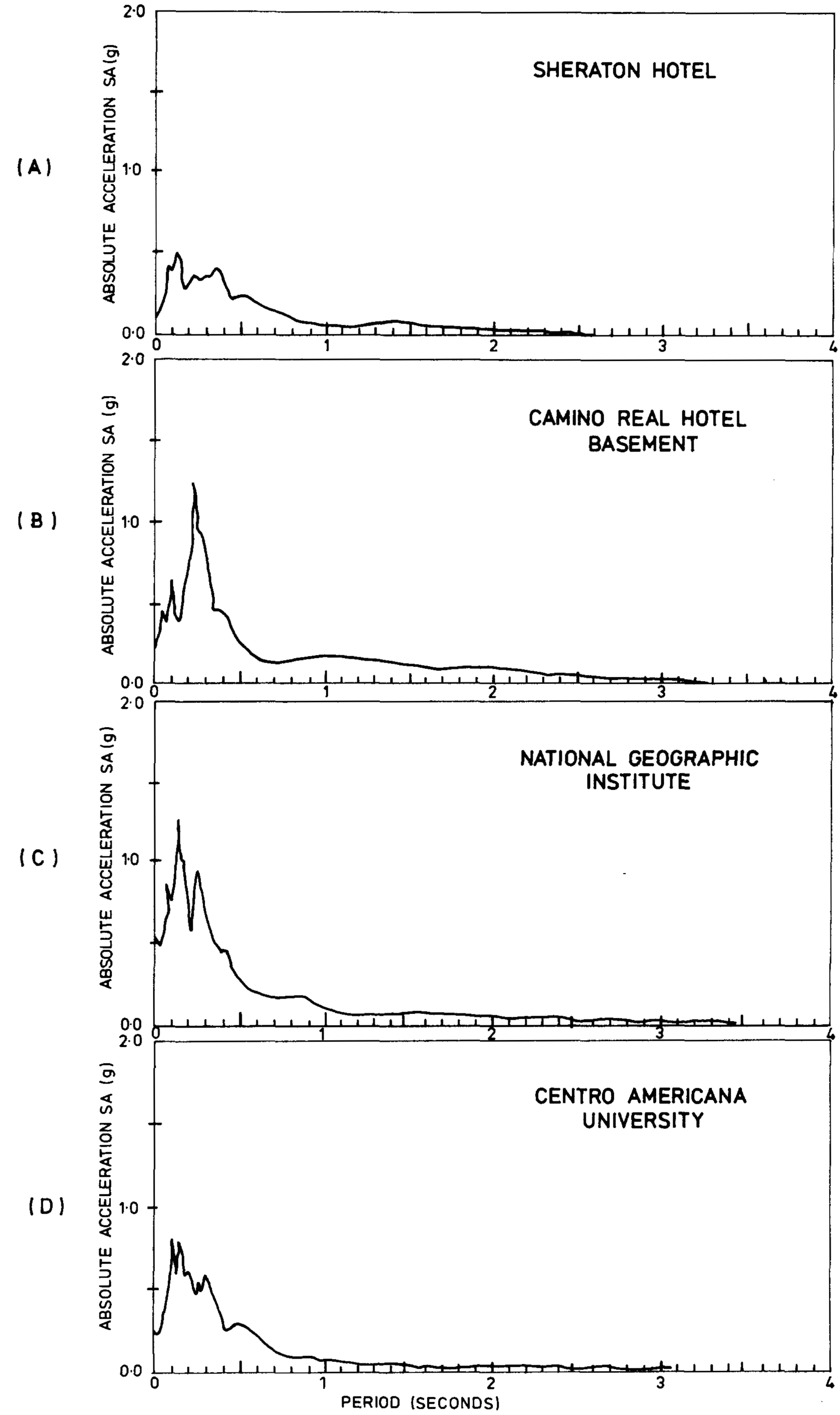
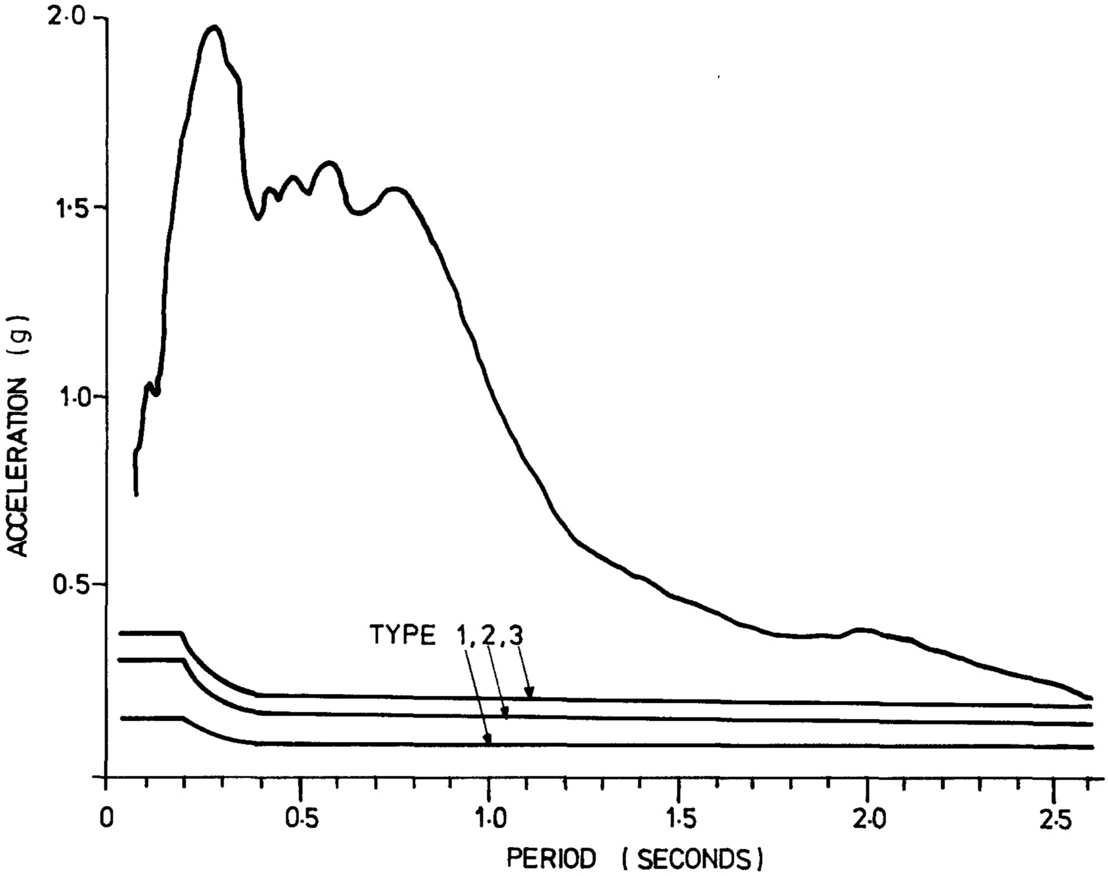


FIGURE 17: RESPONSE SPECTRA OF ABSOLUTE VERTICAL ACCELERATION FOR 5% DAMPING, FROM FOUR STRONG MOTION STATIONS IN SAN SALVADOR.



ENVELOPE OF HORIZONTAL RESPONSE SPECTRA (EXCLUDING THE RECORDS FROM UPPER FLOORS OF THE CAMINO REAL HOTEL) AND THE DESIGN SPECTRA FOR GROUP A STRUCTURES FROM THE 1966 BUILDING CODE.

FIGURE 18

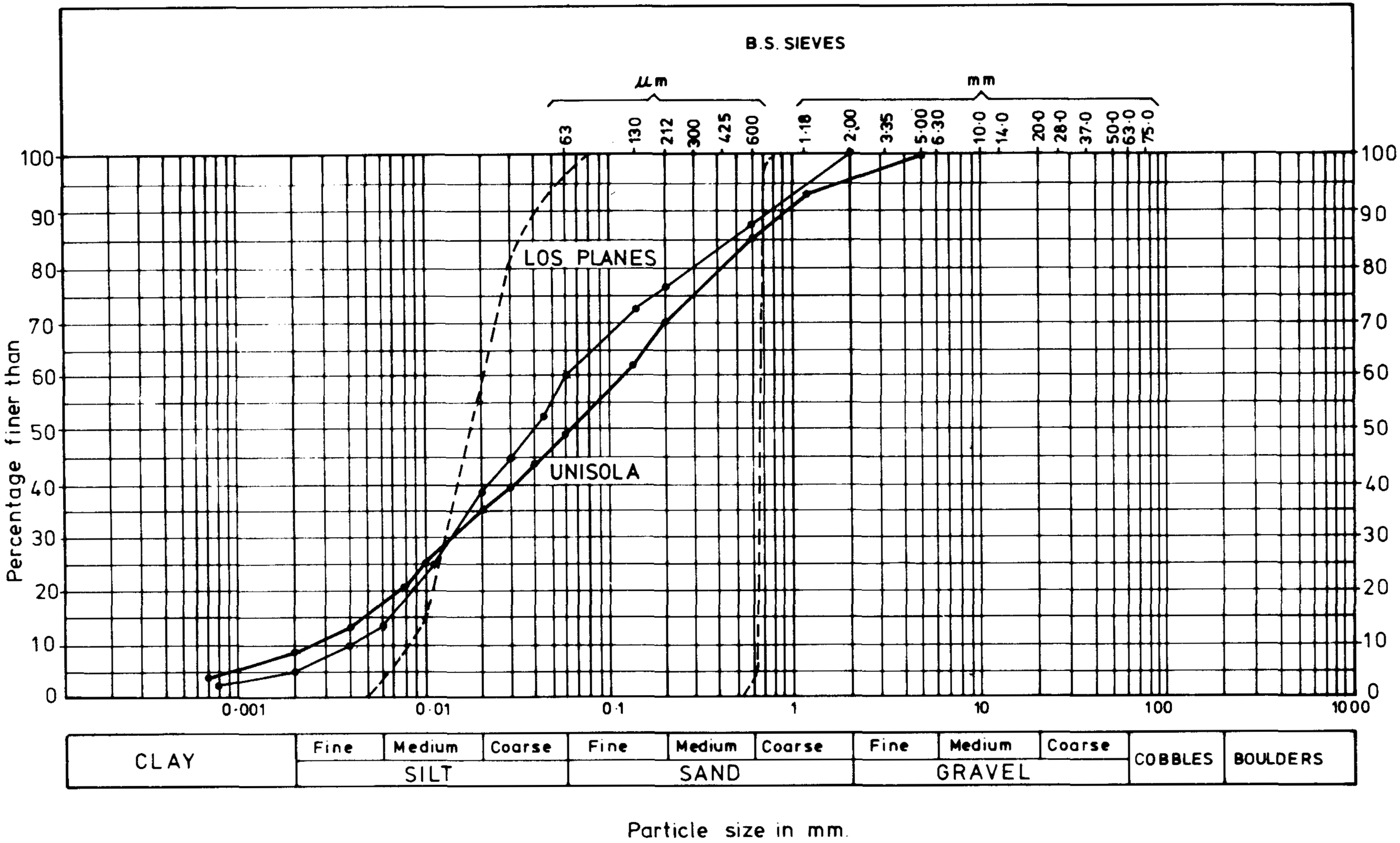


FIGURE 19 : PARTICLE SIZE DISTRIBUTION FOR TWO SOIL SAMPLES FROM SAN SALVADOR (PREPARED BY V.N. GEORGIANNOU CIVIL ENGINEERING DEPT. IMPERIAL COLLEGE LONDON). THE DASHED LINES REPRESENT THE BOUNDS OF THE MOST LIQUEFIABLE SOILS, AS DETERMINED BY LABORATORY TESTS (LEE AND FITTON 1968).

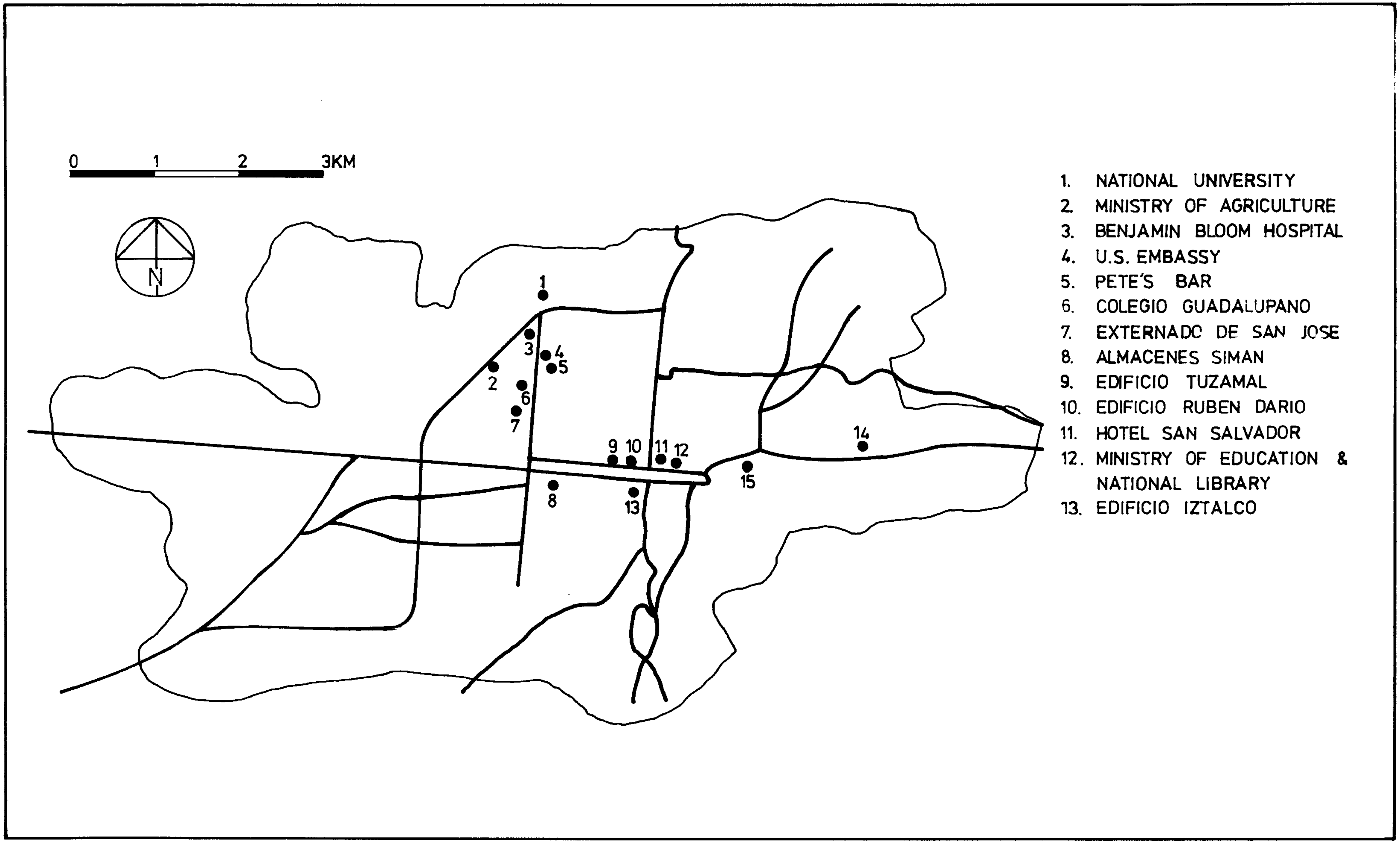


FIGURE 20: LOCATION OF ENGINEERED STRUCTURES SELECTED FOR CASE STUDIES.

Station Code	Station Name	Type and Size of structure	Component	A_{max} (g)	V_{max} (cm/s)	D_{max} (cm)
IGN	National Geographic	1-storey	270°	0.54	72.7	10.6
	Institute.	reinforced	Up	0.46	18.3	2.1
	Ground floor.	concrete bldg.	180°	0.40	56.1	17.8
CIG	Geotechnical	2-storey	180°	0.42	61.8	14.8
	Investigation Cntr.	reinforced	Up	0.40	10.9	2.3
	Ground floor.	concrete bldg.	90°	0.71	80.0	11.9
OBS	National	1-storey	180°	(0.66)+	---	---
	Seismological Obs.	1-storey	Up	(0.37)+	---	---
	Observatory	vault.	90°	(0.54)+	---	---
IVU	Institute of	6-storey	90°	0.37	39.2	9.8
	Urban Housing.	reinforced	Up	(Malfunction)		---
	Ground floor.	concrete bldg.	180°	0.72	55.6	7.1
HSH	Sheraton Hotel.	10-storey	360°	0.22	17.7	4.6
	Ground floor.	reinforced	Up	0.15	7.3	1.4
		concrete bldg.	270°	0.32	26.3	4.4
UCA	Catholic	6-storey	180°	0.39	32 9	6.2
	University.	reinforced	Up	0.24	9.3	1.7
	Ground floor.	concrete bldg.	90°	0.43	48.8	11.6
HCR	Camino Real	10-storey	90°	0.34	32.3	4.2
	Hotel.	reinforced	Up	0.26	13.3	2.5
	Basement.	concrete bldg.	360°	0.47	45.5	13.4
HCR	Camino Real	10-storey	90°	0.69	43.7	4.5
	Hotel.	reinforced	Up	0.37	17.4	2.4
	First floor.	concrete bldg.	360°	0.53	40.6	13.8
HCR	Camino Real	10-storey	90°	0.91	63.7	10.6
	Hotel.	reinforced	Up	(0.43)++	---	---
	Roof terrace.	concrete bldg.	360°	(0.43)++	---	---

\+ From visible part of record; actual values probably higher.

++ Estimated values.

TABLE 2: CHARACTERISTICS OF CORRECTED STRONG MOTION RECORDS FROM SAN SALVADOR

Station	Velocity (cm/sec)	Distance (km)		
		A-A	B-B	C C
CIG	80.0	2.8	0.4	0.3
IGN	72.7	3.7	0.5	1.3
IVU	55.6	1.3	1.8	4.4
UCA	48.8	4.0	7.1	4.8
HCR	45.5	0.2	3.4	4.3
HSH	26.3	2.2	5.4	6.4

TABLE 3. PEAK VELOCITIES AT THE STRONG MOTION STATIONS (TABLE 2) AND THEIR DISTANCES FROM THE FAULTS A-A, B-B AND C-C (FIG. 9)

PLATE 1: SMALL SLOPE FAILURE AT THE NATIONAL UNIVERSITY.

PLATE 2: HOUSE SUNK INTO LIQUEFIED GROUND AT SANTA MARTA.

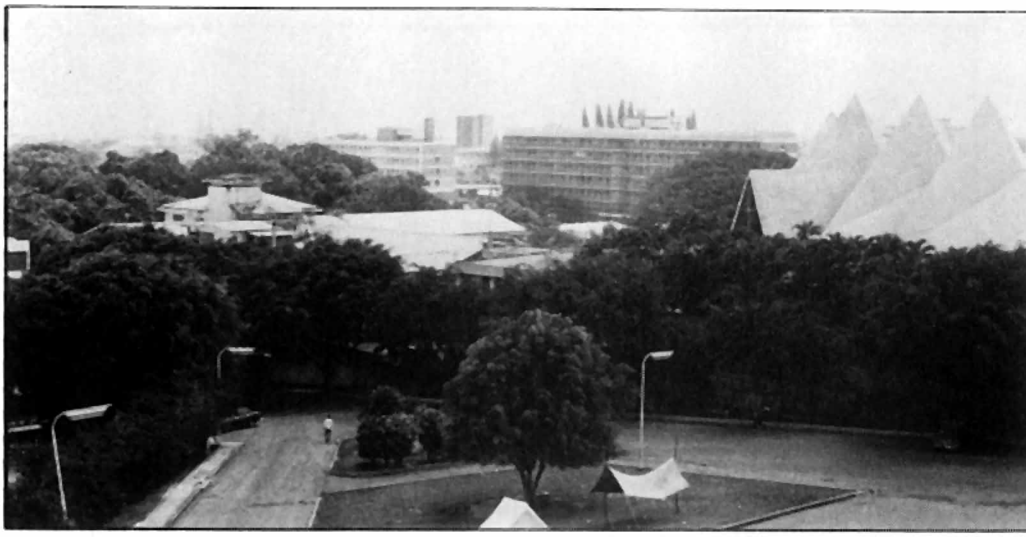


PLATE 3: GENERAL VIEW OF SAN SALVADOR.

PLATE 4: TRADITIONAL TIMBER STRUCTURE.

PLATE 5: DAMAGE TO CONCRETE COLUMN AT EXTERNADO DE SAN JOSE.

PLATE 6: HOTEL SAN SALVADOR.

PLATE 7 : EDIFICIO IZTALCO.

PLATE 8 : DAMAGE TO SHORT COLUMN.

PLATE 9: FREEMASONS' LODGE.

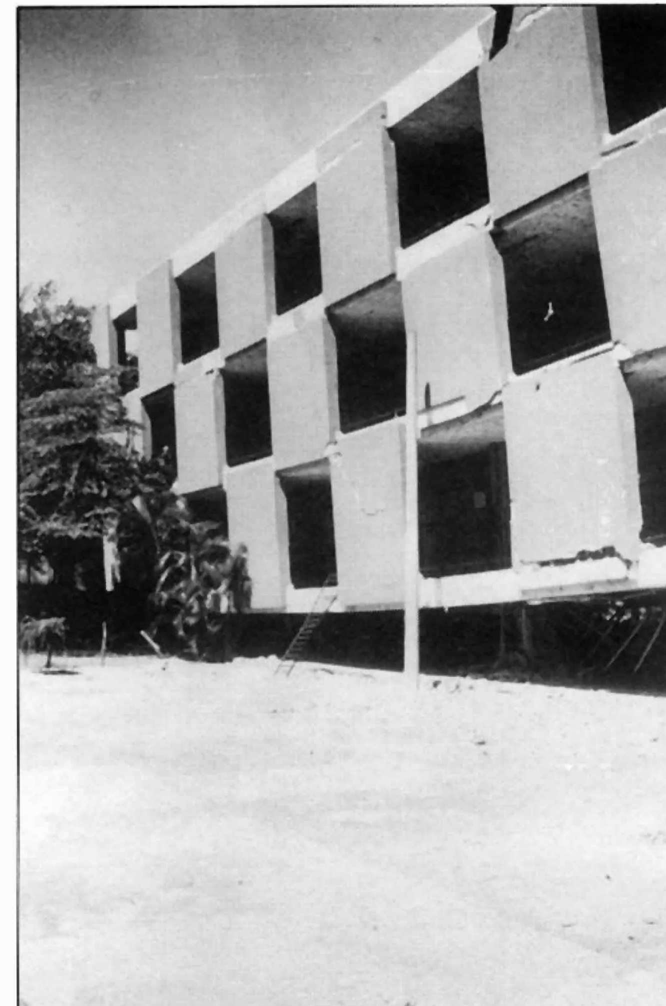


PLATE 10: ECONOMICS FACULTY, NATIONAL UNIVERSITY.

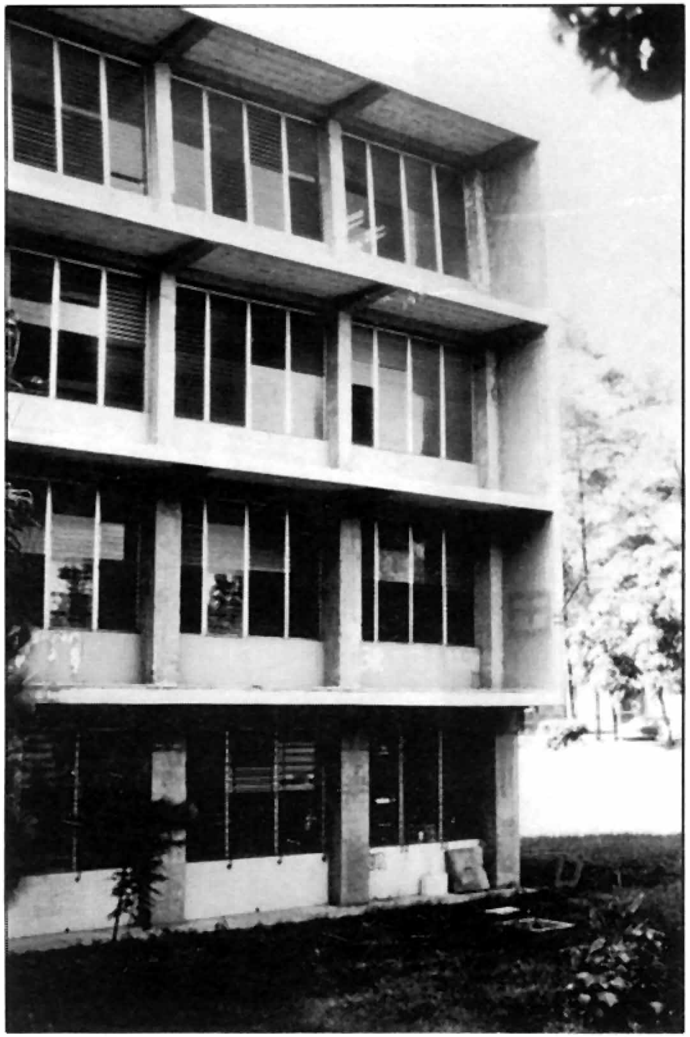


PLATE 11: ARCHITECTURE FACULTY, NATIONAL UNIVERSITY.

PLATE 12: DENTAL HOSPITAL, NATIONAL UNIVERSITY.

PLATE 13: MINISTRY OF AGRICULTURE.

PLATE 14: MINISTRY OF AGRICULTURE, SHOWING SEPARATION OF CLADDING.

PLATE 15 : HOSPITAL BENJAMIN BLOOM.

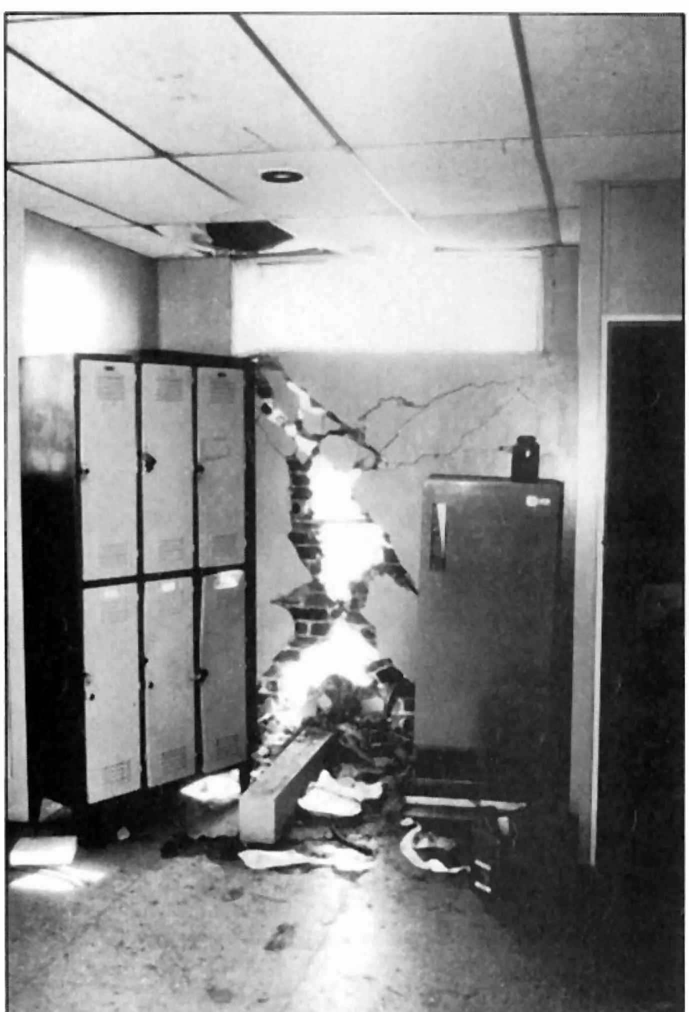


PLATE 16 : HOSPITAL BENJAMIN BLOOM SHOWING FAILURE OF SHEAR PANELS.

PLATE 17 : HOSPITAL BENJAMIN BLOOM, SHOWING FAILURE OF CHILDRENS HOSPITAL.

PLATE 18 : COLUMN FAILURE AT HOSPITAL BENJAMIN BLOOM.

PLATE 19 : PETE'S BAR.

PLATE 20 : COLEGIO GUADALUPANO, SHOWING SETTLEMENT OF FOUNDATIONS.

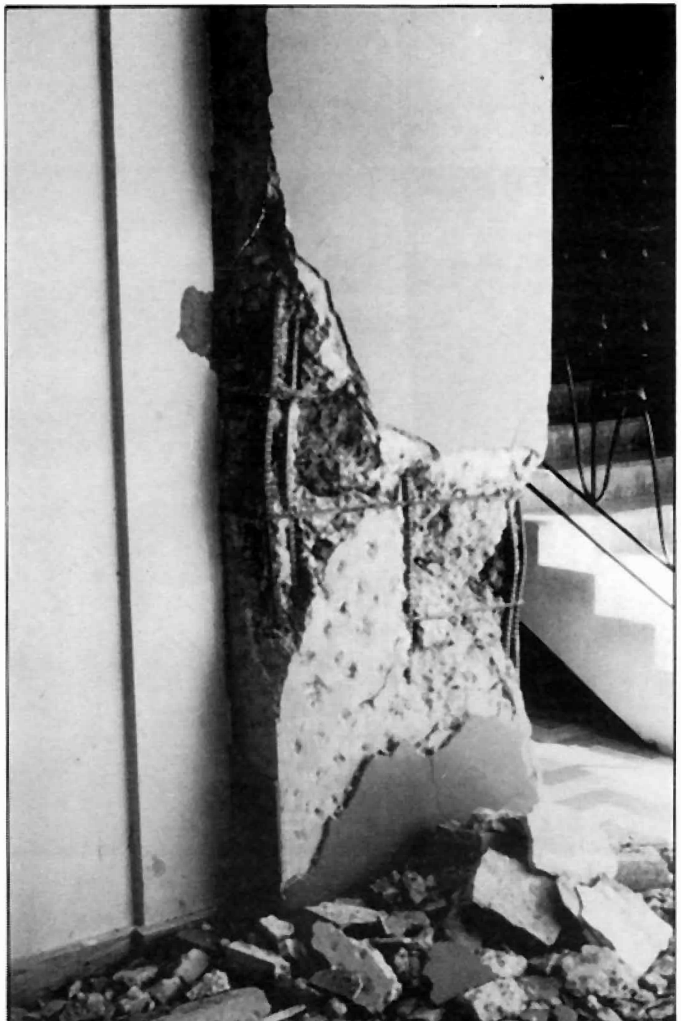


PLATE 21: COLUMN FAILURE AT COLEGIO GUADALUPANO.

PLATE 22: FAILURE OF INTERNAL WALLS AT COLEGIO GUADALUPANO.

PLATE 23: COLEGIO EXTERNADO DE SAN JOSE.

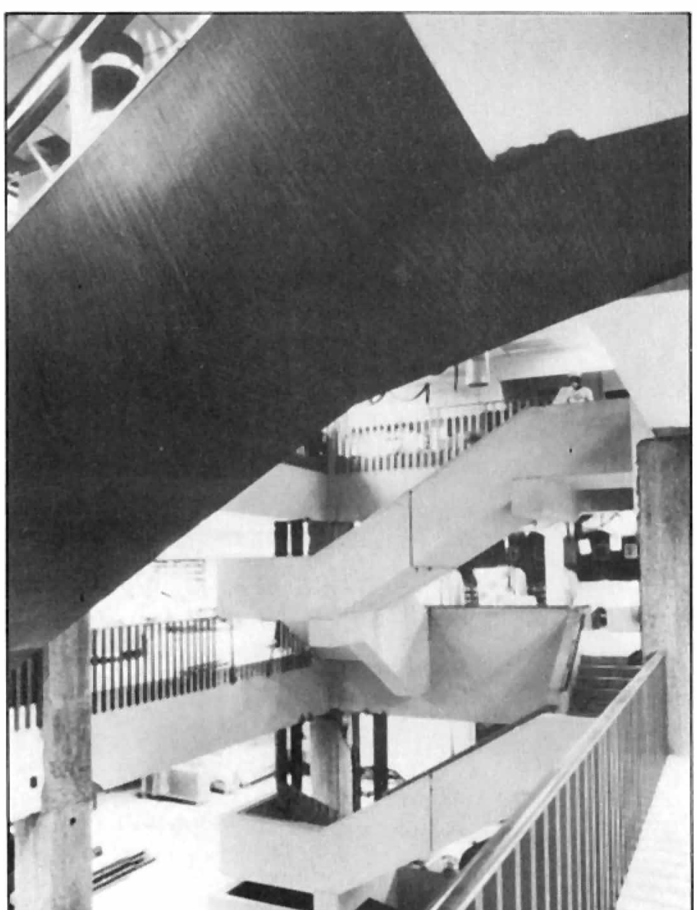


PLATE 24: ALMACENES SIMAN.

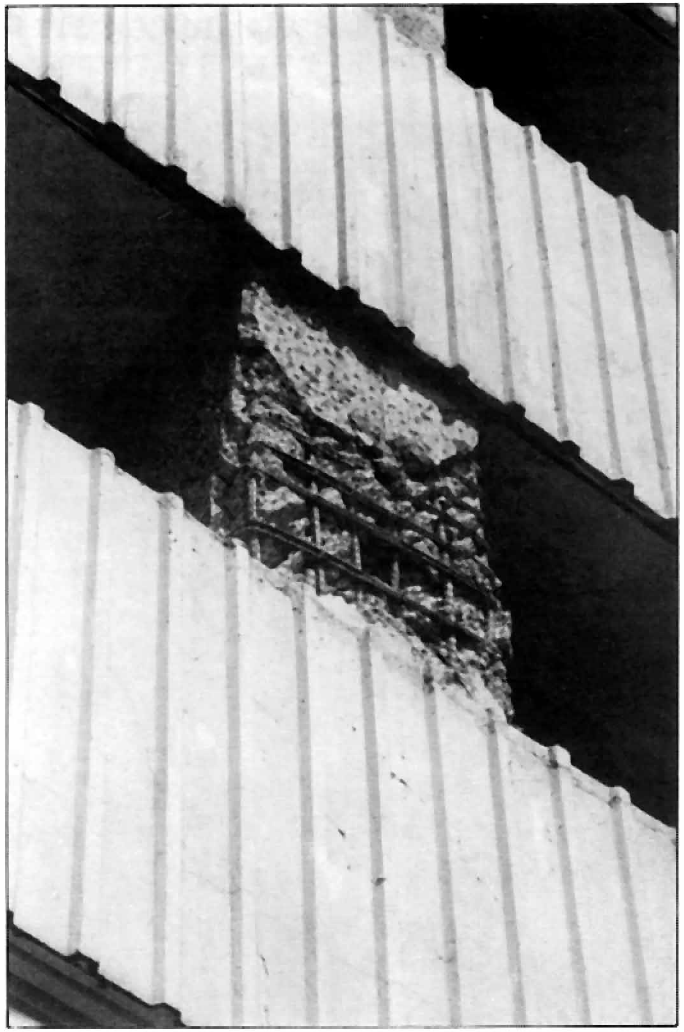


PLATE 25: COLUMN FAILURE AT ALMACENES SIMAN CAR PARK.

PLATE 26: EDIFICO TUZAMAL.

PLATE 27: EDIFICIO RUBEN DAIRO.

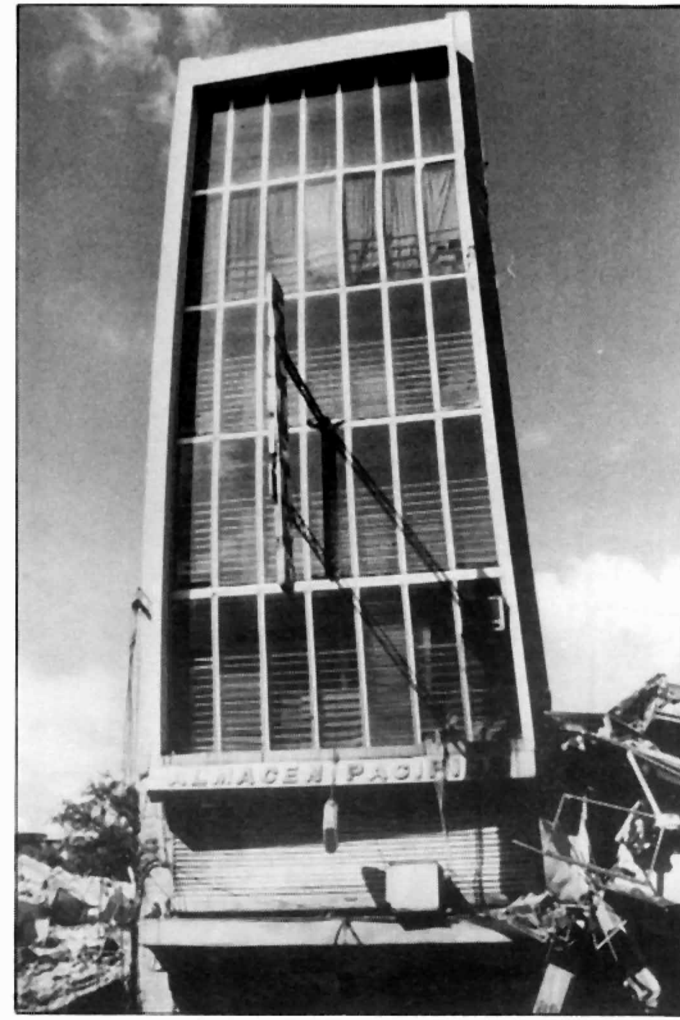


PLATE 28: ALMACENES PACIFICO.

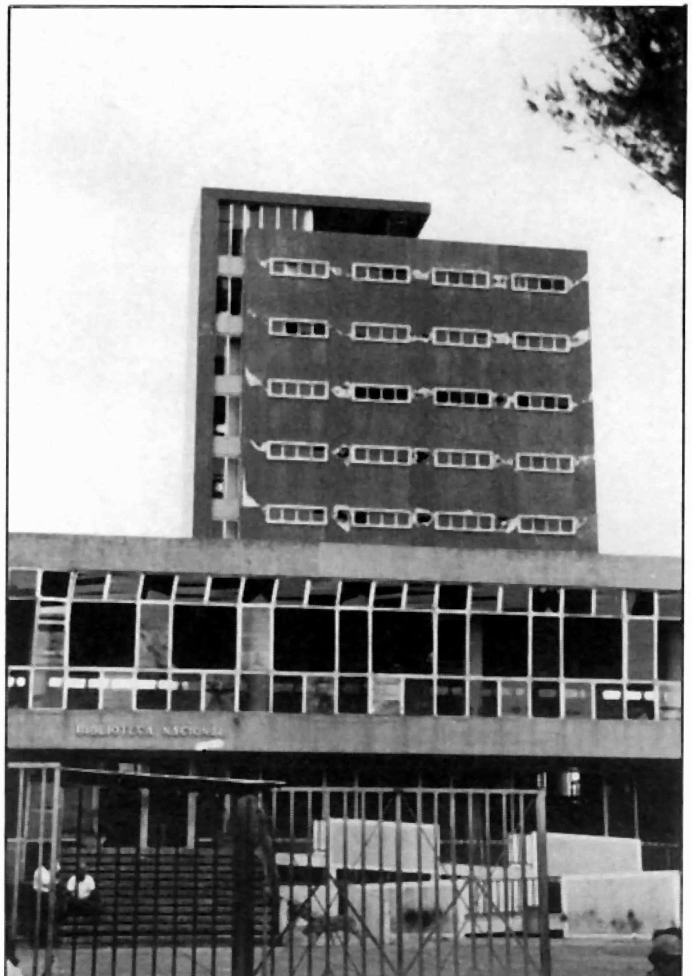


PLATE 29 : NATIONAL LIBRARY AND MINISTRY OF EDUCATION.

PLATE 30 : COLUMN FAILURE AT NATIONAL LIBRARY.

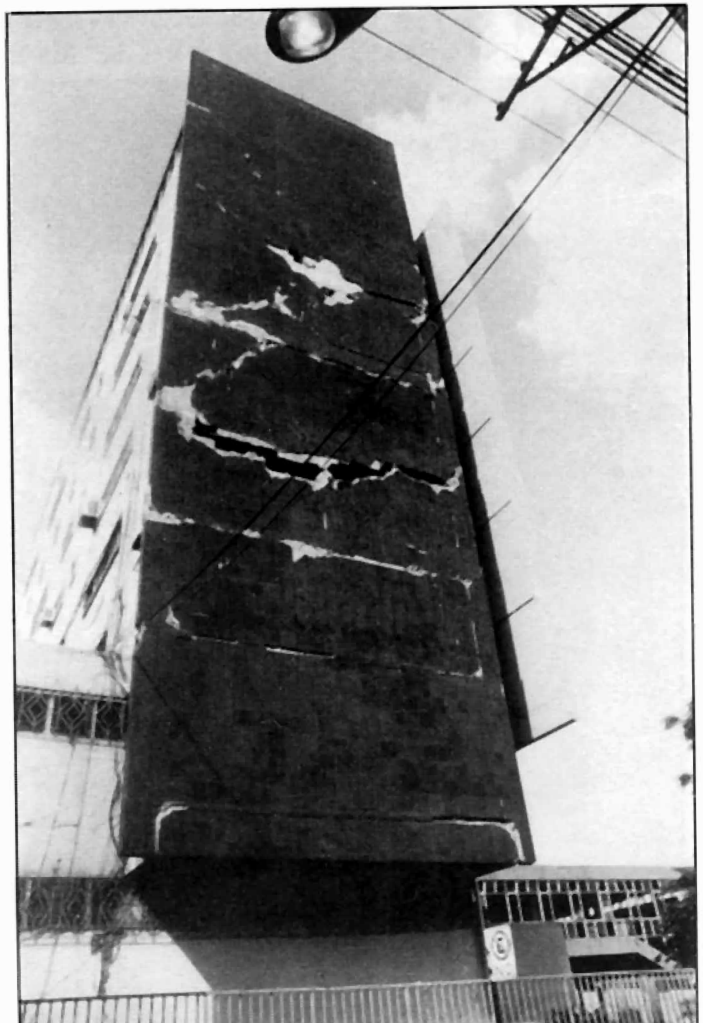


PLATE 31: FAILURE OF MASONRY PANELS AT MINISTRY OF EDUCATION.

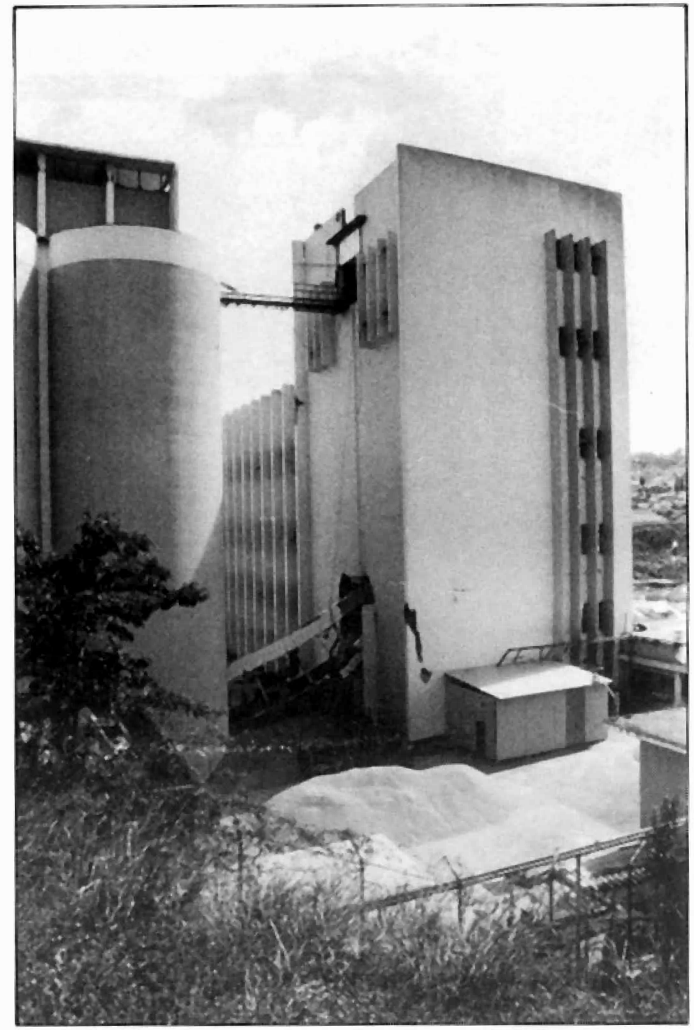


PLATE 32: BRIDGE COLLAPSE AT FLOUR MILL.

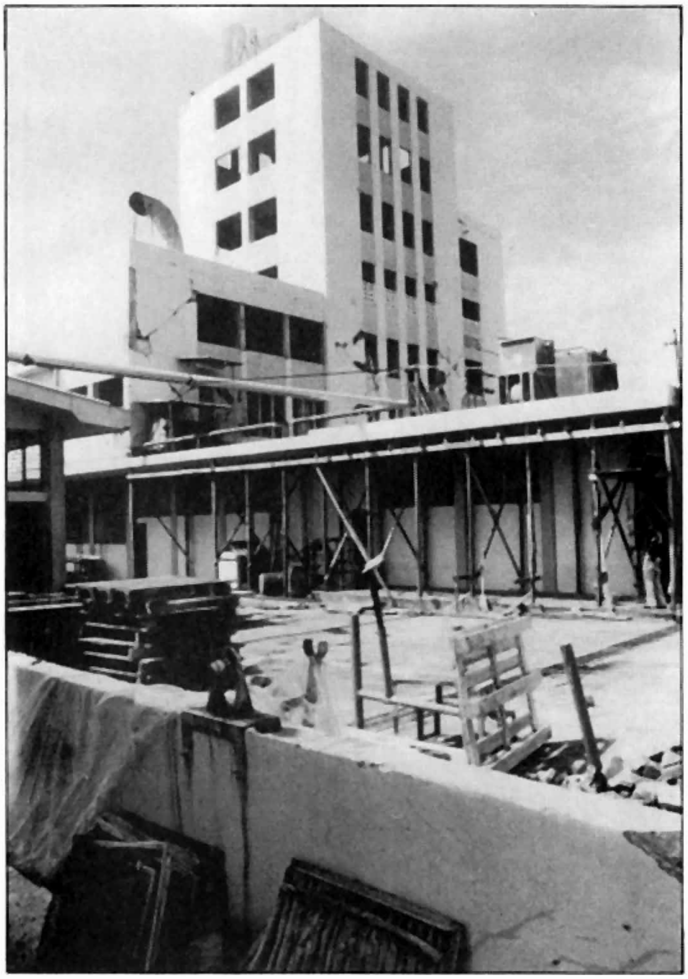


PLATE 33: UNISOLA TOWER

PLATE 34: BANK FAILURE AT EL DORADO PLANT.

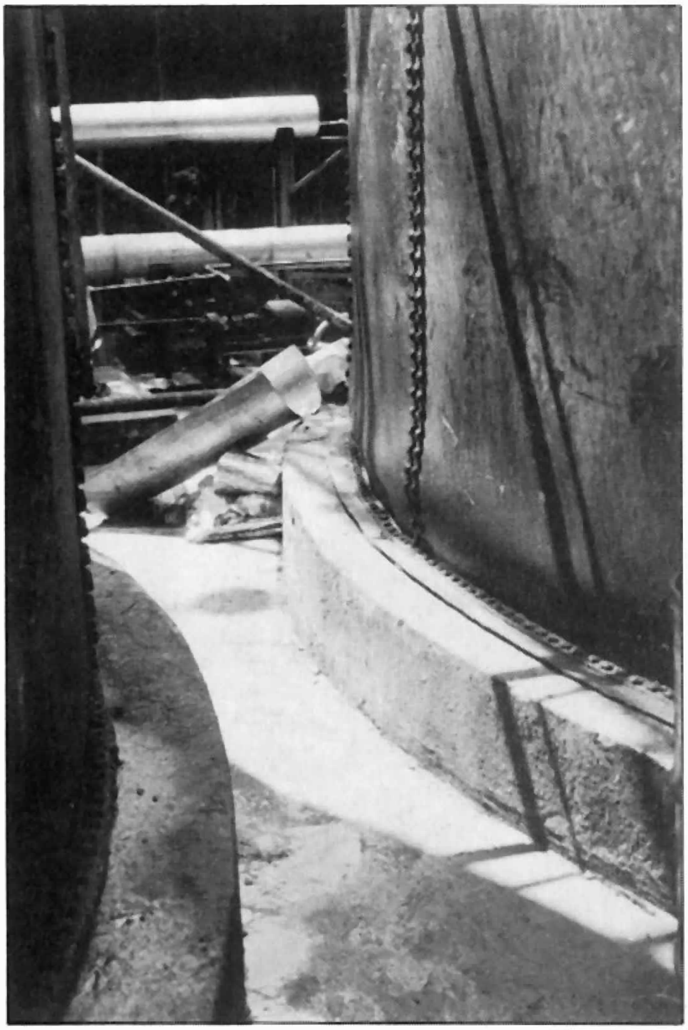


PLATE 35: DAMAGE TO TANK AT EL DORADO PLANT.

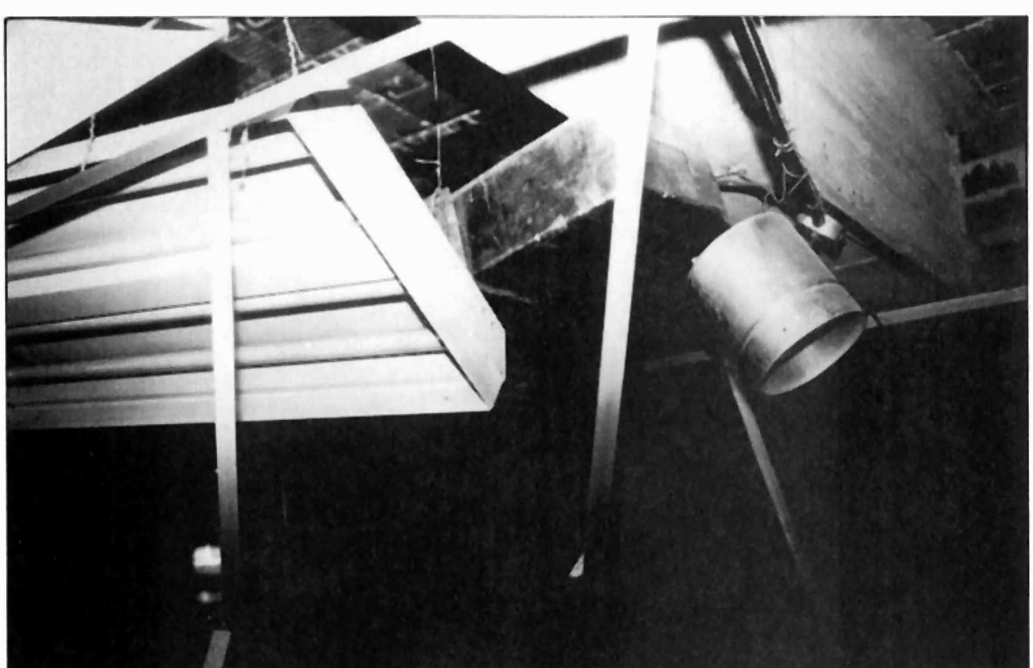


PLATE 36: FAILURE OF SUSPENDED CEILING.

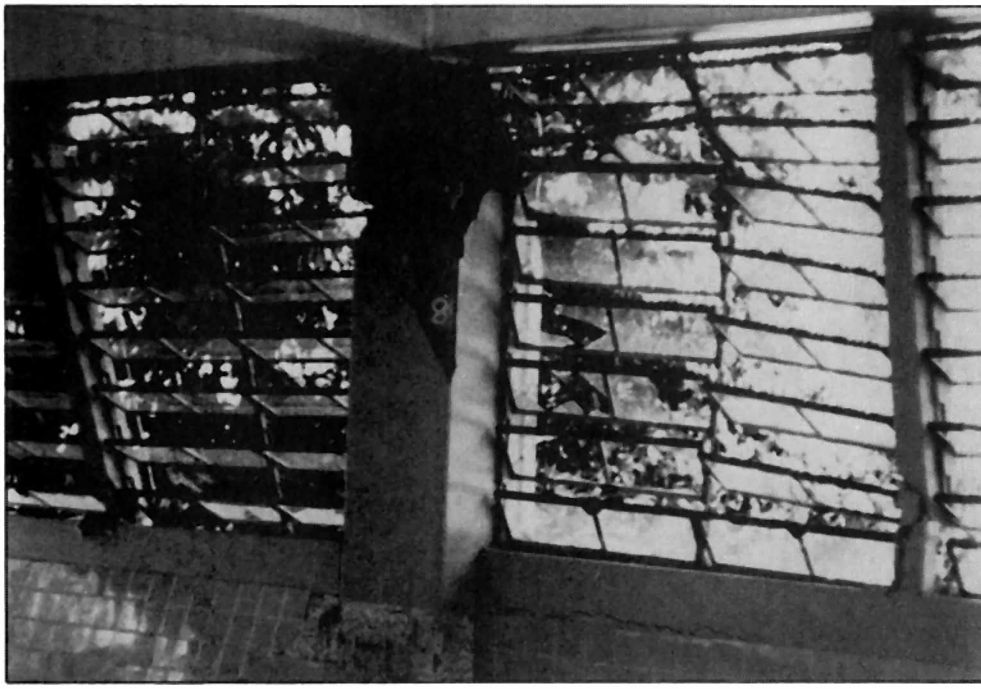


PLATE 37 : TYPICAL WINDOW DETAIL.

PLATE 38 : DAMAGED BRIDGE IN MEJICANOS.

PLATE 39 : DAMAGE TO ROAD CAUSED BY SLOPE FAILURE

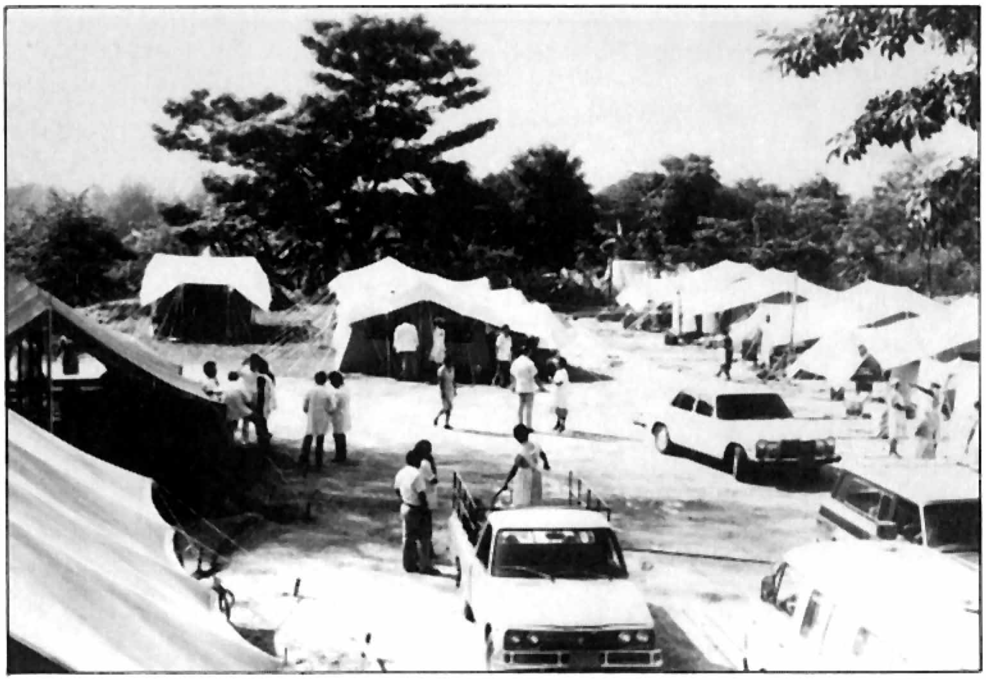


PLATE 40 : FIELD HOSPITAL AT HOSPITAL BENJAMIN BLOOM.

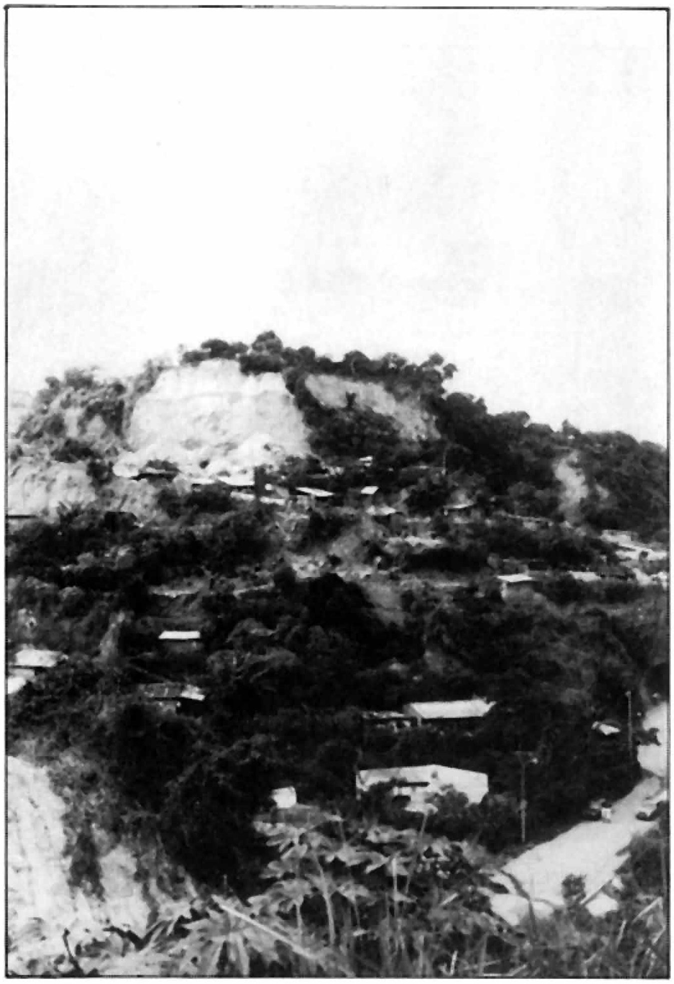


PLATE 41 : HOUSING ON STEEP SLOPES IN SOUTHERN DISTRICTS OF SAN SALVADOR.

PLATE 42 : BAHAREQUE HOUSE.

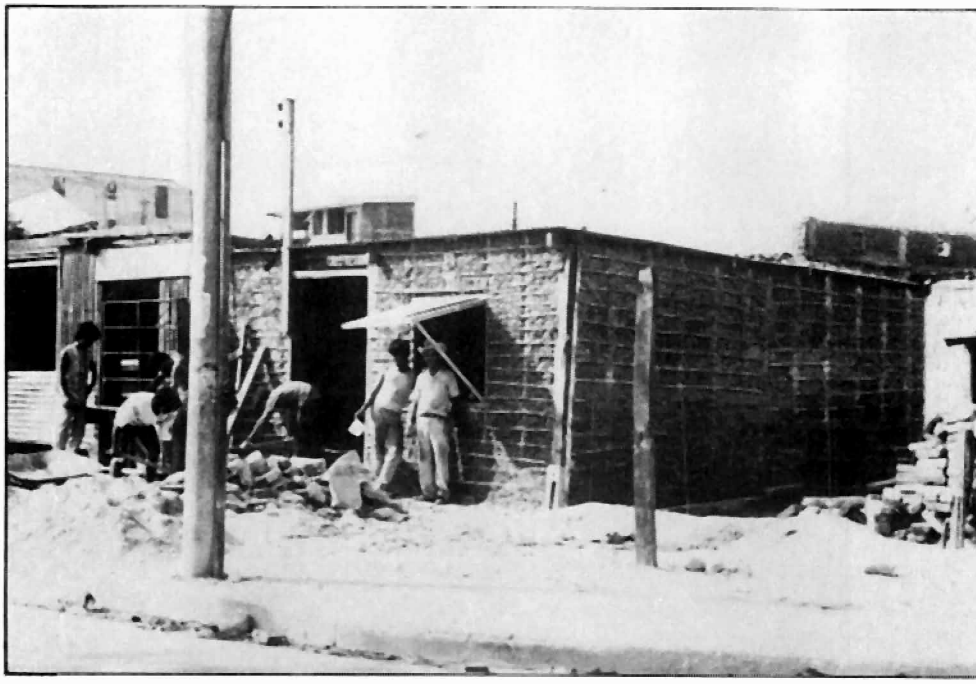


PLATE 43: BAHAREQUE HOUSE, REBUILT WITHIN THREE WEEKS OF EARTHQUAKE.

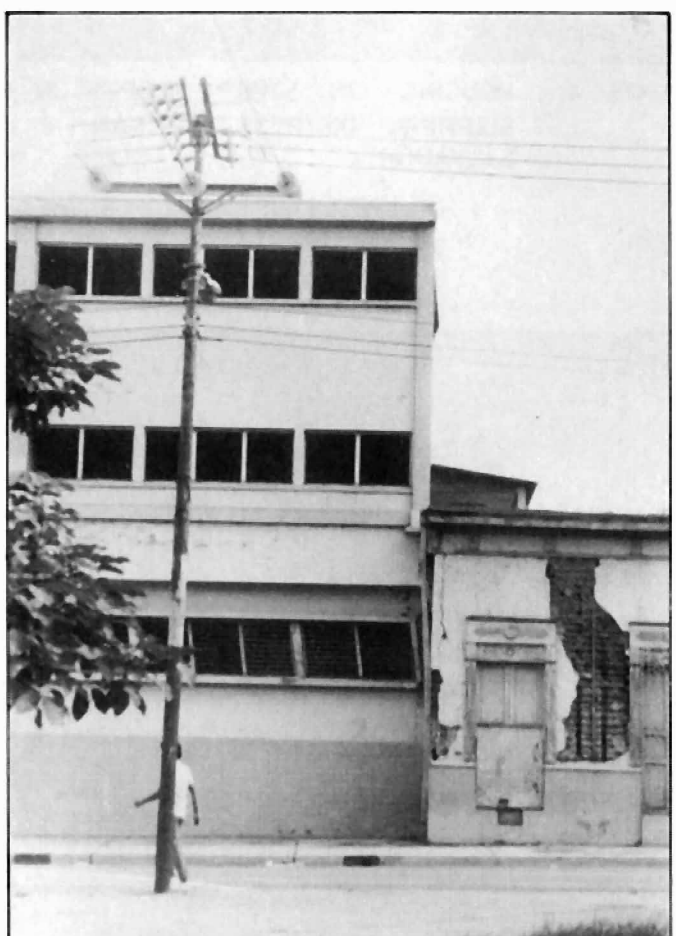


PLATE 44: UNDAMAGED BAHAREQUE HOUSE NEXT TO DAMAGED REINFORCED CONCRETE BUILDING.

PLATE 45: TIMBER FRAMED BUILDING, WITH BAHAREQUE WALLS

PLATE 46: TEMPORARY SHELTER ERECTED IN STREETS