Learning from Earthquakes


This report is compiled from observations made by different teams following the earthquakes that struck the Central American republic of El Salvador in January and February 2001. This report was edited jointly by Conrad Paulson and Julian Bommer from the contributions of numerous individuals, as follows:

The first reconnaissance was made by C. Paulson of Wiss, Janney, Elstner Associates, and Larry Hultgren of the U.S. Department of State, who briefly toured the city of San Salvador and nearby suburbs on January 21, 2001.

A second team, which visited El Salvador from January 26 until February 6, was comprised of engineers and geologists from the United Kingdom: J. Bommer (Imperial College), Bill Murphy (University of Leeds) and Joseph Mankelow (British Geological Survey), joined by Carlos Rodríguez (National University of Colombia). This team worked in the field with Patricia Méndez de Hasbun from the Central American University (UCA), Manuel López Menjívar from the University of El Salvador, and Herman Rosa and colleagues from the foundation PRISMA (Salvadorean Programme for Research on Development and Environment).

Mauricio Ciudad Real (Kinemetrics Inc.), former head of the Department of Seismology at the Geotechnical Investigation Center in El Salvador, processed the strong-motion data and assisted with the interpretation of the records.

A third team from the American Society of Civil Engineers-Technical Council on Lifeline Earthquake Engineering (ASCE-TCLEE) Earth-

Figure 1 Epicenters of shallow (upper) and sub-crustal (lower) earthquakes of magnitude 5.0 and above in the region of El Salvador, indicating main tectonic features and the locations of active volcanoes. (Bommer et al., 1997)
The Earthquake Investigation Committee performed a preliminary reconnaissance survey of the performance of lifelines during the period from February 25 to March 3, 2001. The field investigation team consisted of Le Val Lund, Civil Engineer, Field Leader; Michael Salmon, Los Alamos National Laboratory, Assistant Field Leader; Rossana D’Antonio, Los Angeles County Department of Public Works; Robert Lo, Klohn Crippen; and Mario Velado, Caltrans. Carl Sepponen, Nolte Associates, was the Administrative Leader.

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Introduction

The earthquake of January 13, 2001, was the fifth destructive event to hit El Salvador in a period of 50 years, starting with a sequence of three upper-crustal earthquakes in May 1951 that destroyed towns in the east of the country and killed 400 people (Ambraseys et al., 2001). The January 2001 earthquake caused approximately 800 deaths, the majority due to the effects of landslides. Exactly one month after the first earthquake, on February 13, 2001, a second earthquake struck, adding more than 300 to the death toll, again due to landslides and also the collapse of weak houses in the epicentral region. The earthquakes have caused very heavy disruption and economic losses — estimated at US$1.6 billion — with almost 80% of this loss being due to the January event. The most serious social impact of the earthquakes, whose effects on the country will be far reaching, has been to leave 1.5 million people, one quarter of the population, homeless.

Geographical and Seismic Setting

El Salvador is the smallest of the Central American republics, having a geographical extent just less than 21,000 km². The population, estimated at about 6 million, is very unevenly distributed throughout the country, with well over half the population concentrated in the southwest third, also the zone of highest seismic hazard.

The seismicity of El Salvador is dominated by the subduction of the Cocos plate below the Caribbean plate in the Middle America Trench at a rate of about 7 cm/year (Figure 1). This process gives rise to two main sources of seismicity, the first being earthquakes in Benioff-Wadati zones within the subducted Cocos plate, which can reach large magnitudes. The second source of seismic activity is within the chain of Quaternary volcanoes that extends from Guatemala to Costa Rica, where shallow focus earthquakes of moderate magnitude occur. These upper-crustal earthquakes are generally tectonic rather than volcanic in origin, probably generated by an oblique component of the tectonic convergence between the Cocos and Caribbean plates (White, 1991).

Shallow focus earthquakes, generally not much greater than magnitude 6, have previously caused much greater damage and loss of life in El Salvador, and in neighboring Nicaragua, than the larger earthquakes in the subduction zone (White and Harlow, 1993). Destructive upper-crustal earthquakes struck the capital city, San Salvador, in May 1965 and October 1986, causing death tolls of 120 and 1,500, respectively (EERI, 1987). On June 19, 1982, a subduction...
Table 1. Source parameters for the main shocks of the earthquake series.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Epicentre N°</th>
<th>Epicentre W°</th>
<th>Depth (km)</th>
<th>Magnitude</th>
<th>Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 13, 2001</td>
<td>17:33:30</td>
<td>13.063</td>
<td>89.787</td>
<td>39</td>
<td>7.7 Mw</td>
<td>NEIC</td>
</tr>
<tr>
<td>January 13, 2001</td>
<td>17:33:30</td>
<td>12.868</td>
<td>88.767</td>
<td>60</td>
<td>7.7 Mw</td>
<td>CASC</td>
</tr>
<tr>
<td>February 13, 2001</td>
<td>14:22:05</td>
<td>13.613</td>
<td>89.069</td>
<td>13</td>
<td>6.6 Mw</td>
<td>NEIC</td>
</tr>
<tr>
<td>February 17, 2001</td>
<td>20:25:</td>
<td>13.660</td>
<td>89.248</td>
<td>5</td>
<td>5.1 ML</td>
<td>CIG</td>
</tr>
</tbody>
</table>

Earthquake Characteristics and Strong-Motion

The earthquake struck at approximately 11:30 am local time on Saturday, January 13. The earthquake was located in the subduction zone offshore from El Salvador (Figure 2), within the subducted Cocos plate, with a focal depth estimated at 40-60 km. The magnitude of the earthquake has been determined as Ms 7.6 and Mw 7.7, making it larger than any earthquake in El Salvador during the twentieth century (Ambraseys and Adams, 2001).

The earthquake was followed by a series of aftershocks, many with magnitude greater than 5, which gradually decreased in frequency during the month following the earthquake. The second earthquake of February 13, which was of magnitude Ms 6.6, was centered to the southeast of the capital San Salvador. This second event caused additional damage and added almost 300 casualties to the death toll of almost 800 from the first earthquake. The February earthquake was not an aftershock of the January event, having a different focal mechanism (Figure 2) and a much shallower focal depth (estimates range from 13 to 30 km). Thus, it occurred within the overriding Caribbean plate as opposed to the subducted Cocos plate. The distribution of aftershock epicenters following the February event strongly favor an east-west trending, right-lateral fault rupture. This intraplate earthquake is likely to have occurred in response to complicated stresses in the Caribbean plate as it overrides the Cocos plate.

A third earthquake occurred on February 17 on the western outskirts of San Salvador; this event was of much smaller magnitude (Ms 5.1), but was of very shallow focal depth. Due to its proximity to the city, it caused widespread panic as well as some minor structural damage. The source parameters of the three earthquakes are given in Table 1.

The main shock of January 13 was recorded by a digital accelerograph network installed in El Salvador in 1996 (Bommer et al., 1997). The locations of the instruments are indicated in Figure 3; two of the ten accelerographs in this network did not record the main event due to malfunction, but eight records were obtained. In addition to these, a record from another SSA-2 instrument installed at the geothermal energy plant in Berlín, in eastern El Salvador, was also kindly made available by the energy company GESAL. The peak recorded values of ground acceleration, some of which appear disproportionately high, are shown in Table 2. Two examples of the strong-motion records, from a station on the coast at the port of La Libertad — the closest station to the assumed location of the fault rupture — and another from the town of San Pedro Nonualco, located southwest of the capital on a ridge, are shown in Figures 4 and 5, and their respective response spectra in Figures 6 and 7. The recorded motions are of surprisingly high frequency for such a large magnitude event, with very large peak accelerations and a rapid decrease of spectral ordinates with increasing period.

Figure 3 Locations of the strong-motion instruments. (Mankelow)
Table 2. Recorded values of peak ground acceleration, PGA, in the January 13 earthquake.

<table>
<thead>
<tr>
<th>STATION</th>
<th>COORDINATES</th>
<th>PGA (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>W</td>
</tr>
<tr>
<td>ULLB</td>
<td>13.468°</td>
<td>89.327°</td>
</tr>
<tr>
<td>UARM</td>
<td>13.744°</td>
<td>89.501°</td>
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<td>HSRF</td>
<td>13.671°</td>
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<td>UPAN</td>
<td>13.614°</td>
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<td>USPN</td>
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<td>89.927°</td>
</tr>
<tr>
<td>CSBR</td>
<td>13.705°</td>
<td>89.106°</td>
</tr>
<tr>
<td>ESJO</td>
<td>13.707°</td>
<td>89.207°</td>
</tr>
<tr>
<td>UTON</td>
<td>13.778°</td>
<td>89.114°</td>
</tr>
<tr>
<td>Berlin</td>
<td>13.50°</td>
<td>88.53°</td>
</tr>
</tbody>
</table>


Figure 4  Strong-motion accelerogram from La Libertad station. (Bommer)

Figure 5  Strong-motion accelerogram from San Pedro Nonualco station. (Bommer)

Figure 6  Horizontal response spectra (5% damped) from La Libertad station. (Bommer)

Figure 7  Horizontal response spectra (5% damped) from San Pedro Nonualco station. (Bommer)
The earthquake of February 13 was also recorded by several of the stations in the TALULIN network. Reported values, which have yet to be checked and verified, indicate horizontal PGA values of the order of 0.4g at both HSGT (San Vicente) and HSTR (Zacatecoluca), neither of which recorded the January 13 event. Reported values of PGA from the February 17 event, again as yet not verified as genuine, have been reported as being of the order of 0.1g at the ESJO station in San Salvador.

Buildings

Surprisingly, despite the very high accelerations, structural damage to engineered structures was very limited. Architectural damage, however, was widespread, even in engineered structures.

The most significant structural damage was mainly encountered in adobe (clay brick) houses (Figures 8 and 9). Damage was generally higher in rural areas, where vulnerability is greater, and in towns and villages located on ridges or slopes. There were also many cases of damage, including total collapse, in bahareque houses, which are made from timber vertical members, bamboo horizontals (which are either stems of bamboo or a plant called "vara de castilla"), infilled with mud and covered with stucco (Figure 10). Roofs on these houses are typically light gage corrugated steel. Bahareque construction generally displays good seismic resistance when the structure is newly constructed, but the tropical climate and insects rapidly deteriorate the building materials, causing vulnerability to increase with age.

In San Salvador, residential structures are typically one- or two-story masonry buildings of modern design and materials. Systematic examination of houses in San Salvador was impossible due the ever-present tall, solid masonry security fence around each property, which blocked direct visual observation of houses from the street. However, some feel for seismic performance for this class of structures was achieved through invited inspections of some residential properties.

Overall, it appears that the more modern residential construction found in San Salvador fared much better than the traditional construction in the rural areas. A low percentage of modern housing, less than 10%, suffered observable structural damage, and perhaps less than 1% suffered major damage. Where major damage was observed in San Salvador, it could be attributed to well-known seismic structural design and construction concerns such as: a second-floor shear wall supported only by short piers on the first floor; non-ductile detailing of reinforcement in concrete construction; structures sited on poor soil; and structures only cosmetically repaired after the 1986 earthquake.

As mentioned previously, the structural systems of engineered struc-

Figure 8 Damaged adobe house in Santiago de María. (Bommer)

Figure 9 Collapsed adobe house in Canton La Concordia, near Jiquilisco. (PRISMA)
tures generally faired extremely well. Where structural damage was noted, it could generally be attributed to well-known structural configuration or detailing issues. For example, the structure shown in Figure 11 is comprised of two separate structural towers, both of which were slightly damaged due to pounding. The expansion joint between the two structural units obviously could not accommodate the seismic movements imparted by the January 2001 event.

Figure 10 Partially collapsed baha-reque house in Armenia. (Bommer)

Figure 11 Pounding damage and loss of roof support at upper levels of mid-rise structure. (Paulson)

Significant isolation joints (25 mm and larger) were frequently provided at the ends of wall segments, which effectively separate the walls from vertical structural elements. The isolation joints typically allowed for enough structural movement to prevent structural damage due to “captured column” or other adverse structural effects related to restraint of structural movement. However, the details at the tops of the exterior cladding walls and interior partitions typically provided for little or no relative movement between wall and structure. This caused significant architectural damage when inter-story structural drift was imposed onto the non-structural interior partitions and exterior walls.

One example of these conditions is illustrated by the San Salvador mid-rise shown in Figure 12. A walk-through of several levels of

Figure 12 Mid-rise concrete frame structure in San Salvador. (Paulson)

Damage to architectural elements, such as facade walls and interior partitions, was widespread in mid- and high-rise structures throughout the city of San Salvador. The structures are typically of recent (post-1986 earthquake) construction and have been built with modern seismic lateral load-resisting systems of good engineering and good construction. The exterior walls and interior partitions are typically of concrete masonry unit (CMU) construction with plaster or stucco coating.

Figure 13 Damaged glass, stucco and CMU on exterior wall of structure shown in Figure 12. (Paulson)
this building revealed no observable damage to the reinforced concrete moment frame system, which was generally exposed to direct examination throughout the building. However, window glass, plaster and CMU block suffered significant damage at exterior walls (Figure 13) and also at interior partitions (Figure 14). This particular building also suffered damage to electrical system components that rigidly crossed structural movement joints. These are not isolated instances of damage, but instead are typical examples of widespread damage throughout this particular building. Similar conditions were encountered elsewhere, such as in the steel-framed high-rise shown in Figure 15. In addition to the obvious sliding damage to the exterior walls at each floor line, sheets of stucco have become delaminated from the walls at numerous locations, posing a significant falling hazard. Interior CMU partitions typically exhibited sliding damage at bed joints within the mid-height of the walls.

Low-rise engineered construction also exhibited architectural damage in some instances. The commercial structure shown in Figure 16 is a reinforced concrete frame structure on a sloping site with two stories above ground plus lower-level parking. A cursory walk-through of the parking area revealed only minor cracking in structural concrete elements. The exterior enclosure walls are CMU construction and were apparently not isolated from structural movement, as evidenced by the classic diagonal “X-crack” damage seen in the photograph.

Unusual damage was observed in the low-rise structure seen in Figure 17, illustrating an extreme example of facade damage. It appears that the roof of this structure collapsed,
It has been noted previously that the ground motions produced by subduction earthquakes in El Salvador are generally not damaging to engineered structures, and it is believed that this is due to the fact that the rate of energy input is relatively low. Recordings of the 1982 subduction earthquake obtained in San Salvador had almost exactly the same total Arias intensity (integral of the square of the acceleration) as the records from the local earthquake (Mw 5.7) on October 10, 1986. The motions in the latter case were so much more destructive because of the much shorter duration of the shaking, whereby the same amount of energy was imparted to structures over three seconds as compared with 30 seconds in the case of the subduction event. However, for brittle materials with low initial strength and strongly degrading dynamic response characteristics, such as adobe, the total energy of the shaking seems to be the most important parameter in controlling the overall level of damage. It has also been found that the total Arias intensity is a good indication of the capacity of the ground motion to trigger landslides (Harper and Wilson, 1995).

**Landslides**

The main impact of the January earthquake, in terms of death toll and disruption, was the very large number of landslides triggered by the earthquake, including the infamous case of the debris flow at Las Colinas in Santa Tecla, just to the west of San Salvador. This catastrophic slope failure buried as many as 500 people (Figure 18), and as many as 105 died in another landslide at nearby Las Barrioleras.

Landslides of similar size occurred in many locations and caused great destruction. They also blocked many roads, which hindered emergency response and recovery. A huge slide on the Pan-American Highway at Las Leonas completely blocked this important transportation route for several weeks (Figure 19) and buried several vehicles and their occupants. Hill slopes in the area west of San Salvador showed numerous debris flow failures that are the subject of ongoing investigation.

Smaller landslides also occurred in great numbers, often in near-vertical slopes that exist as a combined result of weak cementation and high negative pore pressure (Bommer et al., 1998). Although these falls were generally small, they frequently produced significant damage as a result of the density of settlement (Figure 20).

Landslides were triggered across most of the southern half of El Salvador, with a particularly high concentration in the Cordillera del Balsamo to the southwest of San Salvador, affecting a much larger area than in previous earthquakes, including the June 1982 earthquake (Bommer and Rodríguez, 2001).
Numerous instances of slope instability were observed on the volcanoes distributed along the central valley that runs from west to east across El Salvador, affecting many coffee plantations on steep slopes. The earthquake occurred during the coffee harvesting period and a number of pickers were buried by these slides.

Landslides mostly occurred in ashes, tuffs, and tephras of the Pleistocene and Holocene San Salvador Formation, originating from volcanic eruptions of the San Salvador volcano to the west of the capital and Lake Ilopango to the east, as well as other volcanic centers along the Central Valley. The ash deposits are poorly consolidated silty sands and sandy silts.

There were occasional rockfalls and rockslides, particularly along the coastal road. Liquefaction and lateral spreading were encountered near the coast in a number of locations, on the shores of Lake Ilopango and also at some locations on the banks of the Rio Lempa (Figure 21).

It is interesting to note that the high risk of landslide hazard was appreciated in El Salvador, and although it is possible that the extraordinary number of landslides may not have been expected, landslide hazard maps had been prepared previously. One of these, prepared in 1997 by OPAMSS, the regional planning office for the capital, identified the area including Las Colinas as a zone of high landslide hazard.

**Lifelines**

In general, lifelines performed well in the capital city of San Salvador. The urban lifelines performed well, due particularly to the lessons learned from the 1986 earthquake and the need of the country to adapt to the hardships endured during the 1977-1992 civil war. The performance of lifelines in the rural areas and villages was very poor. The estimated cost of lifeline damage, in millions of dollars, is as follows:

- **Transportation**: $432.8
- **Water**: 23.1
- **Electric Power**: 16.4

Most agencies or companies responsible for lifelines appeared not to have any formal emergency response plans, although generally they respond to emergencies on a routine basis. As a rule, the unavailability of system maps handicapped their response and investigation.

**Communications:** In general, the telephone systems performed well following the earthquakes. General telephone service in the undamaged areas around San Salvador was restored within one day. The telephone companies reported heavy congestion because of system overload following the earthquakes, which is common following large earthquakes. It was reported that wire, fiber optic, repeater, and satellite facilities worked well in both earthquakes. The good performance of the systems has been attributed to their redundancy.

**Power:** It was reported that the electric power service performed...
well, with outages from a few hours to a day or two, except to those areas with significant structural damage. There was no reported major damage to the generating and primary transmission systems themselves. The companies that distribute electricity locally in the country reported a substantial loss of customer base due to the large amount of housing damage. They also reported significant damage to overhead distribution lines and transformers from landslides, falling structures and falling trees, and they reported foundation failures affecting the supporting concrete poles.

**Water and wastewater:** The operation of the water and wastewater systems in El Salvador is under the jurisdiction of Administración Nacional de Acueductos y Alcantarillados (ANDA). Since the wells and pumping plants did not have emergency generators, loss of commercial power affected their operation for approximately one day.

The Cacahuatí Treatment Plant, a source of potable water for the San Vicente area, suffered damage from the February 2001 earthquake. The treatment plant is located approximately 30 km from the epicenter. Authorities estimated that it would take two to three months to repair damaged or destroyed piping, chlorination facilities, retaining walls, basins, and bridge and electrical facilities at the plant. The damaged access road and a nearby pumping plant also required repair. Until repairs were complete, the communities served by the treatment plan were relying on tanker trucks for potable water.

In the San Salvador area, ANDA reported only three pipeline repairs on their Zona Norte (north zone) supply line. This line is a well water supply line installed in 1999, a 1,215-mm (48-inch) diameter bell and spigot, cement-mortar-lined, ductile iron pipe. It was reported that the bolts became loose on the mechanical fittings that secure the joints between lengths of pipe, causing the failures. A parallel, 1,215-mm (48-inch) spiral-welded steel pipeline, installed in 1977, was undamaged and was used as a bypass to facilitate repairs to the 1999 pipeline.

A limited inspection was made of water storage reservoirs. There was no damage to reinforced concrete post-tensioned tanks. However, it was reported that several brick-and-concrete-block tanks were severely damaged and probably will be replaced. Some of the tanks were partially full, because of the lack of water, and may not have been subjected a normal full-tank seismic loading.

Water authorities visually inspected the wastewater system in San Salvador at critical points. No damage has been reported.

**Transportation**

**Highways:** Highway CA1 (Carretera Panamericana, or the Pan American Highway) is the main highway and runs the length of El Salvador. It is used for transporting and distributing the majority of the country's commercial goods and passenger traffic. Landslides blocked this highway in a number of locations, resulting in detours and complete closure of the highway. In the Los Chorros Canyons, a series of landslides blocked a 7-km (4.3-mile) stretch of highway, requiring one-way traffic between designated hours.

The highway itself incurred minor damage, with the exception of a blocked culvert, but the instability of the slopes adjacent to the roadway prevents the normal operation of the highway. It was also closed at Las
Leonas, east of San Salvador, seen in Figure 19. At the time of the lifelines team investigation, excavation to remove the slide had been halted due to the instability of the mountainside, which had slid twice. Effective slope stabilization measures have to be completed before cleanup and rehabilitation of the highway can be continued. Highway CA2, the coastal highway, also was affected by landslides (Figure 22).

The Comalapa Highway, a divided highway from San Salvador to the El Salvador International Airport, suffered circumferential cracks at five sites on the outer side of the roadway along a hillside location. Core samples had been taken and observation wells installed to monitor the roadway. The situation required the shifting of traffic to two-way traffic on the inner side of the highway.

There was no reported damage to highway bridges, other than some settlement at the abutments and some shear key damage, which are typically expected.

**Airport:** The El Salvador International Airport (Aeropuerto Internacional El Salvador) was closed for one day after the earthquake to permit inspection of the runways and the terminals. At the east end of the runway a cold joint separated and other transverse cracks appeared. A contractor repaired the cracks and the runway was returned to service in one day.

Airport terminal damage included the popping out of control tower windows; cracking of reinforced concrete walls, columns, and beams in the older portion of the terminal building; nonstructural wall damage; and loss of suspended ceilings in both the older and newer parts of the terminal. The airport was returned to service after a simple cleanup of debris, even though not all repairs had been made. The airport performed a major role in providing international emergency response and materials following the earthquakes.

**Railroad:** There are three major railroad lines in the country, one from the west, one from the east and one from the north, all of which converge in San Salvador. Prior to the January 13 earthquake, the east line was not in operation. One railroad bridge on this line, a steel arch truss across the Rio Lempa south of San Salvador, collapsed. Otherwise, there was no reported major damage to the railroad.

**Ports:** The major port facility of Puerto de Acajutla was unaffected by the earthquakes.

**Conclusions**

The majority of the deaths, injuries, and financial loss in both earthquakes can be attributed to earthquake-induced landslides and the collapse of poorly constructed houses, particularly in the rural areas of the country.

Notwithstanding the earthquakes’ occurrence in the dry season, the landslides had very severe impacts.

This points up the effects of uncontrolled urbanization, inappropriate land use, and deforestation, especially when the landslides are compared with those triggered by the 1982 earthquake. When the rainy season begins in May, there are fears that many more landslides will be triggered that will cause additional destruction and loss of life. In September 1982, three months after the previous major subduction earthquake, four days of sustained rainfall led to a mudflow on the slopes of the San Salvador volcano that buried more than 500 people.

El Salvador faces a very severe problem since effective mitigation of the landslide hazard may require strict control on land use, particularly in the heavily populated southwest third of the nation. Scientific studies are required to identify those slopes that can be stabilized and those near to which urbanization must be restricted. Existing planning authorities need to be strengthened to implement such policies effectively; some have characterized the current situation, with respect to both land use planning and building code enforcement, as one of “institutional vulnerability.”

*Figure 22 Landslide on the coastal highway CA2. (Lund)*
Adobe and bahareque housing, which predominate in rural areas, generally performed very poorly. Simple, inexpensive measures are urgently required to increase the resistance of these types of dwellings. In contrast, one- and two-story modern masonry construction in San Salvador generally performed well.

The structural systems for engineered structures constructed after the 1986 earthquake generally performed well in the earthquakes. However, architectural and nonstructural elements suffered significant damage, even in post-1986 engineered structures. This damage was a particular problem with mid- and high-rise structures, and resulted in significant disruption to use of this class of structures.

There is concern that non-engineered and pre-1986 structures may have been weakened sufficiently to be susceptible in future shallow-focus earthquakes.

Lifeline facilities in San Salvador performed generally well, with only minor repairable damage and outages. However, in rural areas of high ground-shaking intensity, lifelines suffered a great deal of damage. Water distribution was particularly affected.

Civil and geotechnical investigations need to be made on the cut, fill, and natural slopes of the highways and hillside pipeline locations to determine safety of the sites. Cracking at the top of slopes was observed adjacent to critical lifeline facilities. Investigations are also needed to provide more comprehensive engineering characterization of the volcanic soils, which exhibit a very brittle behaviour.

Although lifeline agencies have in the past responded to emergency situations, there is a need to develop and practice formal emergency response and recovery plans. Such plans should include the government and private sectors as partners. This partnership would make such emergency plans effective as all roles would be defined beforehand to avoid bureaucratic delays.

Acknowledgments

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References


