Berlin

Berlin is located in Usulutan. The National Emergency Committee (COEN) reported 3,155 destroyed dwellings and 3,216 damaged dwellings there. The damage observed was similar to the damage observed in San Agustin (**Figures 3.28** to **3.31**).

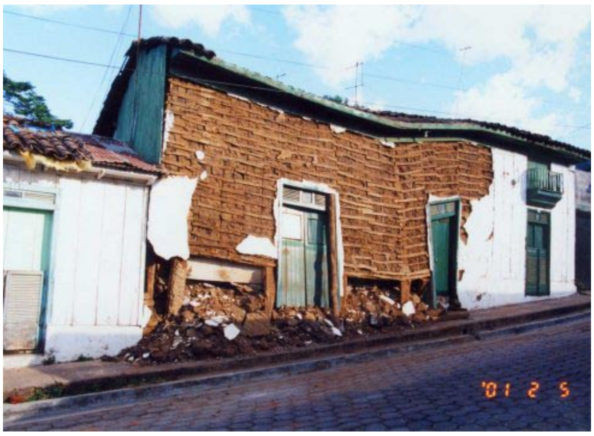


Figure 3.28. Damaged bahareque house with very poor foundation.

Figure 3.29. Bahareque house that suffered mud cover spalling.

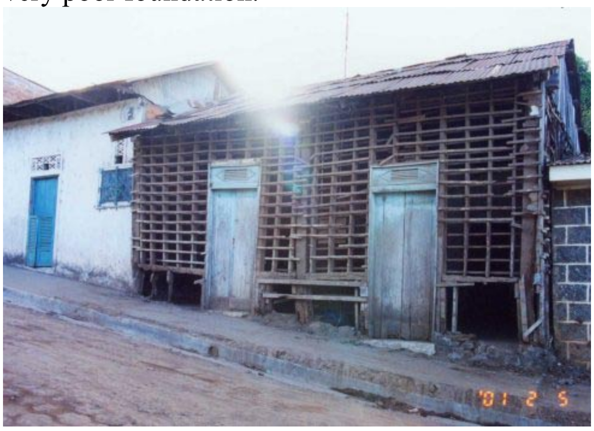


Figure 3.30. Bahareque house that lost all its mud walls.

Figure 3.31. Bahareque house exhibiting mud cover spalling and vertical cracking at the connection between two perpendicular walls.

Microtremors were measured at the Explotation Station (88°30.69W, 13°30.75N) and at Berlin (88°31.70W, 13°29.40N) where the PGA of the January 13th event was around 200gals as mentioned in **Chapter 1**. **Figure 3.32** and **3.33** show the Fourier Spectra for each of the recorded components. The Fourier Spectra was calculated by averaging the spectra of four windows (blue lines). The averaged spectra are shown in a thick red line. The ratio of the horizontal component spectra to the vertical component spectra (H/V ratio) was calculated in order to get the predominant period of the site [Nakamura, Y., 1989]. The H/V ratio is fairly flat which might indicate the rocky nature of the site. On the other hand, at Explotation Station, a peak can be identified at 15-18Hz, which corresponds to a very stiff soil.

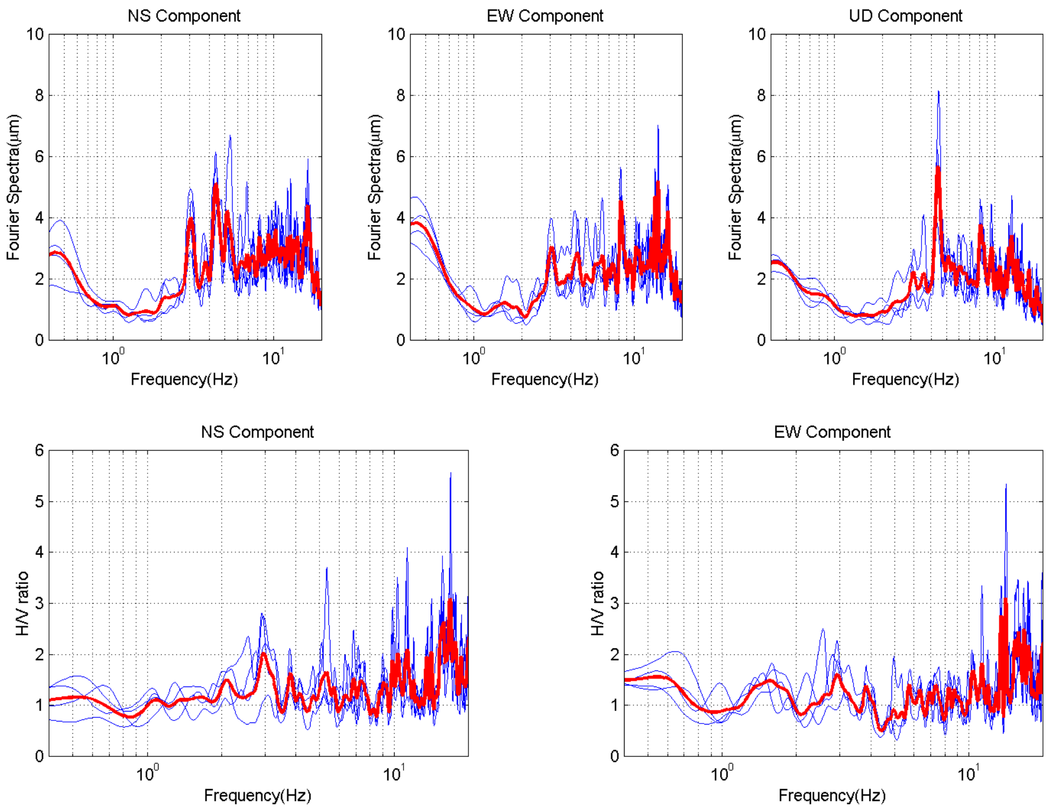


Figure 3.32. Microtremor measurements at Explotacion Station

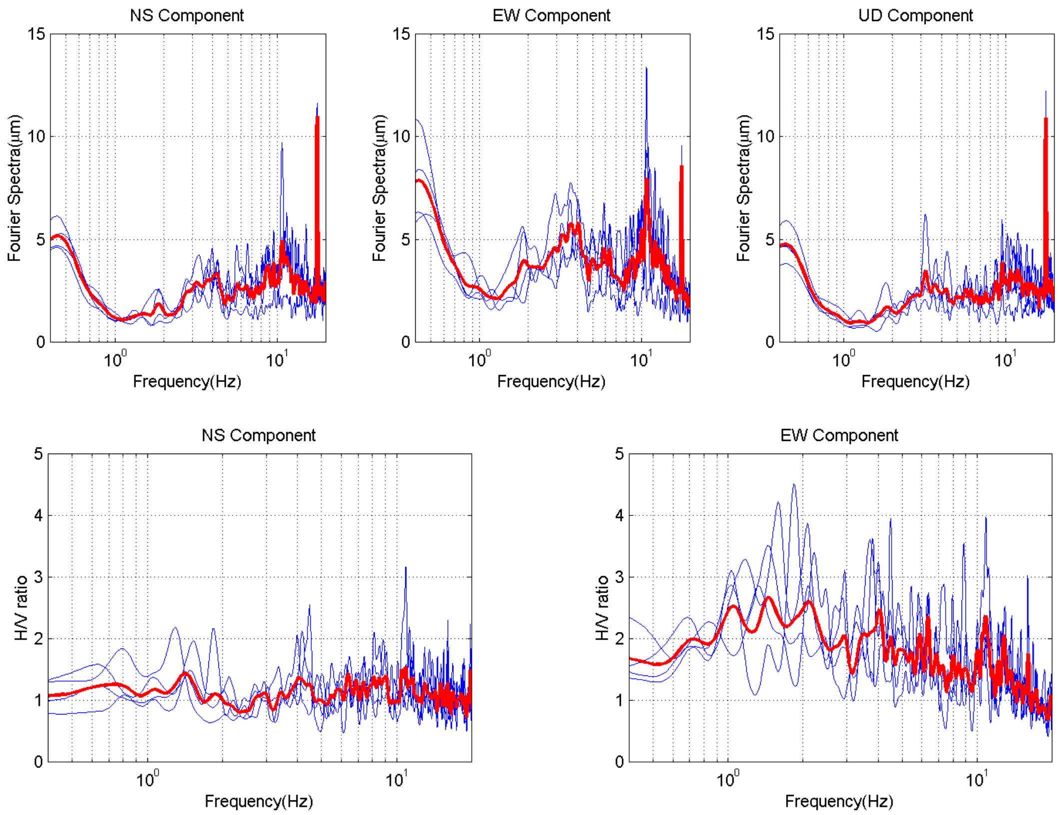


Figure 3.33. Microtremor measurements at Berlin

Santiago de Maria

The National Emergency Committee (COEN) reported 1,116 and 950 destroyed and damaged dwellings, respectively. **Figures 3.34** to **3.36** show the damage to the RC TELECOM building.

Figure 3.34. RC TELECOM building (Courtesy Mr. LaFolie).

Figure 3.35. Typical damage in the TELECOM building. Thin concrete cover spalled (Courtesy Mr. LaFolie).

Figure 3.36. Typical damage in the TELECOM building (Courtesy Mr. LaFolie).

San Julian

Only one public building was reported affected whereas there were 1,100 destroyed dwellings and 2,350 affected dwellings. Reinforced masonry structures performed quite well. The damage was concentrated in the bahareque and adobe houses. **Figures 3.37** to **3.39** show some of the structures observed in San Julian.

Figure 3.37. Spalling of the mud cover in a bahareque dwelling. The wall presents horizontal, vertical, and diagonal canes.

Figure 3.38. Reinforced masonry structure performed well.

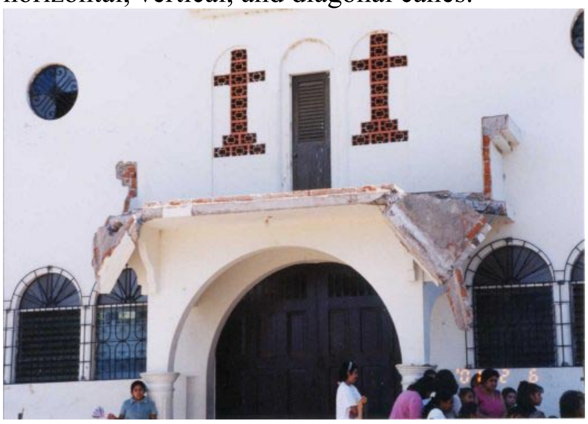


Figure 3.39. Failure of a unreinforced masonry parapet. The slab also shows insufficient reinforcement.

Microtremor measurements were carried out simultaneously on top of a bahareque house wall and at the ground level. The location of the house (89°33.52W, 13°41.41N) and some views of it are shown in **Figure 3.40**. The house consisted of four walls (thickness=24cm; height=3.55m) and the roof composed of a wooden truss and ceramic tiles. The distance between the horizontal and vertical spreaders of the wall was 17 and 35cm, respectively. **Figure 3.40** also shows the location and orientation of the sensors used to measure microtremors (X: longitudinal direction; Y: transverse direction). In general, the house performed well during the earthquake. Only mud cover spalling and cover cracking was observed.

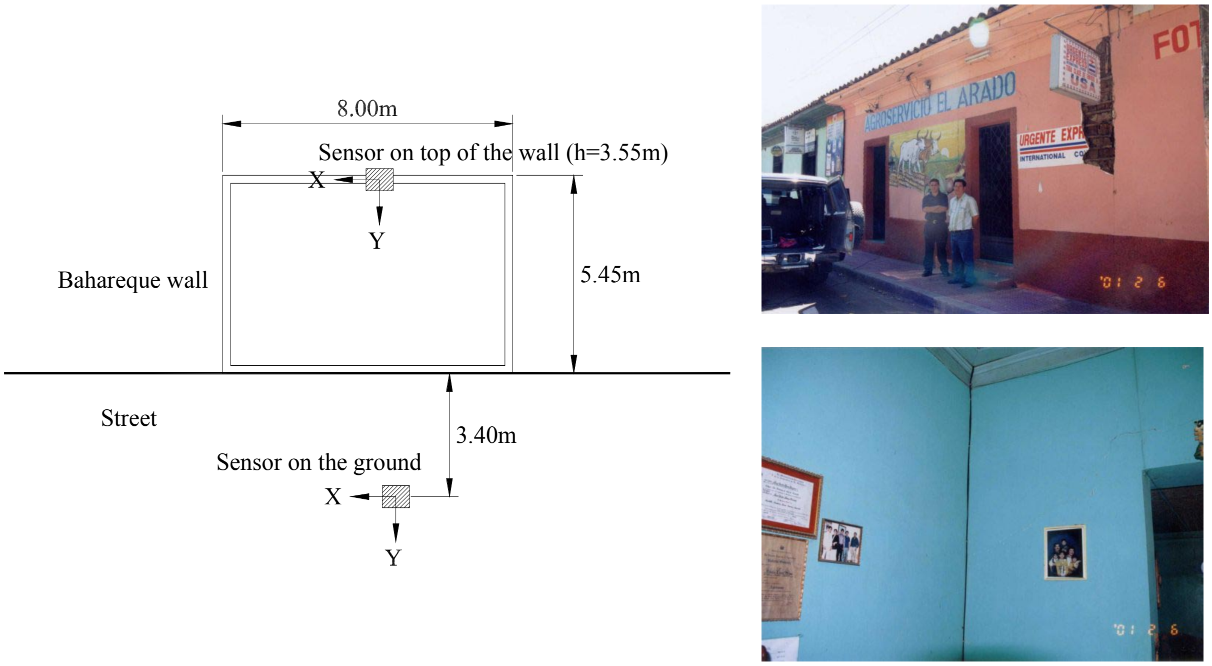


Figure 3.40. Surveyed bahareque house

The Fourier Spectra of these three components recorded as well as the H/V ratio are shown in **Figure 3.41**. The H/V ratio graph does not show any clear peak, which might indicate a rocky type of site.

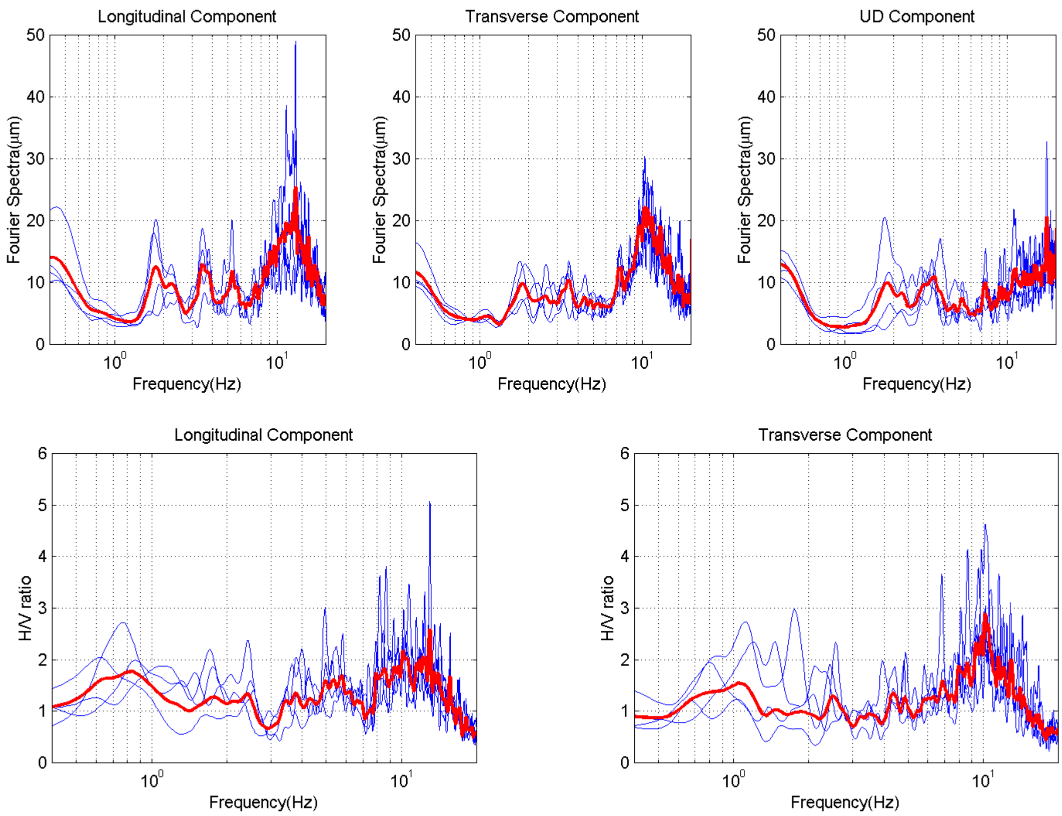
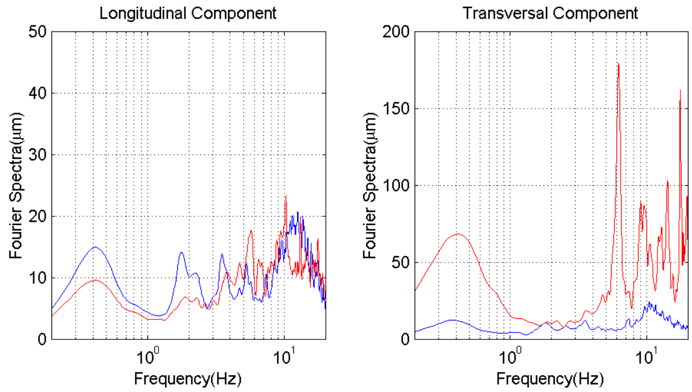
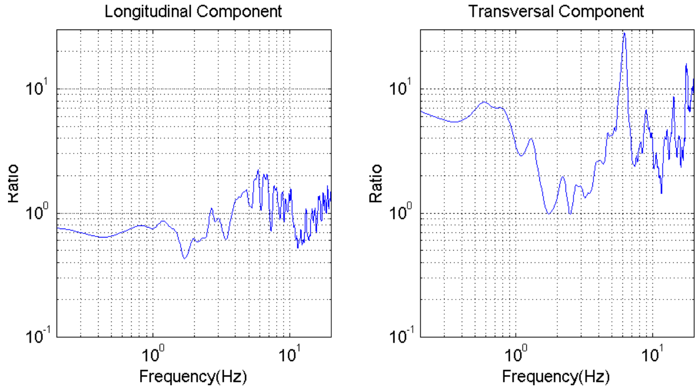


Figure 3.41. Microtremor Fourier Spectra at the ground level in San Julian



(a)



(b)

Figure 3.42. (a) Fourier spectra of the microtremors recorded on top of the bahareque wall (red) and at the ground level (blue); (b) Ratio of the microtremor Fourier spectra

For the analysis of the dynamic characteristics of the bahareque house, the Fourier Spectra of the microtremors recorded on top of the wall were divided by the corresponding microtremors at the ground surface. The results are shown in **Figure 3.42**.

In the longitudinal direction, a slight amplification of the components in the frequency range 4-10Hz can be observed. On the other hand, all frequency components are amplified in the transverse direction, especially at 6Hz. This might indicate that the predominant period is between 0.1 and 0.25sec in the longitudinal direction and 0.16sec in the transverse direction. The amplification of the motion in the transverse direction is higher than in the longitudinal, especially at 6Hz.

Nueva San Salvador

Nueva San Salvador consists of several districts. The team visited Las Colinas and the Historic Center. Las Colinas is a relatively new residential area where most of the dwellings are made of reinforced masonry. In general, the earthquake ground motion did not affect these structures. The major cause of destruction and casualties was the huge landslide that occurred there.

Figures 3.43 and **3.44** show the dwellings located by the side of the landslide. All the houses on the landslide way were totally leveled. The walls of some of the houses on the sides of the landslide were also affected. Other houses just a few meters away from the landslide did not suffer any damage (**Figure 3.45**).

Figure 3.43. Concrete block dwelling affected by the landslide at Las Colinas. There is still soil on top of the roof.

Figure 3.44. Dwelling on the border of the landslide. Neither the earthquake ground shake nor the landslide affected this dwelling.

Figure 3.45. Reinforced masonry dwellings few meters away from the landslide did not suffer any damage.

The Historic Center of Nueva San Salvador is more commercial and older than Las Colinas. Damage to unreinforced masonry and adobe buildings was observed there (**Figures 3.46** and **3.47**).

Figure 3.46. Unreinforced masonry structure suffered structural damage at the historical center of Nueva San Salvador.

Figure 3.47. Adobe construction suffered damage at Nueva San Salvador.

San Salvador

In San Salvador, most of the dwellings and buildings are made of concrete blocks and reinforced concrete, respectively. The building damage was minor in the capital of El Salvador. The seriously damaged buildings were those who experienced the 1986 Earthquake and were not adequately repaired and strengthened. **Figures 3.48** and **3.49** show some slight damages in the RC building of the Faculty of Civil Engineering and Architecture of the University of Central America "José Simeón Cañas".

Figure 3.48. Finishing spalling. The seismic joint between two adjacent buildings was 5cm. No evidence of pounding was observed.

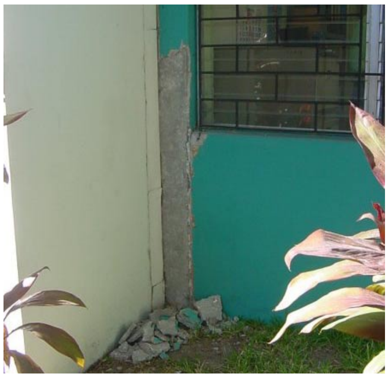


Figure 3.49. A thin layer of styrofoam was placed between the window splay and the column of the main structure.

3.5 CONCLUSIONS AND RECOMMENDATIONS

During the 2001 El Salvador Earthquake, extensive damage to adobe and bahareque dwellings was observed. This was not the case of reinforced masonry and reinforced concrete structures. The main deficiencies observed in the bahareque and adobe structures were:

1. Inappropriate foundation. The foundation did not project above the ground level. As a result, the lower parts of the walls were eroded and/or the bahareque skeleton was rotten.
2. Lack of foundation. Some walls stood directly on the ground.
3. Inappropriate connection between walls and roof.
4. Lack of beams on top of the walls to provide integrity to the structure.
5. Inappropriate connection between adjacent walls.
6. Lack of internal reinforcement for adobe structures.
7. Lack of structure maintenance.

The observed damage included out-of-plane wall collapse, separation of adjacent walls, mud cover spalling, diagonal cracking, vertical cracking of spandrels over the window or door openings, etc.

Several studies were carried out in El Salvador and elsewhere in order to understand the behavior of bahareque and adobe structures [Bukele Gálvez, P. J., et al., 1997, Moreira Peñate, R. A., et al., 1998, Rodríguez Deras, J. A., et al, 1993] and to propose design and retrofit guidelines [Norma Adobe – Código E-080, 1997, Zegarra, L., et al., 2000]. For instance, the Peruvian National Regulation for Construction [Norma Adobe – Código E-080, 1997] requires that all adobe buildings should be provided with: 1) beams on top of the walls, 2) wall reinforcement, e.g. cane, wood, and 3) reinforcement at the wall connections and corners. Recommendations for wall dimensioning, e.g. minimum thickness, maximum unsupported horizontal length and height, location of windows, and doors, etc., are also given. For existing structures, strengthening with ferrocement has proved to be satisfactory and rules of thumb have been proposed for the implementation of such technique [Zegarra, L., et al., 2000].

Reinforced concrete and reinforced masonry structures performed well and just acceptable minor damages were observed. The few structures that were beyond reparation were those damaged by previous earthquakes and not adequately fixed. In order to avoid this situation, a better system to follow up the reparation of damaged structures is needed.

Other urgent steps are to enforce the technical standards for design and construction and the seismic code by law and to prepare professionals in quick damage inspection techniques. The present event evidenced the lack of professionals trained in this issue. In spite of the efforts of the professionals who volunteered to do this work, the demand could not be efficiently satisfied.

The January 13th, 2001 Earthquake proved the high seismic vulnerability of adobe and bahareque structures in El Salvador. Nowadays, there are technical solutions available to deal with this problem. Unfortunately, the people directly involved in the construction of these structures, frequently the owners themselves, are not aware of those techniques or do not appreciate the importance of their implementation. Thus, one of the current main issues is to increase the consciousness among the population of the importance of earthquake preparedness. Otherwise devastation as the one observed during the 2001 El Salvador Earthquake will be repeated again.

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