The San Salvador earthquake of 10th October 1986

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The authors carried out an investigative mission to San Salvador between 20th October and 3rd November 1986, under the auspices of the Earthquake Engineering Field Investigation Team (EEFIT). The mission was funded by Rendel Palmer & Tritton and the Science and Engineering Research Council.

THE SEISMICITY OF EL SALVADOR

The republic of El Salvador lies on the Pacific Coast of the isthmus of Central America, bordered by Honduras and Guatemala, forming part of the so-called "ring of fire," the zones of earthquake and volcano activity that encircle the Pacific Ocean. El Salvador is adjacent to the mid-America trench, a subduction zone where the Caribbean Plate overrides the Cocos Plate. Four distinct bands of seismicity have been identified that affect El Salvador; three of these are located in the Cocos Plate situated 20—30, 60 and 120 km offshore. The first of these is the source of 90% of the earthquakes that are felt in El Salvador. The fourth zone of seismic activity, and the one that produces the most damaging earthquakes, is located onshore running parallel with the chain of young volcanoes that passes through El Salvador and Nicaragua. The earthquakes that occur in this zone tend to be of intermediate magnitude and of shallow focal depth. This seismic zone also gave rise to the earthquake that destroyed Managua, Nicaragua in December 1972.

San Salvador became the capital of El Salvador in 1538—1539, after the original capital founded by the Spanish, Bermuda, was itself destroyed by an earthquake. The city lies on an erosion surface in an area known locally as the "Valley of the Hammocks." The erosion surface lies at an elevation of between 650 and 750 m above sea level overlooked by the San Salvador Volcano, known as El Boqueron, which stands at 1,967 m above sea level, to the west of the city. To the north are the subdued Cerros de Mariona and to the south the coastal cordillera and the extinct volcano, Cerro de San Jacinto. The erosion surface slopes out to the east to Lake Ilopango which lies at 438 m above sea level (Fig. 1).

Almost the entire area of the capital is overlain by "tierra blanca," a white-yellow volcanic ash which is thought to have its origin in the volcano that is now submerged in Lake Ilopango. This volcano was last active in 1880 when its eruption followed a seismic "swarm" beginning in the previous year. 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 volcanic ash vary between 5 and 20 m in depth. Largely as a result of pumping for the city's supply, the groundwater is now located at depths greater than 80 m, although near Lake Ilopango the level rises almost to the ground surface.

San Salvador has been destroyed by earthquake a number of times in its history. There are historical records of destruction in 1576, 1659, 1798, 1839, 1854, 1873, 1917, 1919 and 1965, and it is possible that very heavy damage also occurred in 1594, 1707, 1719, 1806 and 1815. The earthquakes of 1659 and 1917 were both accompanied by eruptions of El Boqueron. After the earthquake of 1854 an attempt was made to relocate the capital a few kilometres westward at Nueva San Salvador, which exists today as Santa Tecla (Lomnitz and Schulz, 1966).

THE EARTHQUAKE OF 3rd MAY 1965

The earthquake of 3rd May 1965 occurred at 4 a.m. local time, with magnitude $M_S = 6.2$ and with its epicentre located a few kilometres south-east of the city (Fig. 2). The focal depth was of the order of 10—20 km. The earthquake caused significant damage within a radius of about 15 km, resulting in 120 casualties and up to 30,000 people being made homeless. The earthquake was investigated by a UNESCO reconnaisance mission which included E. Rosenblueth of the National University of Mexico (UNAM). Amongst the observations were reports of liquefaction of the soil near Lake Ilopango. There were no accelerographs in San Salvador at the time, but Rosenblueth reported that there was no evidence of significant vertical ground accelerations and subjective reports on the nature of the earthquake made no reference to vertical motion. Based on

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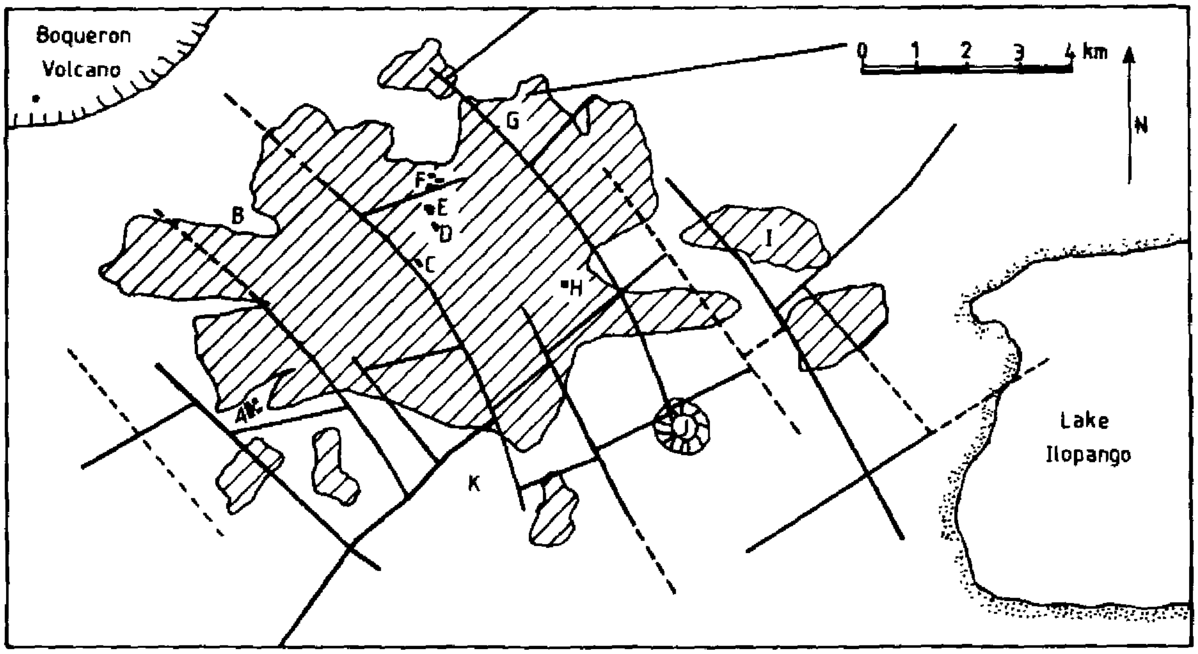

Fig. 1. Geological faults in San Salvador area. ——— fault; - - - - presumed fault; (A) Catholic University; (B) San Antonio Abad; (C) Externado de San Jose; (D) U S. Embassy; (E) Benjamin Bloom Hospital; (F) National University; (G) Mejicanos; (H) La Constancia Brewery; (I) Soyapango; (J) Cerro de San Jacinto; (K) Las Brisas.

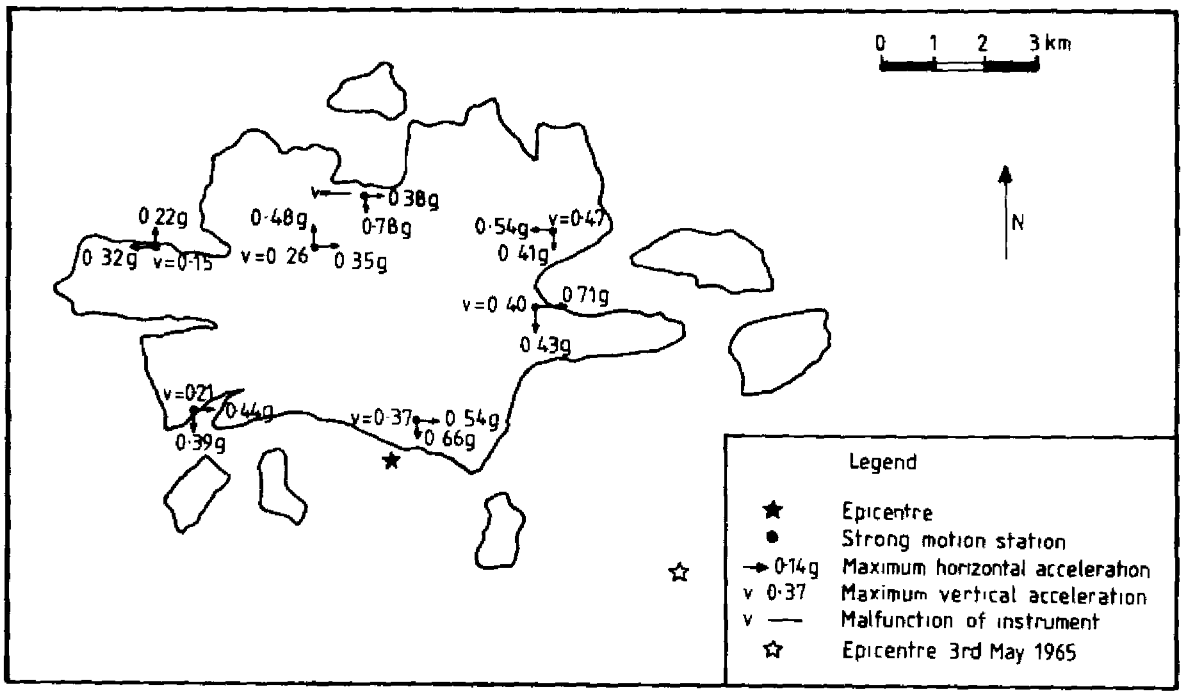

Fig. 2. Peak ground accelerations during 10th October earthquake in San Salvador.

a seismograph record 15 km from the epicentre Rosenblueth estimated a peak ground acceleration of 0.44 g, and from observed displacements of machinery at the Industrias Unidas factory, closer to the epicentre, he estimated peak values of between 0.5 and 0.78 g.

In his report to UNESCO Rosenblueth (1965) proposed a code for earthquake resistant construction in El Salvador. Rosenblueth stated that according to a report on seismological work in El Salvador to the U.S. Coast and Geodetic Survey, in May 1946 a building regulation for earthquake resistant design was about to be adopted, that required the adoption of a horizontal acceleration of 0.2 g. According to Rosenblueth the code was adopted but was never enforced. The code that Rosenblueth proposed in 1965 was essentially that for Acapulco in Mexico. El Salvador was divided into two zones by a line running parallel to the coast, with zone I on the coastal side being of greater seismic hazard.

The code defines three Use Groups for structures depending on their importance and the consequences of their failure, and three types of building depending on structural behaviour under horizontal loading; Type 1 buildings have at least two elements capable of resisting horizontal shear and their deformations under lateral loads are essentially due to flexure in structural members.

The code gives values of the base shear coefficient (the ratio of the horizontal shear force at the base of the building due to earthquake loading to the weight of the building) to be used in the psuedo-static analysis of Group B buildings, which include hotels, apartment and office buildings, industrial buildings and gas stations. These base shear coefficients are shown in Table 1.

For Group A buildings, such as hospitals, fire stations, schools, theatres, telephone exchanges, power stations and pumping stations, the above values of base shear coefficient are increased by a factor of 1.3. For both Group A and Group B buildings a reduction factor of between 1.0 and 0.6 can be applied to the base shear coefficient, depending on the stiffness of the structure; the more flexible the structure the greater the reduction of the base shear.

The base shear coefficient prescribed by the code is the same in all cases within either zone, independent of the local soil profile.

For Group C buildings, which are those whose failure would not normally cause damage to human beings or costly goods or equipment, no earthquake resistant design is required.

Table 1 Base shear co-efficients for Group B buildings

Type of structure	Zone 1	Zone II
1	0.12	0.06
2	0.24	0.12
3	0.30	0.15

The code was adopted in 1966, stating that each new building project or repair of earthquake damaged structures would be required to comply with the regulations before a permit would be granted by the General Director of Architecture and Urbanism. There is little evidence in San Salvador that the code has been enforced, and in many cases where aseismic design features have been considered they have been based on foreign codes, primarily from the U.S.A., rather than on the 1966 regulations for El Salvador.

SEISMOLOGICAL ASPECTS OF THE 1986 EARTHQUAKE

The earthquake of 10th October 1986 occurred at 11.49 a.m. local time with a surface wave magnitude $M_S = 5.4$ and a body wave magnitude $m_b = 5.0$. According to the USGS and Roberto Linares of the Centre for Geotechnical Investigations in San Salvador, the epicentre was located just south of the city, as shown in Fig. 2. The focal depth was about 5 km. The authors' observations suggest a maximum intensity of VIII-IX on the Modified Mercalli Scale. The earthquake was followed by a very large number of aftershocks, including a large tremor on the following day shortly before midnight that caused further damage. Another large aftershock occurred at 5.25 p.m. on 13th October and a strong tremor on 15th January 1987 produced widespread panic in the city but little damage.

It is known that the geology of the San Salvador area is heavily faulted, the predominant trend being north-west to south-east crossed perpendicularly by smaller faults. Figure 1 shows the geological faults identified by a German geological team (Schmidt-Thome, 1975) working in conjunction with El Salvador's National Geographic Institute which produced a geological map of the area on a scale of 1:100,000 in 1978.

It is known that the faults strike steeply, between vertical and 65°, but apart from this relatively little is known about the mechanism of these faults. Some clues to this may be given by a crack in the ground that was observed running along the length of a football pitch in the grounds of the Externado de San Jose. The crack has the same orientation as the fault which, according to the geological map, lies very close to its location; it is unlikely that the crack is a direct surface manifestation of the fault (since the displacements on it reduce to zero at both ends of the pitch), but rather a secondary effect, but the observed displacements of 100 mm vertically and a right lateral horizontal movement of about 30 mm, may nonetheless reflect the displacements on the fault itself. The USGS has reported that the earthquake was recorded at ninety-four seismic stations, so it should be possible to carry out a fault plane solution which would shed further light on the mechanism.

A network of strong-motion instruments exists around San Salvador comprising a total of eleven strong motion accelerographs; two of these machines malfunctioned but nine three-component records of ground acceleration were

Table 2. Comparison of the effects of the San Salvador earthquake of 10th October 1986 with other intermediate magnitude near-field events

Country	Name of earthquake	Date	Time (local)	Magnitude (M)	Distance from epicentre (km)	Number affected (1,000's)	Number of deaths	Number of injured	Number of homeless (1,000's)	Total damage (U.S.$ billions)	GNP/capita (U.S.$)
Yugoslavia	Skopje	26th July 1963	05:17	6.0	0	200	1,070	3,700	50	1.4	177*
El Salvador	San Salvador	3rd May 1965	04:02	6.2	8	325	120	400	30	—	237
U.S.A.	San Fernando	9th February 1971	06:01	6.6	10	1,200	65	2,500	17	1.0	4,794
Nicaragua	Managua	23rd December 1972	00:30	6.2	0	400	15,000	50,000	200	0.7	434
Colombia	Popayan	31st March 1983	08:13	5.5	8½	200	260	2,000	150	0.4	880
U.S.A.	Coalinga	2nd May 1983	16:43	6.5	9	7	0	50	2½	—	13,272
Greece	Kalamata	13th September 1986	20:24	5.7	15	45	20	300	17½	0.3	1,762
El Salvador	San Salvador	10th October 1986	11:49	5.4	2½	1,500	1,500	10,000	300	2.0	372

— Data not available.

*Net material product.

Where reports do not give figures for the number of homeless, the figure has been calculated from the number of destroyed dwellings assuming an average occupancy of 5.5.

The figures for GNP and population are for the same year as the earthquake in question.