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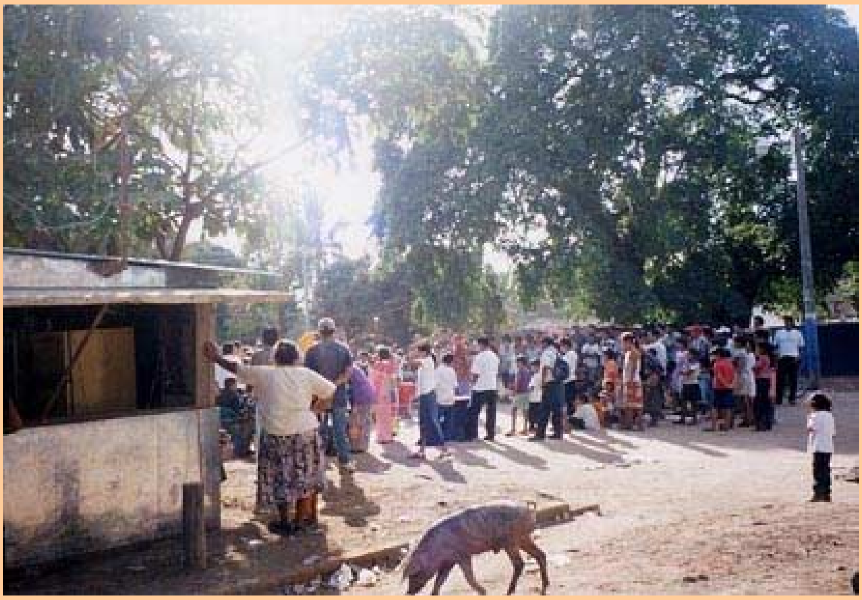
3. BUILDINGS AND DWELLINGS

The January 13, 2001 Off the Coast of El Salvador Earthquake



A voluntary person with a white painted clown-like face is amusing children by acting foolish. People there do not have enough tents, and have spent three weeks in the open air, by dusty roadsides since the earthquake. (San Agustin)

3.1 INTRODUCTION

The main types of building construction materials in El Salvador are reinforced concrete, reinforced masonry, adobe, and “bahareque”. Although the January 13th earthquake caused damage to buildings and dwellings, the number of affected buildings (officially: 1,249 including public buildings, hospitals, and health centers, National Emergency Committee Web page, http://www.coen.gob.sv) highly contrasts with the large number of affected and destroyed dwellings (officially: 277,953, National Emergency Committee Web page, http://www.coen.gob.sv), which are mainly located in the rural areas. The main reason for this is that most of the public buildings are reinforced concrete structures designed according to the current seismic code regulation whereas dwellings, especially in the rural areas, are mainly adobe or “bahareque” structures.

Table 3.1 shows the spatial distribution of dwellings according to the material of their walls and roof cover. Although the number of reinforced masonry structures (concrete blocks) is large, they are mainly concentrated in the San Salvador, San Miguel, La Libertad and Sonsonate. In the rest of the country, adobe is predominant. Another interesting point is that less than 2% of the dwelling roofs are slabs. The lack of a rigid slab causes the whole integrity of the structural system to rely on the connection between the walls only. Almost half of the houses are provided with “relatively heavy” tiles supported on either steel or wood trusses whereas the other half have light asbestos or metallic sheets.

The popularity of adobe construction in the rural areas is basically due to its low price, the easiness of its construction and material procurement and the high housing deficit existing in El Salvador. **Table 3.2** shows the Salvadoran housing indexes from years 1994 to 1999. From the above-mentioned table, it is clear that there is large unattended housing demand (quantitative housing deficit) as well as a large number of inadequate houses (qualitative housing deficit). In this context, the adobe construction appears as a solution to the population needs and is erected on a traditional basis rather than on engineering criteria. Unfortunately, the poor seismic behavior of the adobe buildings and their lack of maintenance make them very vulnerable to earthquakes.

High buildings are scarce in El Salvador and concentrated in San Salvador. Damage to these structures was limited as detailed in **Section 3.3**. The buildings that were left unusable by the 2001 earthquake were those which were not adequately retrofitted after the serious damages caused by the 1986 earthquake. On the view of this, the present report is mainly focused on the damage to dwellings. Because masonry, adobe, and “bahareque” construction practices vary from country to country, a brief description of these techniques in El Salvador is presented.

Table 3.1. Distribution of dwellings in El Salvador (1994)

	According to the wall material				According to the roof material					Total
Department	**Concrete**	**Bahareque**	**Adobe**	**Others**	**Slab**	**Tile**	**Asbestos sheet**	**Metallic sheet**	**Others**	
Ahuachapán	14.892	6.192	20.492	9.540	0	33.616	3.912	10.520	3.068	51.116
Santa Ana	43,333	6,201	48,796	3,413	125	66,983	18,163	16,061	411	101,743
Sonsonate	33,702	9,727	17,262	13,700	137	20,139	18,632	33,976	1,507	74,391
Chalatenango	9,330	954	30,024	324	162	38,388	642	1,440	0	40,632
La Libertad	61,492	17,286	26,526	7,667	307	42,228	36,616	33,104	716	112,971
San Salvador	302,340	28,260	23,352	20,496	16,476	66,786	201,972	88,050	1,338	374,622
Cuscatlán	8,116	5,768	18,386	922	112	25,010	3,174	4,734	162	33,192
La Paz	17,330	7,354	21,462	3,696	366	41,584	4,036	3,096	836	49,918
Cabañas	6,525	2,780	14,011	1,115	49	21,704	1,774	598	152	24,277
San Vicente	8,051	5,308	15,536	2,527	0	26,686	1,714	2,728	154	31,282
Usulután	25,183	8,530	22,838	6,099	124	44,757	9,195	7,854	859	62,789
San Miguel	44,905	11,715	17,315	7,492	780	56,165	18,040	5,965	595	81,545
Morazán	5,302	5,087	14,291	7,370	0	27,307	1,071	2,407	1,283	32,068
La Unión	17,322	7,872	23,327	4,665	188	47,863	1,967	392	2,925	53,335
Total	**597,823**	**123,034**	**313,618**	**89,026**	**18,826**	**559,216**	**320,908**	**210,925**	**14,006**	**1,123,881**
Percentage	**53.2%**	**11%**	**27.9%**	**7.9%**	**1.7%**	**49.8%**	**28.6%**	**18.8%**	**1.3%**	**100%**

Source: Crystal InfoCenter webpage based on the data by the Vice-ministry of Housing and Urban Development (Crystal Infocenter Web page, http://www.guate.net/crystal/.)

Table 3.2. Salvadoran housing indexes

Description	1994	1995	1996	1997	1998	1999
Number of existing dwellings	1,123,881	1,137,305	1,209,319	1,245,795	1,296,635	1,347,970
Housing growing rate	7.1%	1.2%	6.3%	3.0%	4.1%	4.0%
Qualitative housing deficit	549,852	543,173	549,724	534,511	514,637	511,507
Quantitative housing deficit	40,440	35,898	27,654	20,716	45,067	42,817
Total Housing deficit	590,292	579,071	577,378	555,227	559,704	554,324

Source: Plan Salvadoreño de Vivienda y Territorio, Viceministerio de Vivienda y Desarrollo Urbano, Oficina de Planeamiento Urbano.

(1) Masonry:

The reinforced masonry is popular in El Salvador. The use of concrete blocks is more extended than the use of clay bricks due to economical reasons. **Figure 3.1** shows a typical reinforced masonry building under construction.

Figure 3.1. Reinforced masonry house with concrete blocks

In 1994, the Ministry of Public Works published the “Guidelines for the Design and Construction of Masonry”. This document establishes the minimum requirements for the design, construction, and supervision of the construction of these structures. In general, it was observed that modern buildings, presumably constructed under this regulation, did not suffer much damage.

(2) Adobe

The adobe system is composed by unbaked soil blocks and mortar. Both are basically constituted by sand, silt, and clay in different proportions. Sometimes, the blocks are stabilized by adding cement, lime, dry straws, vegetable fibers, wooden chips, palm leaf fibers, etc. **Figure 3.2** shows a typical adobe dwelling.

Figure 3.2. Typical adobe house that was damaged by the earthquake

Adobe buildings have poor seismic performance. They are massive and heavy, which attracts high levels of seismic forces, and the material is brittle and has almost no tensile strength by itself. Poor construction practices often decrease the bond between adobe and mortar. Although there are techniques to provide internal reinforcement to the adobe structures in order to improve their seismic performance, those techniques are not in practice in El Salvador.

(3) Bahareque

The “bahareque” system is commonly used in Latin America although its name varies from country to country. The foundation consists of either stones or bricks and its main function is to transfer the loads to the ground and separate the walls from the ground humidity. The main structure consists of wooden studs (bamboo is also used) and cane spreaders attached with nails, wires, or vegetal fibers. The truss is filled with mud composed of a mix of sand, clay and vegetal fibers. The wall finishing is a mix of lime and clay. **Figure 3.3** shows a typical bahareque structure.

The “bahareque” system has proved to perform better during earthquakes. In spite of this, this construction practice has decreased in the last years. The percentage of “bahareque” dwellings in El Salvador has declined from 33.1% in 1971 to about 11.0% in 1994. According to discussions with Salvadoran engineers, this system is almost not used for new constructions anymore.

Figure 3.3. Bahareque structure which suffered mud cover spalling.

3.2 DEVELOPMENT OF SEISMIC DESIGN CODE

The beginnings of the seismic analysis for the design of structures date from the period from 1942-1957 when the first buildings of more than 3 stories were erected in San Salvador [Lara, M. A., 1987, Bommer, J. J., et al. 1996]. At that time the analysis was carried out applying a horizontal acceleration of 0.10g uniformly distributed over the height of the structure. Since then, three national codes for earthquake resistant design were introduced in 1966, 1989 and 1994 respectively. Before 1965 a variety of US codes were employed by different engineers adopting a base shear coefficient of 0.03 [Rosenblueth, E., 1965].

The 1966 code was prepared as a response to the earthquake of the previous year. It divides the country into two zones, with the higher seismicity Zone 1 including the volcanic chain and the coastal areas. The maximum base shear coefficient prescribed in the code was 0.39. The site geology was not considered in the specification of design loads.

The 1989 code was prepared by the Salvadoran Society of Engineers and Architects in response to the 1986 earthquake. The two-zone division was maintained however the maximum base shear coefficient rose to 0.45. The code mentions the amplification of ground motion by soil layers but does not explicitly relate the seismic loads to the site geology.

The 1994 code was based on the hazard study by Singh et al [1993]. The simple division of the country was maintained. The soil profile at the site was incorporated into the specification of earthquake loads in this code. Vertical design loads are specified for cantilevered structural elements.

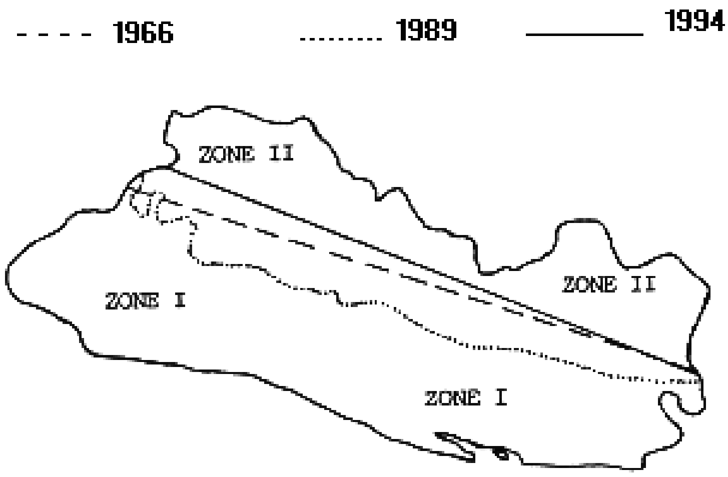


Figure 3.4. Zoning maps of El Salvador from Seismic building codes of 1966, 1989 and 1994

In the 1994 code [Norma Técnica para Diseño por Sismo, Reglamento para la Seguridad Estructural de las Construcciones, 1994, Ministerio de Obras Públicas, República de El Salvador.], the design coefficient, C_s, is calculated according to the following expression:

$$C_s = \frac{AIC_o}{R}\left(\frac{T_o}{T}\right)^{2/3}$$

where:
- A: Area factor (Zone 1, A=0.4; Zone 2, A=0.3)
- I: Building importance factor (essential or dangerous buildings, I=1.5; special buildings, I=1.2; normal buildings, I=1.0)
- C_o,T_o: Site coefficients (see Table 3.3)
- T: Period of the structure
- R: Reduction factor (see Table 3.4)

Table 3.3. Site coefficients

Type	Description	C_o	T_o
S_1	Soil profiles with the following characteristics: (a) Rock with V_s>500m/s (b) Rigid soils, thickness<30m	2.5	0.3
S_2	Soil profiles with the following characteristics: (a) Rigid soils, thickness>30m (b) Compact or medium dense soil, thickness<30m	2.75	0.5
S_3	Soil profile with a cumulative thickness from 4 to 12m of cohesive soft soil or cohesive medium compact soil or non-cohesive loose soil	3.0	0.6
S_4	Soil profile with more than 12m of cohesive soft soil or non-cohesive loose soil and V_s<150m/sec.	3.0	0.9

Note: (1) At the sites where the soil properties are not known in detail as to characterize it according the table above, the soil type S_3 must be used. (2) It is implicit that below the soil profile specified for each type of soil there is just rock of the S_1 type.

Table 3.4. Structural systems and corresponding reduction factors

Basic structural system	Description	R
System A	1. Steel or concrete frames with special detailing	12
	2. Concrete frames with intermediate detailing	5
	3. Steel frames with ordinary detailing	7
System B	1. Walls:	
	a. Concrete	8
	b. Masonry	7
	2. Braced steel frames	
	a. Eccentrically	10
	b. Concentrically	8
System C	1. Concrete walls combined with	
	a. Concrete or steel frames with special detailing	12
	b. Concrete frames with intermediate detailing or steel frames with ordinary detailing	8
	2. Masonry walls combined with	
	a. Concrete or steel frames with special detailing	7
	b. Concrete frames with intermediate detailing or steel frames with ordinary detailing	6
	3. Braced steel frames combined with:	
	a. Eccentric bracing	12
	b. Concentric bracing	10
System D	1. Walls	
	a. Concrete	7
	b. Masonry	6
	2. Braced steel frames	6
System E	1. Systems with the mass concentrated at the top of the structure	3
	2. Systems with the mass distributed along its height	4

The period of the structure can be evaluated by two methods:

1. Method A: The following formula is used:

$$T = C_t h_n^{3/4}$$

where, C_t is 0.085 for buildings of system A with steel frames, 0.073 for buildings of system A with concrete frames, and 0.049 for the other systems; h_n is the building height. Alternatively, for buildings with concrete or masonry shear walls, C_t can be considered equal to $0.074/\sqrt{A_c}$. A_c is calculated with the following expression:

$$A_c = \sum A_e \left[0.2 + (D_e / h_n)^2\right]$$

where A_e and D_e are the effective area and length of the shear walls in the first floor in the direction parallel to the applied loads (in m^2 and m). The ratio D_e/h_n should not exceed 0.9.

2. Method B: The building period can be calculated using the structural properties and the deformation characteristics of the structural elements using an appropriate method of analysis. The value of C_s obtained with this method should not be less than 80% of the value obtained with Method A.

3.3 DAMAGE DISTRIBUTION

The National Emergency Committee (COEN) issued the statistics of damage in the different departments of El Salvador. **Table 3.5** shows the final statistics of the building and dwelling damages caused by the 2001 El Salvador Earthquake. **Figures 3.5, 3.6** and **3.7** show the distribution of damages to dwellings and buildings.

Table 3.5. Building damage statistics (Source: COEN [1])

Department	Affected public buildings	Affected dwellings	Collapsed dwellings	Buried buildings	Affected churches	Affected ports	Affected hospitals
Ahuachapán	60	18540	6553	0	14	0	1
Santa Ana	5	13925	4823	0	49	39	2
Sonsonate	38	17773	10501	0	69	0	1
Chalatenango	47	307	16	1	3	0	0
La Libertad	48	14558	15723	687	45	0	1
San Salvador	76	12836	10372	0	19	0	6
Cuscatlán	47	4762	4282	0	6	0	1
La Paz	272	25076	17996	0	46	0	1
Cabañas	31	1153	309	0	5	0	1
San Vicente	40	17292	5218	0	12	0	0
Usulután	335	30716	29293	0	90	0	2
San Miguel	23	10624	2902	0	38	4	3
Morazán	35	94	5	0	4	0	0
La Unión	98	2136	268	0	5	0	0
TOTAL	**1155**	**169692**	**108261**	**688**	**405**	**43**	**19**

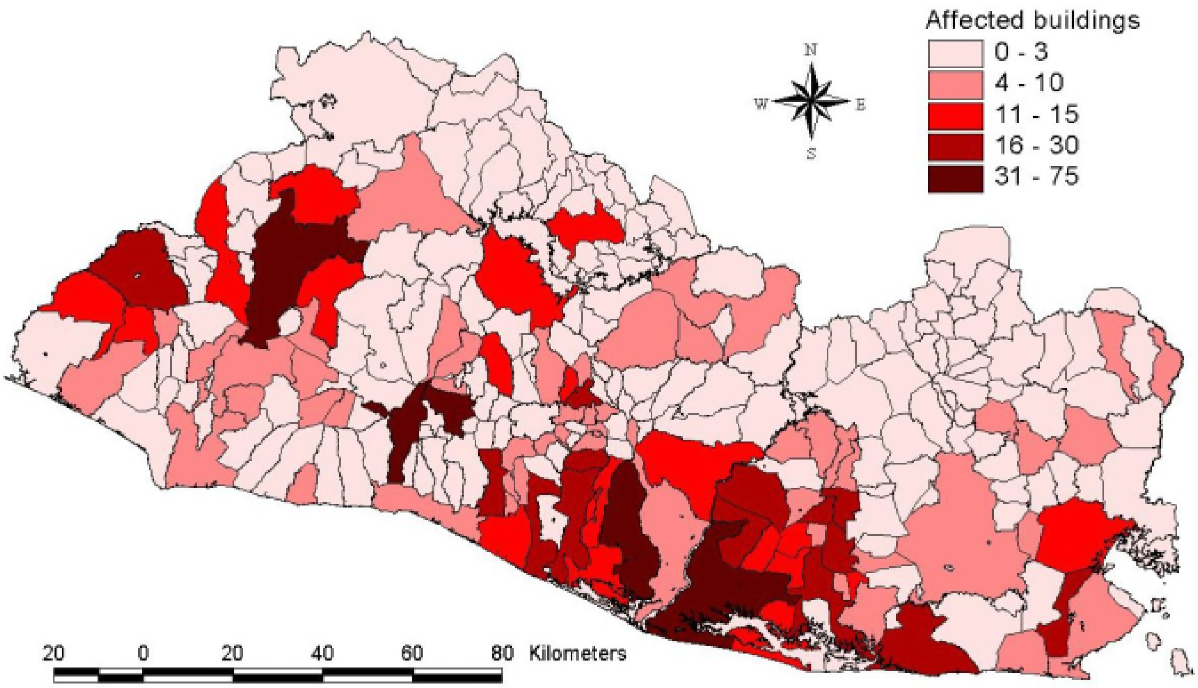


Figure 3.5. Distribution of affected buildings (Courtesy Mr. Miguel Estrada)

Table 3.6 shows the dwelling damage for each department in terms of percentage taking the number of existing dwellings equal to the statistics of 1995. It is clear that the most affected departments were Usulutan, La Paz and San Vicente, which are the closest to the epicenter. However, it is also remarkable that Ahuachapan and Sonsonate exhibit damages in 50 and 40 percent of their dwellings.

Table 3.6. Distribution of dwelling damages in percentage

Department	Affected dwellings	Collapsed dwellings	Total number of dwellings	Affected dwellings	Collapsed dwellings	Total
Ahuachapán	18540	6553	52561	35.3%	12.5%	47.7%
Santa Ana	13925	4823	104026	13.4%	4.6%	18.0%
Sonsonate	17773	10501	71400	24.9%	14.7%	39.6%
Chalatenango	307	16	42372	0.7%	0.0%	0.8%
La Libertad	14558	15723	113798	12.8%	13.8%	26.6%
San Salvador	12836	10372	381869	3.4%	2.7%	6.1%
Cuscatlán	4762	4282	33116	14.4%	12.9%	27.3%
La Paz	25076	17996	51482	48.7%	35.0%	83.7%
Cabañas	1153	309	24836	4.6%	1.2%	5.9%
San Vicente	17292	5218	30093	57.5%	17.3%	74.8%
Usulután	30716	29293	63775	48.2%	45.9%	94.1%
San Miguel	10624	2902	81984	13.0%	3.5%	16.5%
Morazán	94	5	32842	0.3%	0.0%	0.3%
La Unión	2136	268	53151	4.0%	0.5%	4.5%
TOTAL	**169692**	**108261**	**1137305**	**14.9%**	**9.5%**	**24.4%**

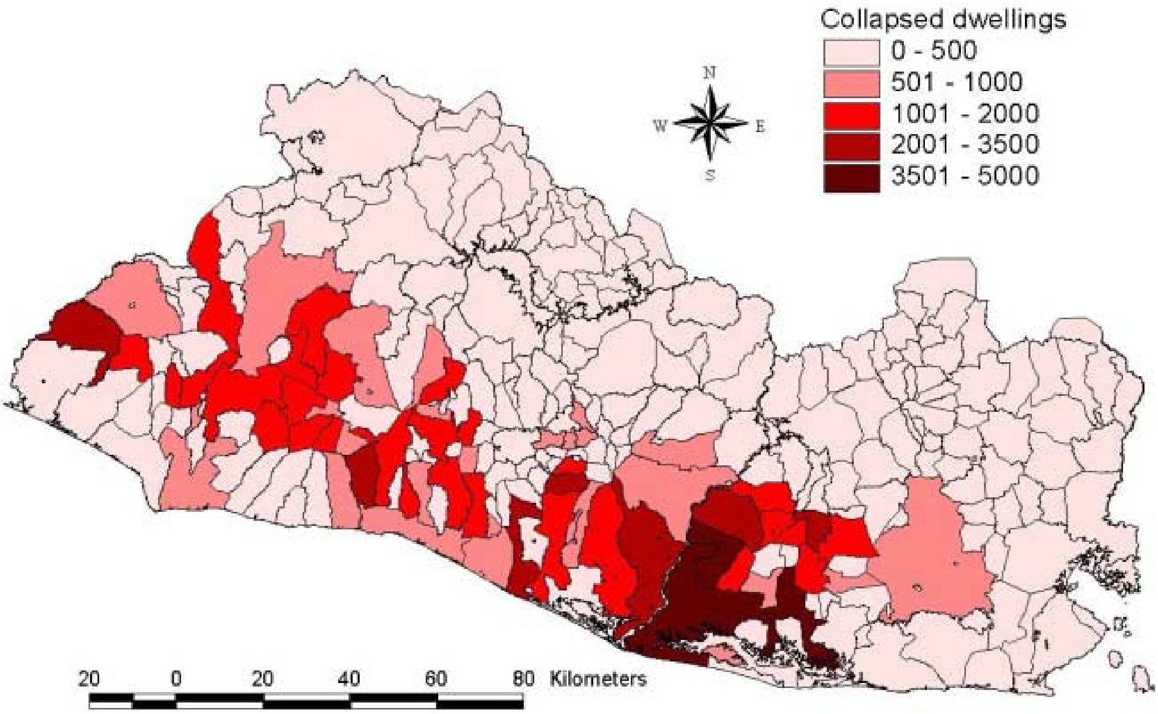


Figure 3.6. Distribution of collapsed dwellings (Courtesy Mr. Miguel Estrada)

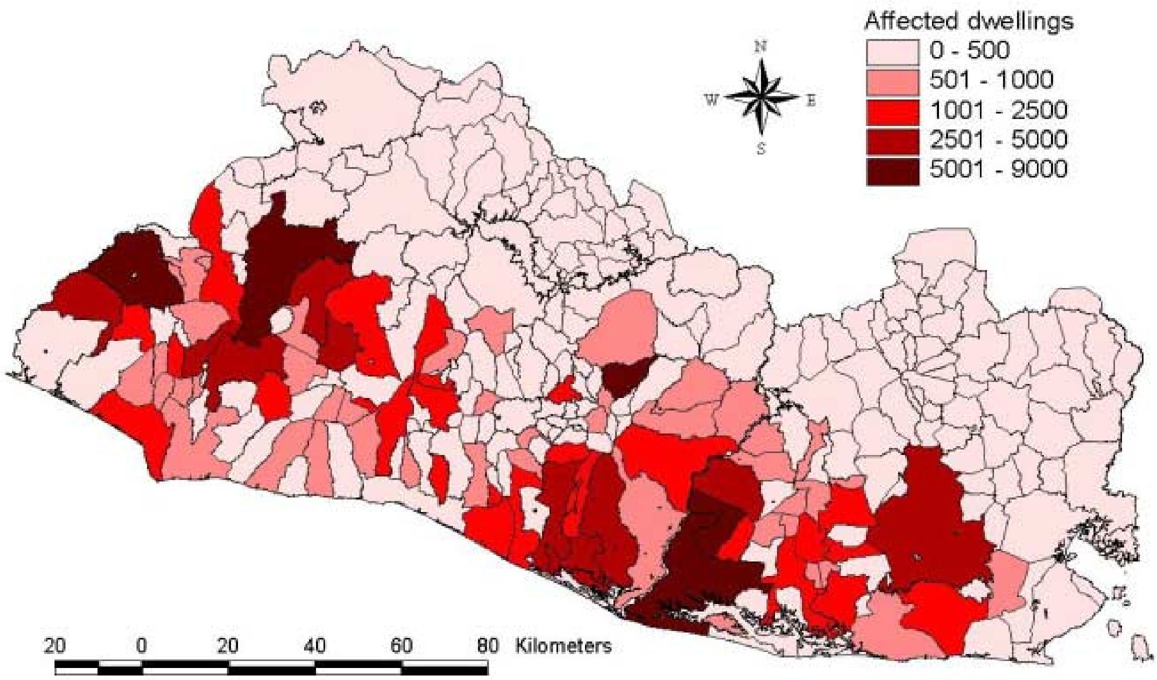


Figure 3.7. Distribution of affected dwellings (Courtesy Mr. Miguel Estrada)

Damage Evaluation Committee

A Damage Evaluation Committee was reconstituted for the evaluation of damaged buildings. This institution was operative after the 1986 Earthquake but was dissolved soon after.

The building inspection was done upon request. According to the importance of the building, the number of committee members and their field of expertise were decided. It is worth mentioning that the current system does not require any special training for the inspectors. Any graduated civil engineer can volunteer for carrying out inspections.

During the inspection, an inspection form was filled. In this form, the following information was included:

1. Building identification
2. Building description (number of stories, shape, area, structural system, construction quality, previous repairing evidence, etc)
3. Inspection observations (damage to structural elements such as columns, beams, joints, shear walls, bearing walls, slabs, stairs, roof, footing; damage to non-structural elements such as façade walls, lateral walls, interior walls, partitions, utilities, roof covers, etc.; settlement; damage estimation; ground failure; estimation of the repairing/reconstruction cost)
4. Recommendations and conclusions (risk classification, recommendation of urgent measures)
5. Comments

A supervision committee constituted by Architect Mario F. Peña (VMVDU), Eng. Luis Murcia (ASIA), and Eng Jorge Tobar (FESIARA) reviewed the report prepared by the inspection committee. Finally, a certain flag color was given to the inspected building according to the damage level and a certificate is issued. The damage classification is shown in **Table 3.7**.

Table 3.7. Damage classification

Flag	Damage description
Green	No damage or unimportant damage
Yellow	Minor non-structural damage
Orange	Major structural damages
Red	Severe structural damages

The number of building inspection requests as of February 3rd was slightly over 1,500. The inspection results as of the same date are shown in **Table 3.8**.

Table 3.8. Inspection results - Number of issued certificates (as of February 3rd)

Building type	No flag	Green flag	Yellow flag	Orange flag	Red flag
Public health	- (-)	14 (19)	5 (5)	6 (3)	- (-)
Private health	- (-)	3 (2)	2 (1)	- (-)	- (-)
Public education	- (-)	3 (2)	3 (2)	- (3)	- (2)
Private education	- (2)	18 (17)	7 (8)	2 (4)	2 (1)
Governmental	- (-)	24 (17)	10 (5)	5 (3)	3 (3)
Offices, commerce, churches	- (-)	12 (11)	5 (11)	1 (-)	5 (2)
Industrial	- (-)	- (-)	- (-)	- (-)	- (-)
Housing buildings	- (-)	- (-)	5 (1)	- (-)	- (-)
Other housing buildings	- (-)	1 (4)	1 (9)	- (-)	3 (-)
Others (museums, cinemas, hotels)	- (-)	2 (5)	2 (3)	1 (1)	1 (3)
No flag	3 (3)	- (-)	- (-)	- (-)	- (-)
T O T A L	3 (5)	77 (77)	40 (45)	15 (14)	14 (11)

Note: The numbers in parenthesis correspond the number of buildings already inspected but whose certificates have not being issued yet.

Despite the efforts of the COED to proceed with celerity, only 20% of the inspection demands was attended 21 days after the earthquake. The inspected buildings were prioritized on the basis of their importance for the community. Due to the lack of experience of the inspectors, all the inspection results had to be reviewed and approved by the supervision committee. Thus, a bottleneck was created and the inspection works did not satisfy the demand.

The experience from the 1986 earthquake showed that a large number of buildings, which were inspected by the COED, were not repaired and/or strengthened as recommended. These buildings were affected again during the 2001 earthquake. For this reason, the COED is currently planning to submit the results of all their inspection activities to the municipalities so that these entities can closely follow the repairing works.

3.4 DAMAGE TO THE VISITED TOWNS

Figure 3.8 shows the map of El Salvador and the visited cities and towns. The damage at the locations were field survey was carried out is described below.

San Agustin

San Agustin is a rural locality in Usulutan. The town lies along one of the roads that join the Littoral and Panamerican Highways. The National Emergency Committee (COEN) reported 3,746 destroyed dwellings and 5,866 damaged dwellings there. The main type of construction at this site is adobe and "bahareque". Due to the reasons mentioned in section 3.1, it is very likely that the "bahareque" structures at this area were more than 30 years old. **Figure 3.9** shows a plan of the main town.

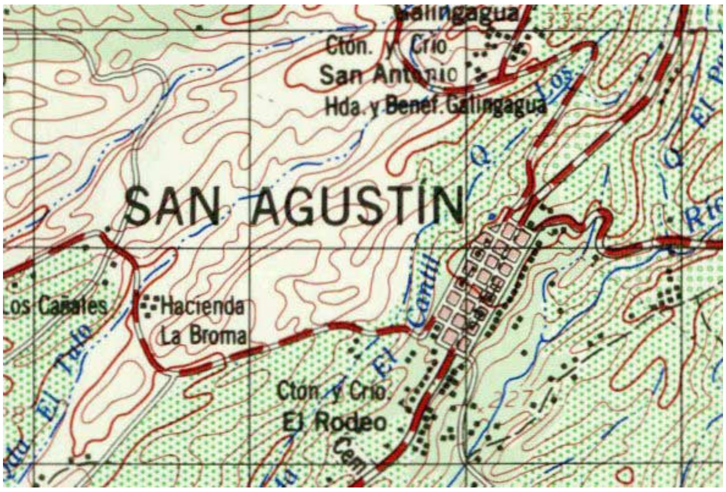


Figure 3.9. Map of San Agustin

Utility poles (5m tall) are embedded upright in concrete-paved sidewalk in this town (**Figure 3.10**). Cracks developing outwardly on the pavement from these poles suggest possible directions in which ground motions were intense (**Figure 3.11**). Some poles (**No. 6** and **7**) are very close to the step-shaped edge of the sidewalk. The thin cover concrete thus might have affected the crack pattern. Though the number of the examined utility poles is not sufficient for thorough statistical manipulations, some poles seem to have been forcibly shaken in about N-S direction.

Figure 3.8. Map of El Salvador and location of the visited towns and cities (Red dots: Field survey; Blue dots: Helicopter survey only)

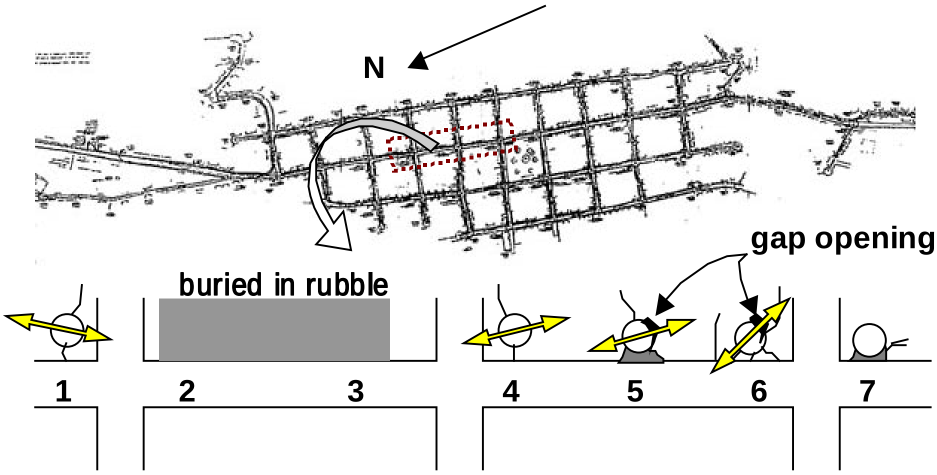
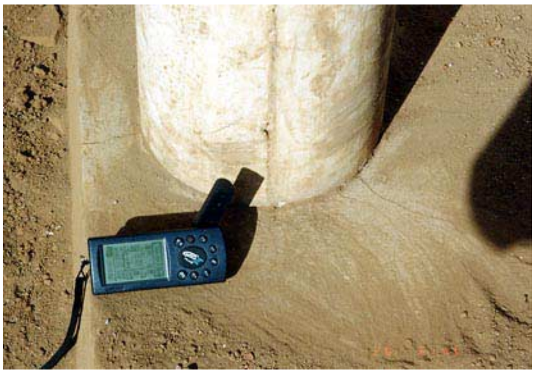


Figure 3.10. Locations of utility poles



Pole #1

Pole #5

Pole #6

Pole #7

Figure 3.11. Cracks appearing around utility poles

Figures 3.12 to **3.27** show the observed damage in the town. The structural damage reinforces the hypothesis of the main shake direction being approximately NS.

Figure 3.12. Bahareque structure that suffer mud spalling**.**

Figure 3.14. Unreinforced masonry house partially collapsed. The walls perpendicular to the street (~NE-SW direction) failed out-of-plane. The roof restrained the displacements of the top of the wall parallel to the street.

Figure 3.13. Detail of the connection between studs and foundation of the house in **Figure 3.12**. The foundation extends above the ground level protecting the wooden members.

Figure 3.15. Completely collapsed adobe house.

Figure 3.16. Collapsed reinforced masonry wall. The separation of the walls from the transverse walls can be observed in the two buildings shown in the photograph. The street direction is approximately NE-SW.

Figure 3.17. Adobe house completely flattened next to a reinforced masonry structure that did not suffer any damage.

Figure 3.18. Detail of the adobe house in **Figure 3.17**. Just the confining wood of one wall remained.

Figure 3.19. Collapsed bahareque house.

Figure 3.20. Detail of the poor foundation of house in **Figure 3.19.**

Figure 3.21. Unreinforced masonry structure. A vertical crack is observed at the connection between walls.

Figure 3.22. Interior of the building shown in **Figure 3.21**. The wall exhibits diagonal cracking.

Figure 3.23. Interior of the building shown in **Figure 3.21**. Vertical cracking of spandrels over the door head can be observed.

Figure 3.24. Reinforced masonry structure that did not suffer damage. However, the roof tiles felt down.

Figure 3.26. Bahareque structure damaged by the earthquake.

Figure 3.25. Masonry wall with clay bricks and concrete blocks. A diagonal crack crosses the concrete portion

Figure 3.27. Details of the walls of the house in **Figure 3.26**. Notice the poor foundation detail.

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