Current Situation of Low-Rise Wall Type Structures

World Federation of Engineering Organizations

Disaster Risk Management Committee

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Participating Countries and Researchers

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1 Introduction

1.1 Purpose of the project

In countries prone to earthquakes, most of damaged buildings are low-rise wall structures including Adobe, unreinforced masonry (URM), and infilled wall. In those countries, researchers have made efforts to establish better and effective seismic code/guideline through doing investigation about the behavior of low-rise wall structure during earthquakes.

But unfortunately, the results of these researches are not necessarily shared between the countries, and this situation may cause duplicate research or inefficient utilization, which might delay the development of low-rise unti-seismic construction.

Under this circumstance, current building construction codes of low-rise buildings of each country are gathered, as well as recent observed damages of low-rise construction under earthquakes so that each country can share related information, knowledge and problem of low-rise construction. Also through this project, the international network of researchers overseas is established.

1.2 Participating Countries

Proposal for this project was sent from Japan to earthquake prone countries, and those organizations who agreed with it have participated. Table 1 shows the participating countries and organization for moment.

Country	Organization
Colombia	-Engineering School of Antioquia
El Salvador	-El Salvador National University
Indonesia	-Institute Technology Bandung, -Andalas University -Syiah Kuala University, -Toyohashi University of Technology, Japan
Japan	-Building Research Institute -Nagoya University -Mie University -Toyohashi Institute of Technology -Yokohama National University
Mexico	-National Center for Disaster Prevention
Romania	-Technical University of Civil Engineering -National Center for Seismic Risk Reduction
Turkey	-Istanbul Kultur University -Istanbul Technical University
USA	-University of Texas at Austin

Table 1 Participating Countries and Organizations

2 Method of Research

To gather information, "Country-Report" style was chosen because of the following aspects.

- Demand level or design methods of each code are different in each country.
- To enforce the human network, it's better to describe in their own style, so that each researcher understand the thought or idea of each member.

Firstly, outline of the country report was send to participants, then opinions had exchanged through E-mail. After that communication, each organization began to describe country report. In the process of preparation of the reports, E-mail communication had also held as needed to avoid from excessive difference between each report. Table 2 Contents of Country Reports shows main contents of country report.

➢ General Information
➢ Code for low-rise wall type structures
➢ Construction Practice
➢ Observed earthquake damages
➢ Current research outputs
➢ Future works

Table 2 Contents of Country Reports

3 Future Plan

It is very useful to share the current situation of wall type structures for earthquake prone countries, so Disaster Risk Management Committee welcomes new participants for this project, at any time.

To utilize this report effectively, analysis of each country report is very important, so now our sub-committee is comparing and analyzing each country report. Also the situation about low-rise wall type construction is changing day by day, so if there is a change of the code or other information, the report will be modified each time.

These new information will update through the website of Disaster Risk Management Committee, WFEO.

Annex 1

Country Report

Colombia

CURRENT SITUATION OF LOW-RISE WALL STRUCTURES IN COLOMBIA

PREFACE

This report was carried out with the support of the Engineering School of Antioquia (Escuela de Ingeniería de Antioquia, EIA) in Medellin, Colombia, for the project "Current Situation of Wall Structures in the World" of the World Federation of Engineering Organization (WFEO). This investigation is conducted on a volunteer basis in cooperation with the university.

It must be emphasized that the opinion expressed in this report is that of the authors and does not reflect the views of EIA, or the organization of the authors.

Investigation team

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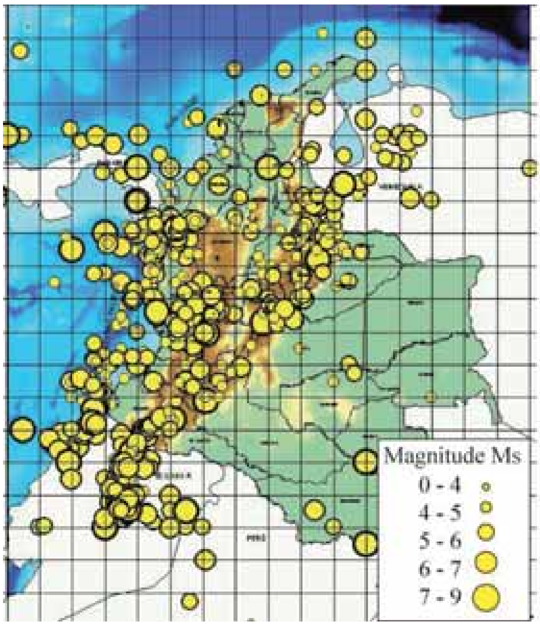
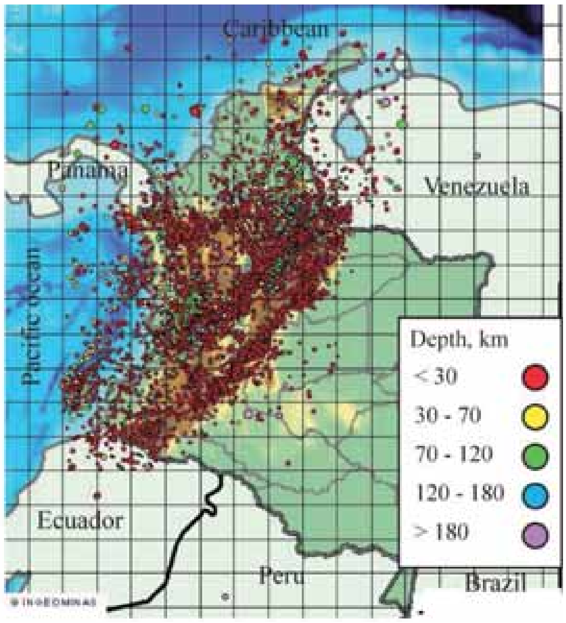
1. INTRODUCTION

Colombia is a seismic prone country that has been struck by the damaging effects of earthquake motions in repeated occasions. Several documents [e.g., 1-4] track the origin of the history of seismicity of Colombia to the year 1566 when an intensive ground motion, which caused significant damage in the South West part of the country, was recorded for the first time. A description of several past studies on the historical seismicity of Colombia dating from the XVIII century can be found in [5]. To date, the seismic catalogue in Colombia contains more than 30,000 seismic events [6], comprising a wide range of values of magnitude, as shown in Fig. 1.



(a)



(b)

Figure 1. Seismicity in Colombia: a) great earthquakes, 1566 -1999, and b) seismic activity, 1993 – 2001 [2].

From Fig.1, it can be observed that a significant seismic activity is concentrated in the mountainous areas of the West part of the country. Colombia has a population of about 42 million, and about 86% of the population locates in these mountainous areas of high and intermediate seismic activity [7]; a situation of risk for millions of Colombian citizens.

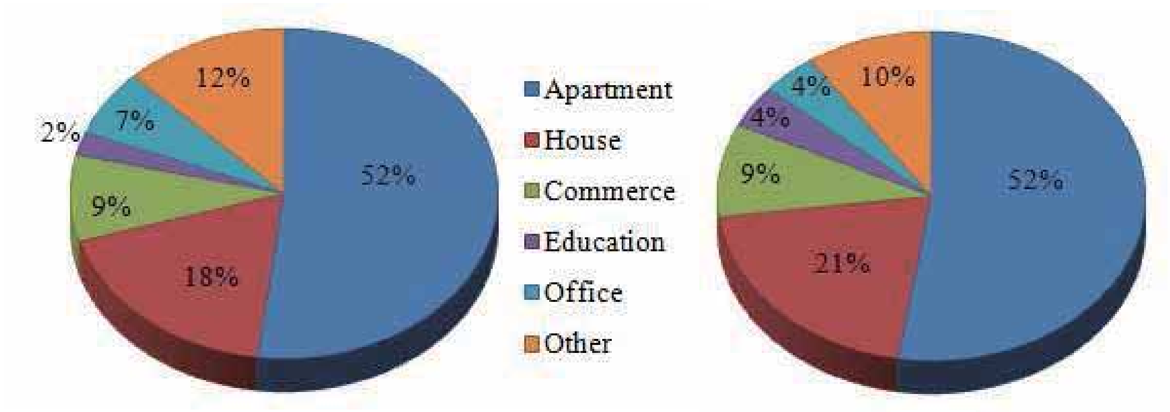
The main reason of a high seismic activity in Colombia lays on the unfavorable convergence of tectonic plates over which Colombia locates. The surrounding tectonic environment of Colombia is characterized by the interaction of four plates: the Cocos in the North West, the Nazca in the West, Caribbean in the North and the South American plates [8, 9]. However, the relative movement between the Nazca and South American plates beneath the Colombian territory is known to have originated the main seismic active faults and produced most seismic events in the mid-West part of the country.

In the past three decades, there has been a significant seismic activity that has affected many cities in Colombia. Table 1 summarizes some events within this time period. The 1983 Popayán earthquake and the 1999 Armenia (coffee-growing region) earthquake are among the most representative earthquakes in the country, due to an extensive impact on the community. In the Popayán earthquake, 300 were reported dead and 30,000 were left homeless, and losses were of the order of US$ 300 million [e.g., 3, 4, 10]. The Armenia earthquake caused over 1,100 deaths, more than 250,000 people affected and an economical impact of about US$ 2 billion [11, 12]. Over 26,000 houses were affected in Armenia city, covering various types of building structures; however, the most structural damage occurred in low-rise wall structures such as in unreinforced masonry (URM: "mampostería no reforzada" in Spanish) and bahareque (a local construction material composed of bamboo and mortar) dwellings [11, 12].

Table 1. Recent earthquakes in Colombia

Date	Location	Magnitude	Depth (km)	Casualties (approx.)	
1979/11/23	Coffee-growing region	$M_S = 6.4$	80	37	[3]
1979/12/12	Pacific Ocean	$M_S = 7.8$	40	453	[3]
1983/3/31	Popayán	$m_b = 5.5$	5	300	[10]
1992/10/18	Murindó	$M_S = 7.2$	15	30	[6]
1994/6/6	Páez	$M_S = 6.4$	< 20	500-1,000	[6]
1995/1/19	Tauramena	$m_b = 6.5$	15	10	[6]
1995/2/8	Calima	$m_b = 6.4$	90	5	[6]
1999/1/25	Coffee-growing region	$M_L = 6.1$	< 30	1,100	[11]
2004/11/15	Cali	$M_L = 6.7$	<33	-	[13]
2008/5/24	Quetame	$M_L = 5.7$	<30	-	[14]

To date, wall structures is the most prevalent structural system in Colombia and has got an important place in the urban planning of most cities in the country, covering different types of use. Fig. 2 shows statistics of censused area of construction as of IV trimester of 2009 [15]. Here, it is clearly seen that residential buildings (apartment + house) represent about 70% of the total area of construction. According to [16], the category 'apartment' corresponds to building structures with more than three stories. The category 'others' includes hotels, hospital, institutional and warehouses. Compared to the year 2006, the participation of the area of construction for residential purposes reduced slightly from 73% to 70% [17]. Fig. 3 shows statistics of censused construction area in major cities in the country. Here, AU and AM stand for urban area and metropolitan area, respectively. It can be observed that the construction activity in Bogotá and Medellín represent more than half of the total area of construction in the country.



(a) (b)

Figure 2. Distribution of censused area of construction by type of use as of IV trimester of: a) 2009 and b) 2006 [15, 17]

With regard to the type of construction, for instance, Fig. 4 shows the distribution of the censused new projects for the IV trimester of 2009. In Fig. 4, SM and CM/F stand for structural masonry ("mampostería estructural" in Spanish) and confined masonry/frame, respectively. According to [15], SM includes URM and reinforced masonry (RM: "mampostería reforzada" in Spanish) wall structures.

Although the study conducted in [15] does not provide a clear distinction between the participation of confined masonry (CM: "mampostería confinada" in Spanish) wall structures and that of frame ("porticos" in Spanish) structures into the total number of new projects, in general, the number of projects of CM wall structures is larger than that of frame structures in most major cities of the country. For instance, it is worth mentioning that the ratio of the number of projects of CM wall structures to that of frame structures in Pereira city was about 1.54 in 1999 [12]. In Fig.4, the percentage of each type of construction to the total number of projects is as follows: Apartment, 69%; House, 24.2%; Commerce, 4%; Education, 0.3%; Office, 1.2% and other use, 1.3%.

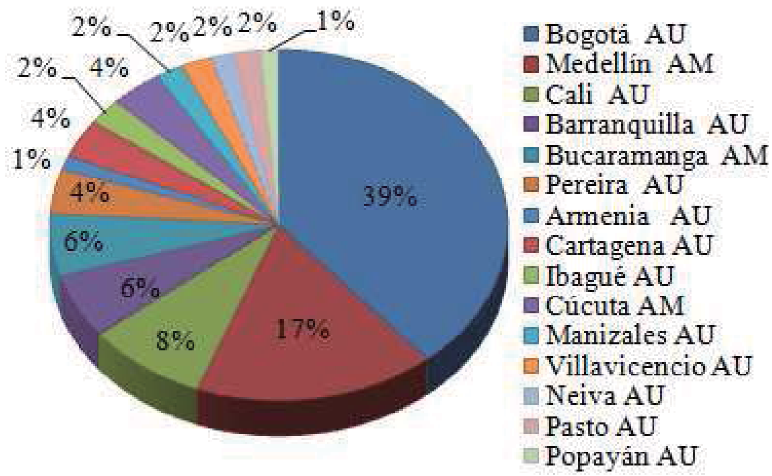


Figure 3. Distribution of censused area of construction by cities as of IV trimester of 2009 [15]

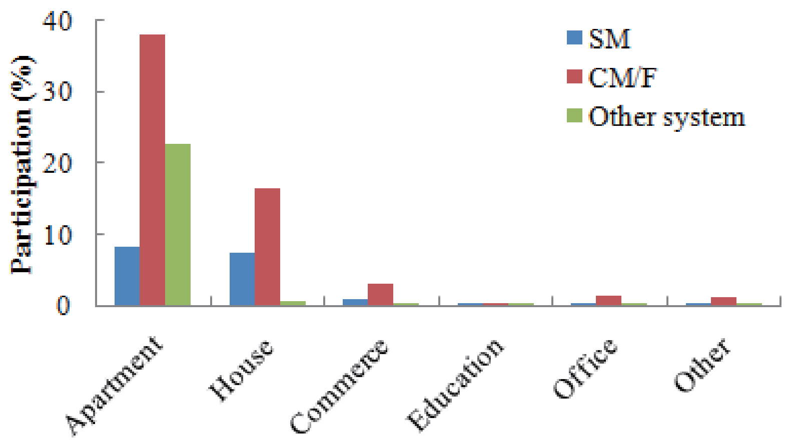


Figure 4. Distribution of censused new projects by type of construction as of IV trimester of 2009 [15]

The objective of this report is to provide an overview of the current situation of low-rise wall structures in Colombia by summarizing information gathered by the team members, particularly on construction and design practices, as well as on efforts being made in the country to reduce the seismic vulnerability of this type of building structures. Thus, we hope that this report contributes to seismic prone countries of the world in order to help mitigate the damaging effect of earthquake ground motions on building structures.

2. OUTLINE OF THE COLOMBIAN EARTHQUAKE RESISTANT STANDARDS FOR LOW-RISE WALL STRUCTURES

In this section, an overview of the history of the Colombian standards for earthquake resistant constructions and an outline of the regulations for low-rise wall structures are presented.

2.1 History of the Colombian Earthquake Resistant Standards

The first step toward the development of a local seismic code in Colombia was the translation of the 1974 SEAOC [18] requirements to Spanish by the Colombian Association of Earthquake Engineering (AIS: "Asociación Colombiana de Ingeniería Sísmica" in Spanish); document that was widely distributed in the country. Soon after, in 1979, the AIS translated the ATC-3-06 [19] document into Spanish. Two years later, the AIS 100-81 [20] document was developed as a set of regulations for earthquake resistant design and construction in 1981. The first Colombian code set in practice (CCCSR-84, Colombian Code for Earthquake Resistant Constructions) was authorized by the Government of Colombia (Decree 1400 of 1984) through the AIS 100-83 [21] document and published in May 1984, incorporating regulations for RM and URM wall structures for the first time. The CCCSR-84 standard was revised, being replaced by the NSR-98 standard [7] (Colombian Standards for the Design and Construction of Earthquake Resistant Structures; Decree 33 of January 9 of 1998). After a period of continuous effort, the NSR-10 standard [6] (Colombian Standards for Earthquake Resistant Constructions) has been recently published, replacing the NSR-98 standard. The NSR-10 standard was set in practice after being authorized by the Government of Colombia through the Decree 926 of March 19 of 2010.

2.2 Development of Regulations for Low-rise Wall Structures

As previously mentioned, regulations for both URM and RM low-rise wall structures, as well as a particular set of simplified design and construction regulations for one- and two-story dwellings built with masonry bearing walls were firstly introduced in the CCCSR-84 standard through the Title D (Structural Masonry) and Title E (One and Two Story Dwellings), respectively. The Title E, unique in the world, was developed to reduce the impact on non-engineered URM dwellings by providing persons, not necessarily engineers or architects, with a set of practical rules on how to build an earthquake resistant low-rise wall house. The requirements in both titles were developed based on the experience gained in the country with these types of wall structures since the 1970s, and in response to their increasing popularity throughout the country.

The NSR-98 standard revised both the Title D and E of the CCCSR-84, taking into consideration local research efforts and construction experience gained in the country since 1984. In the Title D, the scope for the use of structural masonry was widened, including design requirements for CM wall structures for the first time as a result of extensive research programs carried out by the Los Andes University [7]. Moreover, construction requirements, and quality control and construction material testing procedures were revised. With regard to the structural design method, although the Limit State Design for Resistance method (LSD: "método del estado límite de resistencia" in Spanish) was regarded in the NSR-98 as the main calculation method for wall structures, the NSR-98 also permitted the use of the Allowable Stress Design method (ASD: "método de los esfuerzos admisibles" in Spanish) as an alternative procedure. In the Title E, simplified design and construction requirements were modified to be compatible with those of

CM in the Title D, and the use of cemented bahareque ("bahareque encementado" in Spanish) walls was incorporated for the first time.

The NSR-10 standard revised and updated both the Title D and E of the NSR-98. In the Title D, a more clear classification of structural masonry systems is provided, which comprises seven types of systems for wall structures. Among these seven types, the system 'externally reinforced masonry' ("mampostería reforzada externamente" in Spanish) is introduced for the first time as an alternative for low-rise dwellings built in zones of low seismic hazard. In general, modifications to and new requirements included in both Title D and E are based on numerous local experimental research outputs and construction experience gained in the country since the NSR-98, leading to an improved earthquake resistant standards for wall structures.

2.3 Current Regulations for Low-rise Wall Structures in the NSR-10 standard

The Colombian seismic code aims to regulate the design and construction of any type of structures through the country. The current standards, NSR-10, is divided into 11 Titles as follows:

A. General requirements for earthquake resistant design and constructions
B. Loads
C. Structural concrete
D. Structural masonry
E. One- and two-story houses
F. Steel structures
G. Wooden and bamboo structures
H. Geotechnical studies
I. Technical supervision
J. Fire-protection requirements for building structures
K. Other complementary requirements

Table 2. Bearing wall structural systems for masonry [6]

Bearing Wall Systems		R_0 (1)	Ω_0 (2)	Seismic Risk Zone					
				High		Intermediate		Low	
Earthquake resistant system (horizontal load)	Vertical load resistant system			Allowed?	Max. height	Allowed?	Max. height	Allowed?	Max. height
Reinforced masonry walls of vertical hollow bricks. All brick cells are filled with mortar/grout (DES)	The same	3.5	2.5	Yes	50 m	Yes	No limit	Yes	No limit
Reinforced masonry walls of vertical hollow bricks (DMO)	The same	2.5	2.5	Yes	30 m	Yes	50 m	Yes	No limit
Partially reinforced masonry walls of vertical hollow bricks (DMO)	The same	2.0	2.5	Group I	2 stories	Yes	12 m	Yes	18 m
Confined masonry	The same	2.0	2.5	Groups I and II	15 m	Groups I and II	18 m	Groups I and II	21 m
Reinforced cavity masonry walls	The same	4.0	2.5	Yes	45 m	Yes	60 m	Yes	No limit
Unreinforced masonry walls (no energy dissipation capacity)	The same	1.0	2.5	Not permitted		Not permitted		Group I (3)	2 stories

(1) Seismic modification factor
(2) Overstrength factor
(3) Allowed in low-risk seismic zones where acceleration coefficient is lower than 0.05.

Any building structure to be built should fall into any of the four types of structural systems stipulated by the NSR-10: Bearing walls systems, combined systems, frame systems and dual systems. Table 2 shows the masonry structural systems under the category of bearing walls.

In Table 2, Groups I and II refer to normal occupancy structures and special occupancy structures, respectively. DMI, DMO and DES refer to the energy dissipation capacity in the inelastic range of a structural system. The NSR-10 stipulates three levels of energy dissipation capacity, namely: DMI (minimum capacity), DMO (moderate capacity) and DES (special capacity).

2.3.1 Calculation steps

In general, any type of new or existing masonry structure adopts the following calculation procedure:

1. Pre-dimensioning and coordination with other professionals
2. Evaluation of loads
3. Localization and determination of level of seismic risk (acceleration coefficient A_a and velocity A_v)
4. Definition of the design earthquake ground motion (based on the acceleration, site and importance coefficients)
5. Definition of the earthquake resistant system (bearing walls, combined, frame or dual system), structural materials (R/C, steel, wood, masonry, timber) and energy dissipation capacity (DMI, DMO or DES)
6. Definition of grade of irregularity of structure (based on plan and elevation irregularity coefficients) and analysis procedure (equivalent horizontal force, elastic dynamic analysis or inelastic dynamic analysis method)
7. Definition of design earthquake force
8. Structural analysis
9. Calculation of horizontal displacements
10. Verification of story drifts (drift limit: 0.5% of story height h_{pi})
11. Combination of different loading conditions
12. Design of structural elements
13. Design of foundations
14. Design of non-structural elements
15. Revision of structural design
16. Construction and technical supervision

2.3.2 Requirements for structural masonry (Title D)

The Title D of the NSR-10 corresponds to Structural Masonry and contains 12 chapters and an appendix, herein briefly presented, highlighting the most relevant aspects.

Chapter 1: General requirements.

- Minimum requirements for structural drawings and calculation
- Supervision is mandatory
- Masonry wall structures are to be designed by the LSD method. However, the ASD method is also permitted.

Chapter 2: Classification, use, requirements, nomenclature, and definitions. As previously mentioned, masonry wall structures are divided into seven types: (a) reinforced cavity masonry, (b) reinforced masonry, (c) partially reinforced masonry, (d) unreinforced masonry, (e) confined masonry, (f) diaphragm wall masonry and (g) externally reinforced masonry. This chapter also presents requirements for quality control and minimum mechanical properties of materials used for masonry construction (according to the NTC standard), as well as construction practices for this type of structures. The NTC standard is equivalent to the ASTM standard in The United States, and it is stipulated that ASTM standard should be followed in case there is not any requirements in the NTC standard for a particular structural material.

Chapter 3: Quality of materials for structural masonry. It presents the minimum requirements for materials used for structural masonry, such as water, mortar, infill mortar, sand, reinforcement and masonry units. The compressive strength of infill mortar f'_{cr} is limited to be as large as 1.5 times the compressive strength of masonry wall f'_m. Vertical and horizontal hollow and solid clay, concrete and silica-calcareous masonry units are permitted, as shown in Fig. 5. The area of vertical cells of a vertical hollow brick must not exceed 65% of the entire cross-sectional area of the brick. The dimension of cells of vertical and horizontal hollow bricks must not be lower than 50 mm, and external and internal walls of brick must not be lower than those in Table 3. It is worth mentioning that in Table 3, the nominal external thickness determines the thickness of masonry wall.

Table 3. Minimum dimension for masonry units [mm]

Nominal external thickness	External wall thickness	Transversal wall thickness
100	20	20
120	22	20
150	25	25
200	30	25
250	35	30
300	40	30

Vertical hollow bricks are permitted in the seven types of structural masonry mentioned above. On the other hand, horizontal hollow and solid bricks are permitted only in reinforced cavity, confined and externally reinforced masonry walls. Table 4 shows the minimum requirements for compressive strength of mortar. For a mortar type, the higher value of compressive strength between its minimum requirement given in Table 4 and the value used in the design should be specified in the necessary documents for construction.

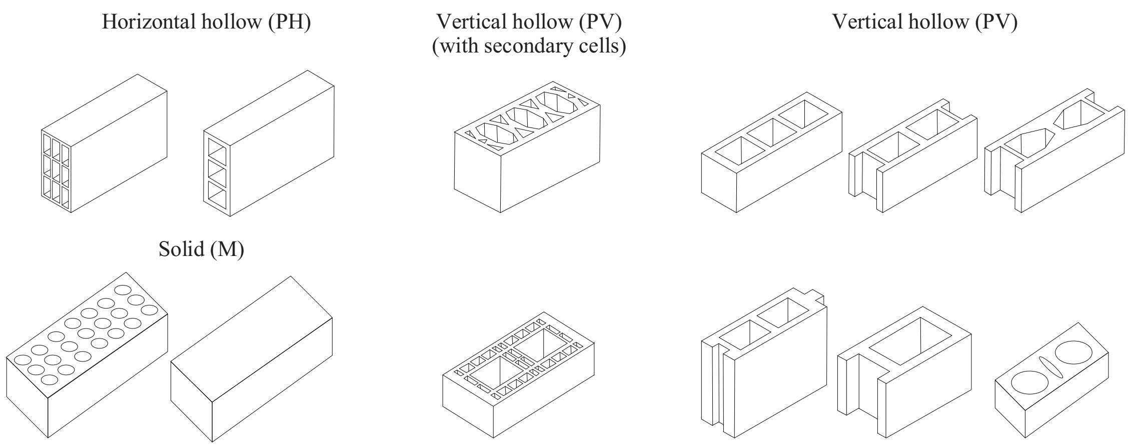


Figure 5. Permitted masonry units.

Table 4. Mortar properties [6]

Mortar type	N	S	M	H
Compressive strength (f'_{cp}) [MPa]	7.5	12.5	17.5	22.5

Chapter 4: Construction requirements for structural masonry. It presents recommendations for reinforcement detailing, reinforcement embedded in the mortar, development and overlap length of reinforcement. Moreover, this chapter provides construction recommendations for mortar and infill mortar, for foundations and masonry walls, and recommendations for adequate curing practices.

Chapter 5: General requirements for analysis and design. It presents all requirements for the design of masonry structures by the LSD design method; however, the ASD design method is also presented as an alternative for the design.

Chapters 6 to 12 provide minimum requirements for the seven types of masonry wall stipulated in the NSR-10. Hereafter, a short description of each type is presented and a comparative table is given in Appendix.

Chapter 6: Reinforced cavity masonry. It presents technical guidelines and requirements for this type of masonry walls. As seen in Fig. 6, a reinforced cavity masonry wall consists of two masonry walls with a cavity in between them that is reinforced and filled with infill mortar/grout after the construction of the two external walls. The minimum wall thickness is 190 mm (cavity wall: 50 mm and masonry walls: 70 mm). Fluid concrete can also be used for the inner cavity. Minimum reinforcement ratio with respect to the gross cross-sectional area of the cavity is 0.0015 and 0.002 for vertical and horizontal reinforcement, respectively. The spacing of reinforcement in the cavity must be larger than 50 mm and lower than 400 mm. The size of rebar at wall ends, openings, top and bottom must be No.4 (1/2") as minimum.

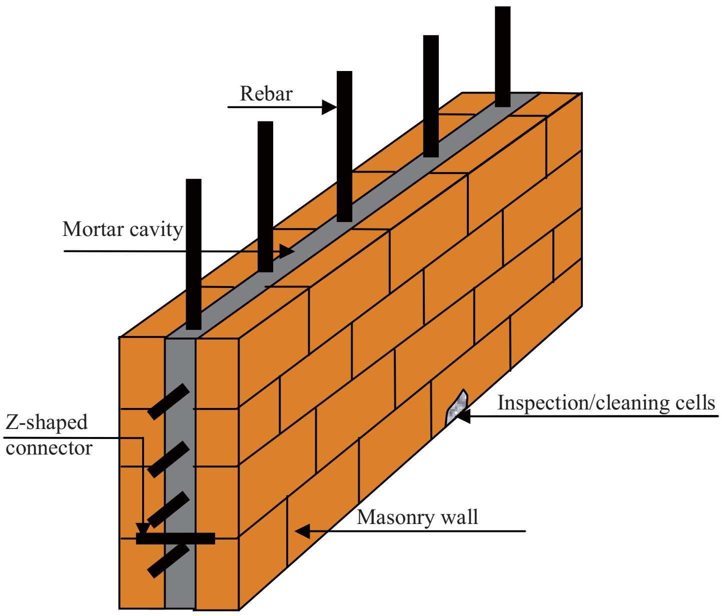


Figure 6. Schematic of a reinforced cavity masonry wall.

Chapter 7: Masonry walls built with vertical hollow bricks. This chapter presents technical guidelines and requirements for reinforced masonry walls built with vertical hollow bricks. The following requirements are given:

- Minimum wall thickness: 120mm
- Type N mortar is not permitted
- Minimum compressive strength of wall, f'_m: 10MPa
- Energy dissipation capacity: DMO (R_0=2.5)
- Minimum reinf. ratio (vertical and horizontal): 0.0007
- Spacing of vertical rebar: ≤ 1200mm
- Size of rebar at wall ends and at openings: ≥ No.4 (1/2")
- Diameter of horizontal rebar embedded in mortar: ≥ ϕ 4 mm
- Spacing of horizontal rebar embedded in mortar: ≤ 600 mm
- Spacing of horizontal rebar in special bricks: ≤ 120 mm
- Minimum rebar in beams at top and bottom of a wall: 2@No.3(3/8")

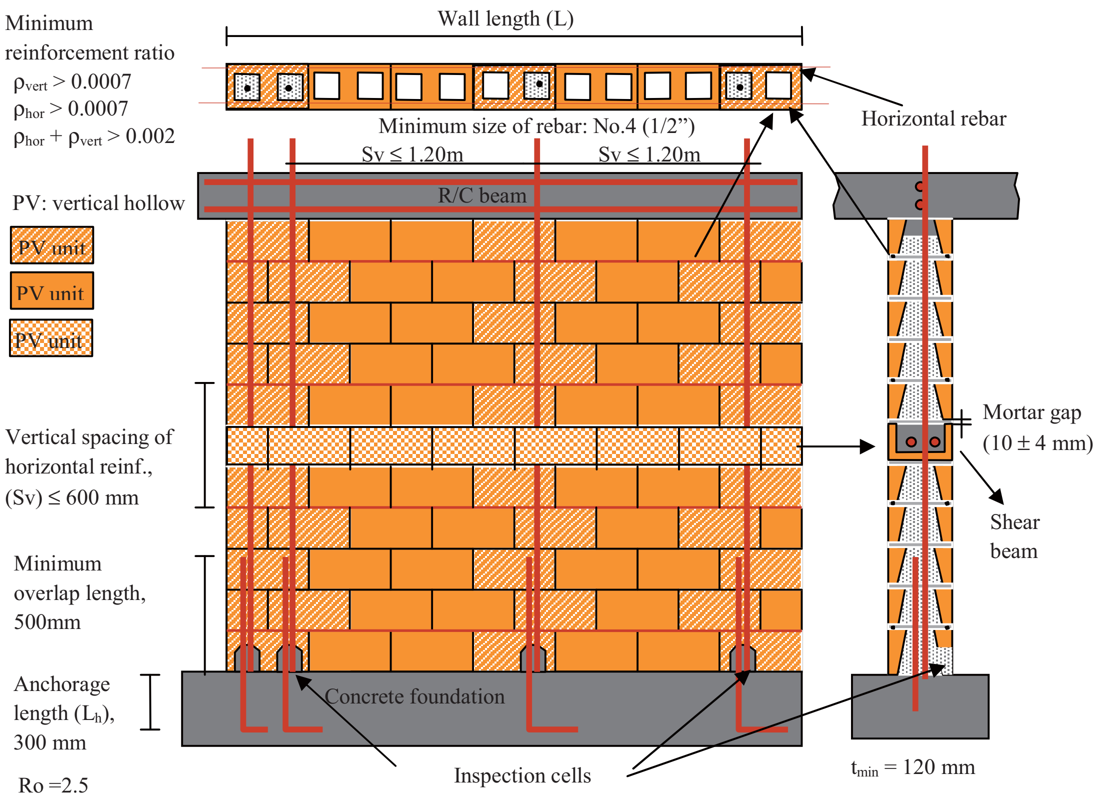


Figure 7. Schematic of a DMO reinforced masonry wall.

In reinforced masonry walls, if all brick cells are filled with mortar/grout, the energy dissipation capacity is assumed to be special (DES, R_0=3.5); but If only cells with vertical reinforcement are filled with mortar, the energy dissipation capacity is considered as moderate (DMO, R_0=2.5), as illustrated in Fig. 7.

Chapter 8: Partially reinforced masonry walls built with vertical hollow bricks. The following requirements are given:

- Minimum wall thickness: 120mm
- Type N mortar is not permitted
- Minimum compressive strength of wall, f'_m: 8MPa
- Energy dissipation capacity: DMO (R_0=2.0)
- Minimum reinf. ratio (vertical and horizontal): 0.00027
- Spacing of vertical rebar: ≤ 2400mm
- Size of rebar at wall ends and at openings: ≥ No.3 (3/8")
- Diameter of horizontal rebar embedded in mortar: ≥ ϕ 4 mm
- Spacing of horizontal rebar embedded in mortar: ≤ 800 mm
- Spacing of horizontal rebar in special bricks: ≤ 3000 mm
- Minimum rebar in beams at top and bottom of a wall: 2@No.3(3/8")

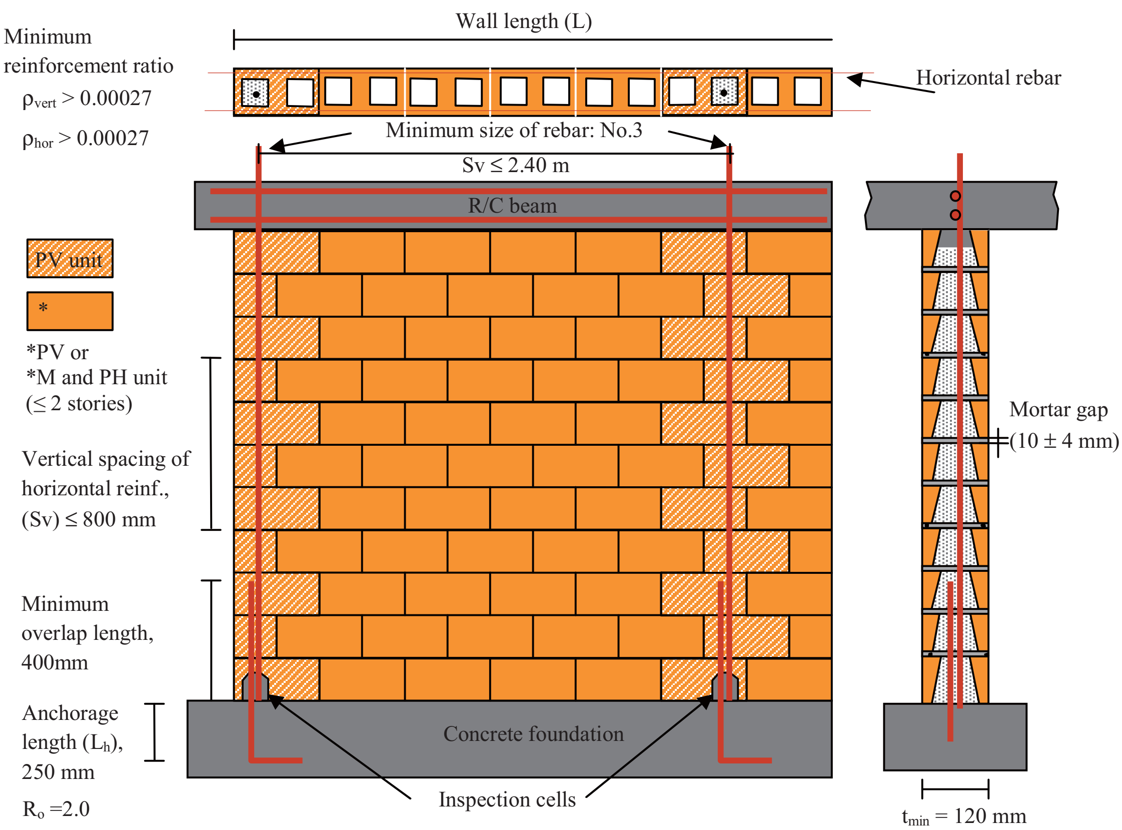


Figure 8. Schematic of a DMO partially reinforced masonry wall.

Partially reinforced masonry walls are similar to those of DMO reinforced masonry in a way that only cells with vertical reinforcement are filled with mortar/grout. However, the two types of masonry differ from each other in terms of reinforcement detailing and minimum requirements, as seen in Fig. 9.

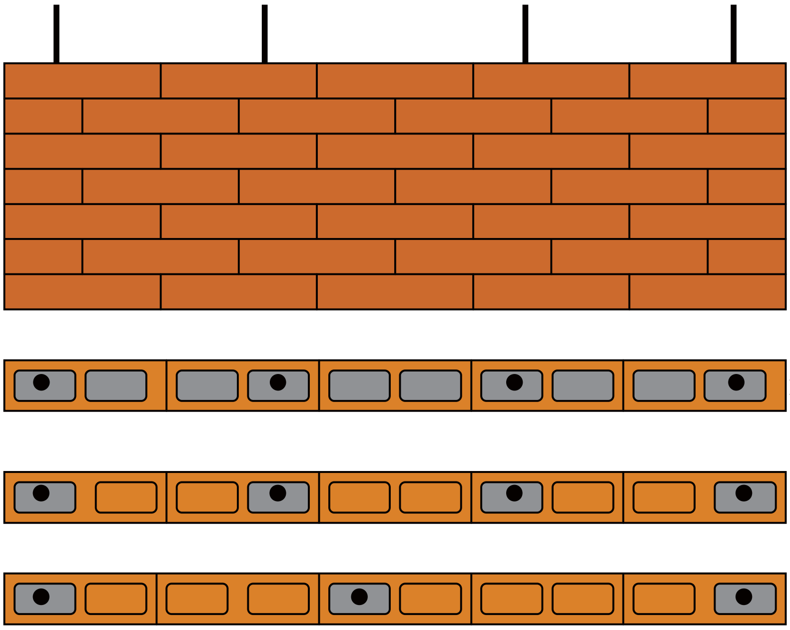


Figure 9. Schematic of reinforced and partially reinforced masonry walls.

Chapter 9: Unreinforced masonry walls. This type of construction is permitted in low-risk seismic zones where acceleration coefficient is lower than 0.05. URM walls must be designed by the ASD method. The minimum wall thickness is stipulated as 120 mm.

Chapter 10: Confined masonry walls. Confined masonry walls should have full continuity from foundation to roof level. The surrounding, confining RC beams and columns must be constructed after the completion of the inner wall, and concrete should have a minimum compressive strength of 17.5 MPa. All reinforcement must be placed in the RC elements. The minimum thickness of confining RC columns is the thickness of the wall. The minimum cross-sectional area of confining elements is 20,000 mm^2. RC columns must be placed at wall ends, at the intersection of walls and at other locations given by spacing limits. RC beams must be placed at top and bottom of a wall at each story and at other locations within a story height depending on spacing limits. The minimum reinforcement ratio for RC columns is 0.0075 with respect to the cross-sectional area, and the minimum size of rebar is No.3 (3/8”).

Chapter 11: Diaphragm walls. According to the NSR-10, diaphragm walls are those with full continuity from foundation to roof level and that are fully attached to the surrounding RC frames so that walls stiffen the whole structure in a similar manner as concentric braces do. Diaphragm walls must not have any openings and must be designed to resist forces generated as a result of their interaction with the RC frames.

Diaphragm walls can be constructed either before or after the RC frames, as long as an adequate attachment to the RC frames is assured. Here, it should be noted that this type of construction is not permitted for new structures but for the reform of existing structures built before the NSR-98 standard.

Chapter 12: Externally reinforced masonry walls. This type of construction consists of a masonry wall externally reinforced with electro welded steel wire meshes that are embedded in the finishing mortar on the wall surface. Reinforcement should be placed at both wall surfaces and fastened with connectors and/or steel nails/studs. The minimum wall thickness is 130 mm (masonry wall: 90 mm and finishing mortar: 40 mm).

Appendix D1: Design of structural masonry by the ASD method. This appendix presents recommendations for the design of structural masonry structures by the ASD method. Load combinations, allowable stresses for tension, compression, shear and in- and out-of-plane bending in masonry walls, and allowable stress for reinforcement are given.

3. OUTLINES OF CONSTRUCTION PRACTICES FOR LOW-RISE WALL STRUCTURES

3.1 Type of Constructions

The history of low-rise wall structures in Colombia dates back to the 1970s when bearing walls started to be used as a viable solution [7] in the structural design. From the early 1970s, however, frame structures remained as the most prevalent structural system in Colombia, until just after the NSR-98 standard was set on practice in the latest 1990s. The NSR-98 brought along more strict requirements for story drifts, which led wall structures to regain popularity in Colombia. To date, wall structures is the most prevalent structural system in Colombia and has got an important place in the urban planning of most cities in the country, covering different types of use. In general, wall structures are most used for dwelling purposes, from low- to high-rise buildings. RM and CM wall structures are more common in low- and mid-rise buildings and in low-rise buildings, respectively, whereas reinforced concrete (RC: "concreto reforzado" in Spanish) walls and the combination of RC and RM wall structures are most common in high-rise buildings. However, there still exist a large number of URM, adobe or rammed earth ("tapia pisada" in Spanish) one- and two-story dwellings all over the country, even in high or intermediate seismic risk regions at which the use of these types of structures is not permitted[6]. Adobe and rammed earth wall dwellings basically correspond to old urban housing projects or rural housing. In general, the structural integrity of these two types of construction is low since it is significantly affected by the lack of an adequate maintenance, poor quality of construction materials, and by continuous modifications (e.g., openings) to bearing walls. It has been reported severe structural damage and impact on habitants in these types of low-rise wall structures in many past earthquakes in Colombia.

Another two types of wall structures in Colombia, which have been used for low-cost housing projects, are the ferrocement ("muros en ferrocemento" in Spanish) and cemented bahareque wall structures. A brief description of the history of ferrocement wall structures in Colombia can be found elsewhere [e.g., 22]. Here, it should be noted that ferrocement wall structures are not included in the Colombian seismic code. On the contrary, the use of cemented bahareque wall structures is permitted but only for one- and two-story houses [6]. The application of these two types of wall structures, however, has been limited to a very small number of housing projects in Colombia.

Although the use of URM wall structures is not permitted in high and intermediate seismic risk zones, its application is still very popular throughout the country, especially in low-budget, empirically built dwellings. To date, the most common three types of construction for dwelling purposes in Colombia are URM, CM and RM wall structures.

3.1.1 Unreinforced masonry (URM) [23]

Masonry walls of this type of construction are usually composed of solid or horizontal hollow clay bricks with no reinforcement that are joined together through a low-resistant mortar. Up to the early 1950s, solid clay bricks were often used for walls, with a slenderness ratio of about 1/6. Wooden floor slabs and heavy roofs were often used for houses of more than one story. From early 1950s to early 1970s, horizontal hollow bricks gained more popularity together with the use of Portland cement for mortar and floor slabs. The slenderness ratio of wall became 1/12. From early 1970s, there was a significant demand of housing projects that triggered the spread of this type of construction, even up to 3- to 5-story buildings. Improved floor slab systems led to the use of longer spans and to the reduction of area of bearing walls per floor, which certainly increased the seismic vulnerability of this type of dwellings. The slenderness ratio of wall became about 1/20. URM walls have been traditionally applied to houses, churches and some institutional buildings.

3.1.2 Reinforced masonry (RM)

This type of construction started to be used in Colombia in the 1970s, following the engineering practice in The United States [23]. RM walls are usually composed of vertical hollow clay or concrete bricks with vertical and horizontal steel reinforcement. Vertical steel bars are inserted in specific cavities of certain bricks that are also filled with grout, and horizontal reinforcement is placed in mortar. To date, clay bricks have been more employed than concrete bricks, which has led to a wide range of types of brick units for structural purposes. RM walls are well attached to solid floor slabs. The most common thickness for RM walls is 120 and 150 mm for clay and concrete bricks, respectively. Horizontal hollow bricks can also be used in between zones at which there is vertical reinforcement.

3.1.2 Confined masonry (CM)

This type of construction started to be used in Colombia in the 1930s and became the most prevalent structural system in the early 1970s [23]. Since then, it has kept its popularity and is still the most common type of construction in Colombia, as seen in Fig. 4. CM walls are commonly used in one- to five-story building structures. CM walls consist of horizontal hollow clay bricks surrounded by an RC frame which confines the masonry wall. The surrounding RC frame is intended to help resist shear and tension forces generated in the wall during an earthquake motion.

3.2 Urban Development

From a general stand point, construction licenses are approved by special local governmental offices located in different zones of a city or department. These offices are to check and confirm that the project under application fully complies with (1) requirements of the current earthquake resistant standards, (2) architectural requirements and (3) urban development law. In general, an engineer working at these governmental offices is the one to evaluate applications for granting the corresponding construction license; however, it is also permitted that the owner of a project seeks for a qualified engineer who can certify the conformity of the designs of the project with what by law.

4. EARTHQUAKE DAMAGE IN LOW-RISE WALL STRUCTURES

As listed in Table 1, Colombia has been affected by the destructive effects of earthquake motions in several occasions in the last three decades. This section provides an overview of recent earthquakes and their impact on low-rise dwellings structures.

- Coffee-growing Region, 1979/11/23 [24]

The November 23, 1979, earthquake struck the center of the country, generating damages in a vast area. There was a significant structural damage in low-rise dwellings as well as the collapse of some 4- to 6-story building structures. Building structures with an adequate structural design and construction process behaved satisfactorily.

The most common type of construction affected during this earthquake was one- to two-story URM dwellings built with clay masonry; church towers built in the same manner were highly affected as well. This ground motion also triggered landslides that destroy a significant number of houses. In neighboring cities to the epicenter zone, non-structural, façade and partition walls suffered some extent of damage in many RC frame structures. Fig. 10 shows the collapse of low-rise masonry dwellings.

(a)

(b)

Figure 10. Affected dwellings: a) Milan (Manizales city), and b) Pereira city. (Source: Ramírez, Jesús Emilio y José Goberna, "Terremotos colombianos Noviembre 23 y Diciembre 12 de 1979")

- Popayán earthquake, 1983/3/31 [24]

The March 31, 1983, Popayán earthquake generated a significant impact on the community and infrastructure of the city. Popayán is characterized by having a colonial architecture, with old buildings structures made of adobe with little or no reinforcement. As a consequence of this earthquake motion, about 70% of building structures in Popayán suffered structural damage and 12% and 34% of dwellings collapsed and were severely affected, respectively [25].

The structural damage spread over the entire city. Some areas of the city were more affected than others due to differences in type, quality and age of structures of each neighborhood. However, modern neighborhoods were affected as well. This is the case of the Pubenza Condominium where severe damage was accounted for the existence of a weak first story caused by the disruption of the vertical continuity of structural walls, as seen in Fig .11. This failure pattern was observed in many low-rise wall structures.

Fig. 12 shows other a collapse pattern observed in modern low-rise wall structures. Here, this 4-story masonry wall structure presented shear failure between the structural walls and the floor slab. It is clearly observed the out-of-plane failure of structural walls.

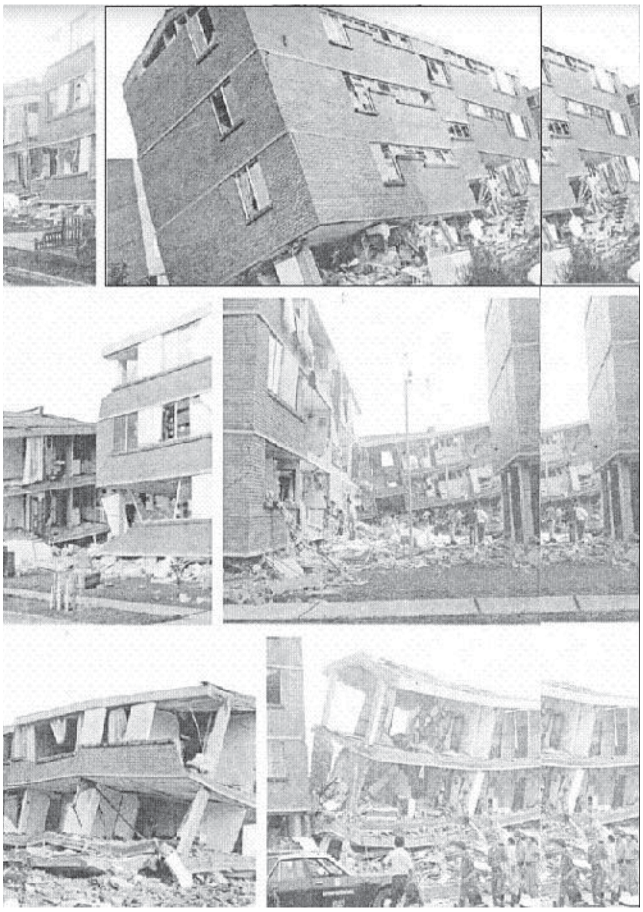


Figure 11. Collapse of Pubenza Condominuim (Source: Paredes Pardo, Jaime. Popayán, Litografía Arco. Bogotá, 1983)

Figure 12. Collapse of a modern masonry wall structure [26].

Figure 13. Structural damage in the Metropolitan Cathedral.

Figure 14. Structural damage in the Santo Domingo Temple.

Another type of structure highly affected by the earthquake motion was colonial churches. In this type of structures, sever damage was caused by the lack of bracing at roof truss. The collapse mechanism started at the roof level where trusses would push out walls, generating the collapse of most bearing walls. The lack of an adequate diaphragm action at roof level and adequate connection between perpendicular walls led structural walls to behave independently, becoming highly vulnerable to horizontal accelerations [23]. Moreover, the failure of corner colonial constructions was another major collapse pattern. Figs. 13 to 15 show structural damage in colonial structures.

- Murindó, 1992/10/18 [24]

The October 18, 1992, Murindó earthquake generated a vast destruction in the Atrato region, particularly the areas of Murindó and La Isla communities. Effects such as soil liquefaction and landslides also caused a high impact on the community. Fig. 16 shows structural damage in low-rise unreinforced, unconfined clay masonry wall dwellings.

In the city of Medellín, located about 120vkm from the epicenter, many building structures were affected by the Murindó earthquake. It was reported that most of the damaged occurred in non-structural masonry elements of building structures [23]. As a result of a large extent of economical loss occurred in building structures in Medellín, story drift limits were then revised in the NSR-98 standard, as well as methods to separate non-structural walls from the main structural system.

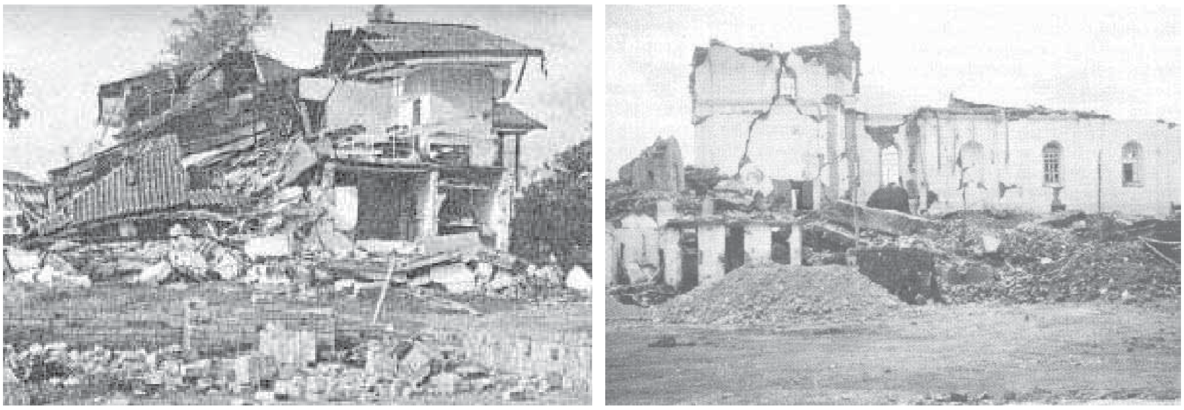


Figure 15. Collapse of rammed earth colonial houses. (Source: Peñuela Ramírez, Alvaro. Popayán, Ediciones Avanzada Ltda. Bogotá, 1984)

Figure 16. Typical damage pattern in Belén de Bajirá, en Mutatá. (Source: El Colombiano, Medellín. Octubre 21, Pág.1)

- Coffee-growing Region, 1999/1/25 [24]

The January 25, 1999, Armenia earthquake is the recent seismic event that has generated the largest extent of destruction in Colombia. Not only did this ground shaking bring material loss but also many casualties and social chaos. It was reported that about 75% of the total number of affected structures corresponds to one- and two-story dwellings [27]. The ground shaking had a significant impact on low-rise wall dwellings, especially those of rammed earth, bahareque and URM walls completed before the CCCSR-84 standard.

Other aspects that contributed to the high level of destruction that occurred were landslides, poor quality of construction materials and practices, significant asymmetry, lack of confinement and dwelling projects built on heterogeneous deposits in filled areas that amplified the ground acceleration [11]. Figs. 17 and 18 show some examples of the extensive structural damage caused by the coffee-growing region earthquake of 1999. Here, it is worth mentioning that a large number of those injured and/or dead were victims of the fall of non-structural façade walls.

(a) (b)

Figure 17. Damage on masonry structures: a) two-story house, and b) old church [28].

Figure 18. Collapse of several one- and two-story wall houses at the south part of Armenia [28].

- Quetamme, 2008/5/24 [14, 29]

During the May 24, 2008, Quetame earthquake, many dwellings resulted affected and some collapsed. Poor construction practices together with heavy roofs and insufficient foundations led to the collapse of many adobe houses. Fig. 19 shows damage on rammed earth and adobe single-story dwellings.

Figure 19. Typical damage in rammed earth and adobe dwellings in Quetame.

5. CURRENT RESEARCH OUTPUT

This section provides an overview of research efforts carried out by universities, NGO's and private institutions.

In Colombia, most formal and informal constructions correspond to clay masonry wall structures. By tradition, the use of this construction material has been preferred by individuals wanting to give solution to their dwelling needs. This aspect has brought the attention of universities, professional associations, and governmental entities to join efforts toward a reduction of the seismic vulnerability of this type of construction.

The AIS together with the support of national and local government and the FOREC ("Fondo para la Reconstrución y Desarrollo del Eje Cafetero" in Spanish) have been continuously working on the development of simplified manuals of good practice for the construction of one- and two-story masonry wall dwellings, such as the Manual of Earthquake Resistant Construction, Evaluation and Rehabilitation of Masonry Dwellings and the Manual for one- and two-story Constructions. For instance, the Manual of Earthquake Resistant Construction serves as easy-to-understand, illustrated technical guidelines for both construction professionals and non-professionals for the application of at least the minimum construction requirements stipulated in the Colombian Code under the Title E. This manual aims to reduce the seismic vulnerability of informal dwelling projects, i.e., without the supervision of a qualified engineer or architect.

On the other hand, the SENA ("Servicio Nacional de Aprendizaje" in Spanish), governmental entity in charge of the non-professional education in the country, continuously offers courses of good construction practices for low-rise wall masonry dwellings to construction workers.

5.1 Development of Research in Colombia

Before setting on practice the CCCSR-84 standard, most research effort was put on the determination of mechanical properties of materials used for masonry construction (clay masonry bricks, mortar, sand, etc.) and those of masonry walls, as well as on their consistency with international standards. Experimental research programs included the determination of compressive strength and flexural capacity of vertical hollow clay bricks, water absorption index, workability of mortar, horizontal and vertical bearing capacity of full-scale masonry walls, among others.

Between 1984 and 1993, quality controls stipulated in the CCCSR-84 standard helped create a data base of bearing capacity for different types of masonry walls. Thus, research direction changed toward the improvement of the CCCSR-84 standard, especially those requirements for CM walls. For this purpose, Los Andes University started an extensive experimental program to determine the mechanical properties of all types of masonry brick units fabricated in the country and the load-carrying capacity, shear strength, compressive strength of masonry walls, and to evaluate retrofitting methods for this type of constructions.

From 1993 until the present time, universities and private entities have been researching continuously on new construction techniques toward a reduction of the seismic vulnerability of masonry wall structures, as well as on the development of new wall-based structural systems. Hereafter, an outline of research efforts carried out by some universities in Colombia, which contributed to the current status of the development of the investigation on wall structures in the country, is presented.

Los Andes University:
- Cyclic loading and shaking table tests on horizontally- and vertically-loaded masonry walls.
- Retrofitting methods for rammed earth and adobe walls.
- Dynamic tests on full-scale masonry wall systems to evaluate the structural performance.

EAFIT University:
- Shaking table tests to evaluate the out-of-plane response of URM walls.
- Shaking table tests to validate mathematical models for uniaxial and biaxial bending in walls.
- Validation of structural systems through shaking table tests toward their inclusion in the Colombian code as a type of construction suitable for seismic zones.

Santander Industrial University:
- Analytical research programs on the estimation of seismic damage in masonry wall structures through simulated vulnerability functions based on the real status of masonry construction in Colombia, damage indexes and damage probability matrices.

Colombian School of Engineering:
- Analytical studies on masonry wall structures to compare different design and analysis methods commonly used in the Colombian engineering practice for this type of structures.

National University of Colombia:
- Research programs on historic wall structures such as bridges and dwellings.
- Detailed analytical studies on historic wall structures to develop new techniques for the rehabilitation and maintenance of colonial architecture and national heritage.
- Experimental studies on masonry walls with boundary columns to determine the load-carrying capacity, seismic modification response factor (factor R) and curvature and displacement ductility.
- Experimental studies on clay solid brick walls horizontally reinforced by steel elements.

Medellín University:
- Analytical studies to compare different methodologies for evaluating the seismic vulnerability and performance of ferrocement wall dwellings.
- Shaking table tests on ferrocement wall dwellings and prestressed masonry walls.

Javeriana University:

- Experimental studies on religious colonial adobe wall structures to evaluate the seismic performance.
- Seismic retrofitting of religious colonial adobe wall structures through steel tensors.
- Finite element analysis of adobe wall structures.

Other universities:

- Influence of URM walls on the inelastic behavior of RC frames.
- Compressive strength of existing masonry walls.
- Mechanical characteristics of concrete block masonry walls.

5.2 Research Efforts on Construction of Mid- and High-rise Wall Structures

This section presents a general description of some aspects of the current situation of the construction of mid- and high-rise wall structures, particularly in Medellín city, as well as research efforts to improve the seismic performance of this type of structures.

Mid- and high-rise building structures have gain popularity in the recent years, as a result of a densification of population in major cities of the country. Among them, wall structures are playing an important role in the development of urban areas so as to provide a feasible solution for housing needs. In cities such as Medellín and Bogotá, mentioned previously as the two cities that currently contribute the most to the construction industry in the country, mid- and high-rise wall structures usually consist of RM or RC walls or the combination of RM and RC walls at the same floor. RM wall structures of either clay or concrete bricks/blocks are often used from three- to eight-story buildings, whereas RC walls or the combination of RC and RM walls are often used for taller buildings, generally up to 20 stories.

Recently, there have been an increasing number of applications for high-rise wall structures in which RC walls are used for the lower and middle stories while RM walls are used for the upper stories, generally within the uppermost eight stories. For instance, in the case of a 20-story wall structure, RC walls are used from the first to the 12th story and RM walls are used for the remaining eight stories. This construction practice intends mainly to avoid the potential failure of RM walls at lower stories when subjected to high compressive stresses such as in the case of high-rise buildings under ground motion excitations.

The height limit for mid- and high-rise wall structures depends on the level of seismic hazard and on the energy dissipation capacity of the structural system. Table 5 shows permitted heights for construction of wall structural systems (commonly used for mid- and high-rise buildings in Colombia) as a function of the structural system, energy dissipation capacity and level of seismic hazard.

Table 5. Height limit for wall structures [6]

Structural system	Energy dissipation capacity	Seismic risk level		
		High	Intermediate	Low
RC walls	DES	50 m	No limit	No limit
	DMO	Not permitted	50 m	No limit
	DMI	Not permitted	Not permitted	50 m
RM walls	DES	50 m	No limit	No limit
	DMO	30 m	50 m	No limit

In the case of mid- and high-rise RC wall structures, wall thicknesses from 200 to 350 mm and compressive strengths from 28 to 42 MPa are often used at lower stories, whereas for middle and upper stories, wall thickness and compressive strength decrease to about 100 mm and 21 MPa, respectively. On the other hand, in the case of RM wall structures, the engineering community together with several universities in the country have been very active toward the development of masonry units and mortars of high compressive strength to overcome the high compressive strength required in high-rise wall building structures. Recently, local universities together with the masonry industry have joined efforts toward the development of high-resistant masonry units (e.g., [30]). As a result, masonry units with a compressive strength as large as 40 MPa have been used in several projects in Medellín and other cities in the country. Regarding the strength requirements for the mortar, the NSR-10 included for the first time, the mortar type H for use in high-rise constructions, as shown in Table 4.

6. FUTURE WORKS

Based on the history and development of masonry construction in Colombia, major concerns for this type of construction can be summarized as the lack of good construction practices and control of informal/non-engineered constructions, along with its large number of housing projects, especially in neighborhoods of low-income families. In Colombia, masonry units are still widely used from small housing (as bearing walls) up to high-rise building (not only as structural but partition and façade walls) projects. In the case of mid- and high-rise building structures, masonry elements present disadvantages such as heavy weight, need of an adequate attachment between walls and floor slabs (which is somehow expensive) and an inadequate interaction of walls and main structural system, which might affect the structural performance under earthquake excitations.

Despite the abovementioned, non-engineered masonry construction is still considered by low-income family zones as the best solution for their housing needs (for both new projects and reforms). This is because masonry construction offers the possibility of purchasing material constructions little by little as their budget permits, and because this group of project owners consider that there is no need of construction professionals to finish their houses; instead, they team up with friends who have some construction experience and can help them finish their projects as time permits. Moreover, masonry construction offers a great sense of security and durability over time.

Thus, special attention is given by national and local government together with universities and private institutions to improve the condition of informal masonry construction, as well as to reduce the seismic vulnerability of both engineered and non-engineered masonry wall structures. The following points outline future research direction:

- Seismic risk awareness programs and technical training for construction workers.
- Implementation of efficient programs of social housing projects led by the national and local government.
- Development of new techniques and solutions for wall structures; light-weight construction materials such as plastic, wood and plaster are given full research attention.
- Detailed experimental programs on strengthening methods for URM and CM walls.
- Development of high compressive strength mortars for RM wall construction.
- Development of new techniques to improve mechanical properties of mortar-to-brick joints.
- Seismic performance of wall structures that combine RC and RM walls.

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APPENDIX. Comparative chart for masonry structural systems.

	Chapter 9		Chapter 10		Chapter 11		Chapter 12	
	Unreinforced masonry		Confined masonry		Diaphragm walls		Externally reinforced masonry	
Energy dissipation capacity	No energy dissipation capacity		DMO		Not specified		DMI	
Seismic risk zone / max. permitted height	High Intermediate Low	Not permitted Not permitted No limit	High Intermediate Low	15 m 18 m 21 m	High Intermediate Low	45 m 60 m No limit	High Intermediate Low	Not specified
Response modification factor R_o	1.0		2.0		2.0		Not specified	
Masonry unit type	PH, PV, M		PH, PV, M		PH, PV, M		PH, PV, M	
Mortar type	H, M, S, N		H, M, S, N		H, M, S, N		H, M, S, N	
Minimum compressive strength	No special requirements		(PH) f'cu = 3 MPa (PV) f'cu = 5 MPa (M) f'cu = 15 MPa		No special requirements		f'm = 8 MPa f'cre = 12.5 MPa	
Minimum wall thickness	120 mm		110 mm		120 mm		130 mm	
Minimum reinforcement ratio	N/A		Special requirements		Special requirements		$\rho_H = 0.00035$ $\rho_V = 0.00035$	
Spacing of vertical reinforcement	N/A		According to confining elements		According to the type of masonry used		Max. 300 mm	
Spacing of horizontal reinforcement	N/A		According to confining elements		According to the type of masonry used		Max. 300 mm	
Minimum vertical rebar	N/A		3 No.3 in RC columns. Reinf. ratio > 0.0075		According to the type of masonry used		Special requirements for steel wire mesh	
Minimum horizontal rebar	N/A		3 No.3 in RC columns. Reinf. ratio > 0.0075		According to the type of masonry used		Special requirements for steel wire mesh	

	Chapter 6	Chapter 7		Chapter 8
	Cavity reinforced masonry	Reinforced masonry with vertical hollow bricks		Partially reinforced masonry
Energy dissipation capacity	DES	DES	DMO	DMO
Seismic risk zone / max. permitted height	High: 45 m Intermediate: 60 m Low: No limit	High: 50 m Intermediate: No limit Low: No limit	High: 30 m Intermediate: 50 m Low: No limit	High: 2 stories Intermediate: 12 m Low: 18 m
Response modification factor R_o	4.0	3.5	2.5	2.0
Masonry unit type	PH, PV	PV	PV	PV
Mortar type	H, M, S, N	H, M, S	H, M, S	H, M, S, N
Minimum compressive strength	f'm = 6.25 MPa f'cr = 12.5 MPa	f'm = 10 MPa	f'm = 10 MPa	f'm = 8 MPa
Minimum wall thickness	190 mm	120 mm	120 mm	120 mm
Minimum reinforcement ratio	In the cavity $\rho_H = 0.0015$ $\rho_V = 0.0020$	$\rho_H = 0.0007$ $\rho_V = 0.0007$ $\rho_V + \rho_V = 0.0020$	$\rho_H = 0.0007$ $\rho_V = 0.0007$ $\rho_V + \rho_V = 0.0020$	$\rho_H = 0.00027$ $\rho_V = 0.00027$
Spacing of vertical reinforcement	Min. 50 mm Max. 400 mm	Max.1200 mm	Max.1200 mm	Max.2400 mm
Spacing of horizontal reinforcement	Min. 50 mm Max. 400 mm	In mortar: < 600 mm Special elements: <1200 mm	In mortar: < 600 mm Special elements: <1200 mm	In mortar: < 800 mm Special elements: <3000 mm
Minimum vertical rebar	Rebar diameter smaller than 0.25 times cavity thickness	1 No.4 at wall ends and at openings wider than 600mm	1 No.4 at wall ends and at openings wider than 600mm	1 No.3 at wall ends and at openings wider than 600mm
Minimum horizontal rebar	Rebar diameter smaller than 0.25 times cavity thickness	In mortar: $< \phi$ 4 mm Embedded elements: No.3	In mortar: $< \phi$ 4 mm Embedded elements: No.3	In mortar: $< \phi$ 4 mm Embedded elements: No.3

Annex 2

Country Report

El Salvador

Country Report WFEO-UNESCO

Guidelines for low rise wall type structures

EL SALVADOR

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CONTENTS

1 Introduction.

1.1 General information

Official name : República de El Salvador

Area: 21,040 km^2

Population: 5,744,113

Density: 341.5/km^2

Capital city: San Salvador

Coordinates: *WGS84* 13° 40′ 0″ N, 89° 10′ 0″ W

Area: 620.86 km^2

Population:1,766,000

Figure 1. Location of El Salvador (Available from: http://en.wikipedia.org/wiki/File:LocationElSalvador.svg)

1.2 Geography

(The following information can be found in Wikipedia).

Situated on the Pacific coast of Central America, El Salvador has Guatemala to the west and Honduras to the north and east. Two parallel mountain ranges cross El Salvador east to west with a central plateau between them and a narrow coastal plain bordering the Pacific Ocean. The mountain ranges and central plateau cover 85 percent of the land comprise the interior highlands. The remaining coastal plains are referred to as the Pacific lowlands.

The northern range of mountains forms a continuous chain along the border with Honduras. Elevations in this region range from 1,600 to 2,200 meters.

The southern range of mountains is actually a discontinuous chain of more than twenty volcanoes, clustered into five groups. The westernmost group, near the Guatemalan border, contains Izalco and Santa Ana, which at 2,365 meters is the highest point in El Salvador.

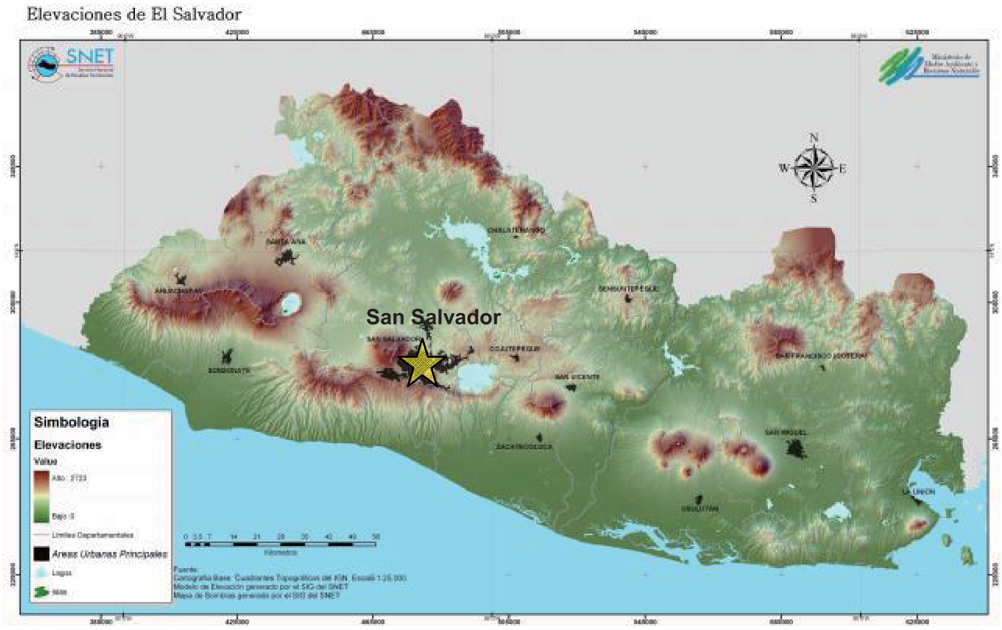


Figure 2. Relief condition of El Salvador

(Available from: http://atlas.snet.gob.sv/snet/?q=node/257)

The central plateau constitutes only 25 percent of the land area but contains the heaviest concentration of population and the country's largest cities. This plain is about 50 kilometers wide and has an average elevation of 600 meters. Terrain here is rolling, with occasional escarpments, lava fields, and geysers.

A narrow plain extends from the coastal volcanic range to the Pacific Ocean. This region has a width ranging from one to thirty-two kilometers with the widest section in the east, adjacent to the border with Nicaragua. Near La Libertad (approximately 40 kms south from the capital), however, the mountains pinch the lowlands out; the slopes of adjacent volcanoes come down directly to the sea. Surfaces in the Pacific lowlands are generally flat or gently rolling and result from alluvial deposits from nearby slopes.

1.3 Seismic sources for El Salvador[4]

Central America is subject to a series of geotectonic failures at the global level and is also exposed to local faults in all the countries comprising it (Figure 3). To the north in the Atlantic, the North American and Caribbean Plates are interacting, divided by the Pit of Grand Cayman; to the south in the Pacific, the Cocos Plate can be found along all Central American countries (subduction zone), forming the

Pit of Mesoamerica. This tectonic structure generates important seismic activity and has created major, destructive tremors in the Central American region.

El Salvador is affected by earthquakes from two main sources of seismicity (Figure 3). The largest earthquakes are generated in the Benioff – Wadati zones of the subducted Cocos Plate, which is converging with the Caribbean plate in the Middle American trench at an estimated ratio of 7 cm/year. The second source is a zone of upper-crustal earthquakes that coincide with the Quaternary volcanoes that extend across the country. Due to their shallow focus and their coincidence with main population centers, these earthquakes have been responsible for far more destruction in El Salvador than larger earthquakes in the subduction zone.

Figure 3. Active plates and volcanoes in Central America (ref: Google Earth)

In the last hundred years, El Salvador has been hit by at least 13 major earthquakes. Recent examples include the earthquake on January 13, 2001 (Mw 7.6), attributed to the subduction zone, which caused a landslide that killed more than eight hundred people. Another earthquake, a month after the first one, February 13, 2001, (Mw 7.6), attributed to a local failure, killed 315 people damaging about 20% of the nation's housing. The country has over twenty volcanoes, although only two, San Miguel and Izalco, have been active in recent years. Violent eruptions are rare. El Salvador's most recent destructive volcanic eruption took place on October 1, 2005, when the Santa Ana Volcano spewed up a cloud of ash, hot mud and rocks, which fell on nearby villages and caused two deaths.

San Salvador, the capital city, is known as Valley of the Hammocks due to its constant seismic activity. Destructive earthquakes in San Salvador were registered in 1576, 1659, 1798, 1839, 1854, 1873, 1880, 1917, 1919, 1965 and 1986. The 5.7 Mw-earthquake of 1986 caused 1,500 deaths, 10,000 injuries, and 100,000 people left homeless.

1.4 History of building regulations[5]

Building regulations in El Salvador have been historically based on foreign regulations. Before mid 1940's, no regulation was officially used to design buildings. Before 1965 (after a strong earthquake hit the capital city), buildings were designed following the regulations used in USA (UBC and San Francisco codes). Guidelines for concrete or steel structures were adopted from ACI (USA) or DIN (Germany).

First official regulation was introduced in 1966, following the building code of Acapulco (Mexico). This regulation was modified in 1989, due to the 1986' earthquake which collapsed many building in San Salvador. This regulation was named as Emergency Seismic Design Code and was introduced by the Salvadorian Association of Engineers and Architects (ASIA). The last modification for building regulations was conducted in 1994. The official name of the last regulation published in 1994 is "Regulations for the Structural Safety on Constructions". Regulations include the following guidelines:

- Technical guideline for seismic analysis
- Technical guideline for wind analysis
- Technical guideline for foundation and slope analysis
- Technical guideline for concrete structures
- Technical guideline for steel structures
- Technical guideline for wood structures
- Technical guideline for masonry structures
  - Special guideline for design and construction of houses
  - Special guideline for adobe constructions
- Technical guideline for quality control of materials

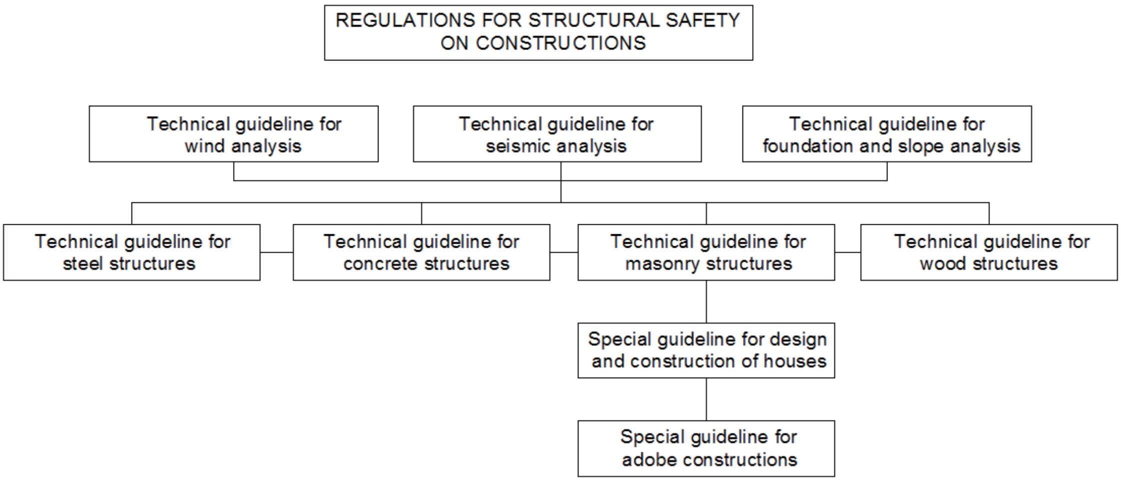


Figure 4. Technical guidelines in El Salvador (Edgar Peña and Vladimir Escobar)

1.5 Current situation of building regulations

Legal problems affect the code enforcement around the country. Although the regulations exist, these have not been approved by the legislative assembly. The official document which includes the regulations is part of a presidential decree, created in 1994. The application of the regulations is limited to medium and high rise constructions, which are supervised by the Ministry of Public Works through the Vice Ministry of Housing and Urban Development. Low rise constructions are not enforced by local governments and depending on the area of construction, calculations may be omitted. Besides, technical information has not been properly disseminated to local governments or to the people in general, because the contents of the guideline are oriented for engineers.

Some efforts have been conducted in order to improve the contents described on the special guidelines for design and construction of houses (including the adobe constructions guideline). In 2003, the Ministry of Public Works adjudicated this task to the Salvadorian Association of Engineers and Architects (ASIA) introducing a new proposal in march 2004. The information described in this document corresponds to the special guidelines introduced on 1997.

2 Guidelines for low rise wall type structures.

2.1 Basic information

The technical guideline for seismic analysis describes the constructive systems which can be employed for constructions in El Salvador. At same time, specifies the parameters that must be used to evaluate the seismic demand[1]. Calculation of seismic coefficient is based on the following expression:

$$V = Cs\ W$$

Cs must be calculated from:

$$Cs = (A\ I\ Co)\ (1 / R)\ (To/T)^{3/4}$$

T is the fundamental period of the structure.

The other factors are determined as follows:

2.1.1 Seismic zone factor A

The seismic zone map divides El Salvador in 2 regions (Figure 4). Seismic zone factor A for buildings in Zone I corresponds to 0.4; for buildings in zone II, Seismic zone factor is 0.3.

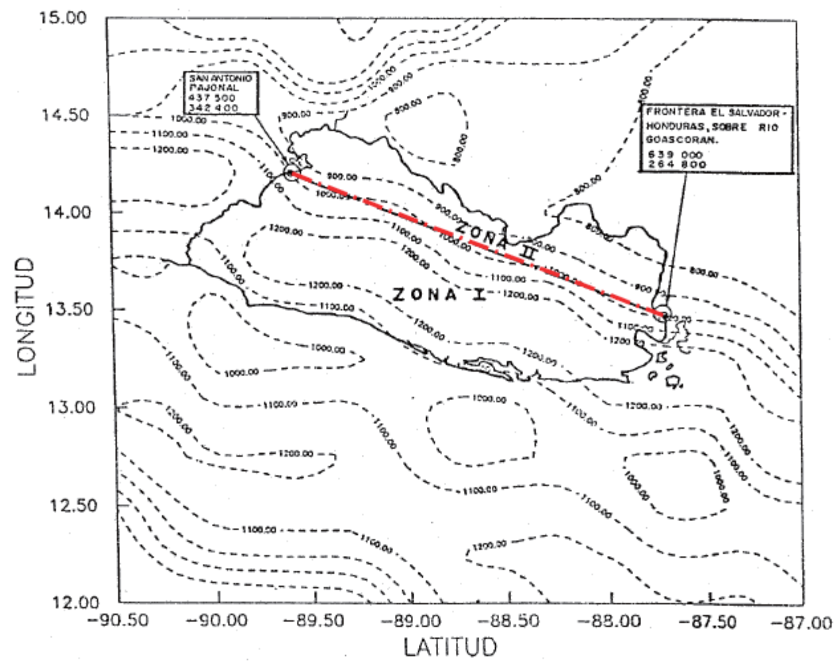


Figure 5. Seismic zonation of El Salvador[1]

2.1.2 Soil profiles

Four different soil profile types are described. Soil classification varied from very stiff soils (shear wave velocity >500m/seg) to soft cohesive soils (shear wave velocity <150m/s). Coefficients assigned to each soil are described in Table 1. When the soil properties are not known in detail to determine the soil profile type, type S3 shall be used.

Table 1. Coefficients based on soil condition

Soil profile	Co	To
S1	2.50	0.3
S2	2.75	0.5
S3	3.00	0.6
S4	3.00	0.9

2.1.3 Importance factor

Depending on the occupancy category, three seismic importance factors are described assigned to the structures: essential facilities after disasters, special occupation facilities (high concentration of people) and standard occupation facilities.

Table 2. Coefficient based on occupation of structure

Category	Occupation	I
I	Essential facilities	1.5
II	Special facilities	1.2
III	Standard facilities	1.0

2.1.4 Structural systems

Structural systems are classified in 5 groups:

- System A: Moment resisting frame system construction.
- System B: Frames shall resist the gravitational loads. Walls or a bracing system are designed to resist totally the lateral loads.
- System C: Dual system, where both systems (frames and walls or bracing system) shall be designed to resist gravitational and lateral loads in proportion to their relative rigidities. Frames must be designed at least to resist 25% of the lateral load.
- System D: Walls or bracing system shall be designed to resist gravitational and lateral loads.
- System E: Cantilever systems, where mass can be considered as concentrated.

The value of R is selected for each system. In case of masonry walls resisting gravitational and lateral loads (System D) the factor R must be taken as 6.

2.2 Calculation methods

Depending on the type of construction, two different methods can be used to perform the structural design:

- Load and resistance factor design: applied to concrete and steel structures.
- Allowable stress design: applied to masonry and wood structures.

2.3 Technical requirements for low rise wall type structures[2]

As described in the special guideline for design and construction of houses, in El Salvador low rise constructions are built using three different modalities: concrete walls, confined masonry and reinforced masonry (hollow concrete block). A special guideline is included for adobe constructions.

2.3.1 Requirements to apply the special guideline for houses.

The application of the special guideline is limited to the following conditions:

- The construction must be a single unit up to 2 floors height. For one floor houses, maximum height is 3.5m and for two floors houses height is limited to 6.5m.
- Shape of the construction must be approximately rectangular with aspect ratio less than 3.
- Internal distribution of walls must be symmetrical with respect to two orthogonal axes. Gravitational and horizontal loads must be supported 100% by the walls.
- Openings at the second floor can not exceed 20% of the total area of the second floor and cantilevers can not exceed 1.2m.

In case the conditions are not fulfilled, the special guideline and values described on it can not be used.

2.3.1.1 Diaphragms

Two different diaphragms can be used: rigid diaphragm and flexible diaphragm. The roof or floor can be considered as rigid diaphragm if is able to transmit lateral forces to the connected walls based on their individual in-plane stiffness properties. Concrete slabs casted in situ or prefabricated slabs with a minimum of 5 cm concrete layer casted in situ can be considered as rigid diaphragm. If the 5cm layer of concrete is not required, the rigid behavior of the prefabricated system must be proved. If the diaphragm is not able to transmit lateral forces, is considered as flexible.

2.3.1.2 Analysis considerations

The guideline provides general requirement to analyze three different conditions:

- One floor houses with flexible diaphragm: walls can be considered as individual elements (vertical slabs) distributing the lateral load perpendicular to its plane
- One or two floor houses with rigid diaphragm: lateral loads must be applied concentrated at the level of each diaphragm. Applied force for each wall must be distributed in proportion to their rigidities.
- Two floor houses with rigid diaphragm and flexible roof: lateral load must be applied concentrated at the level of the first floor and distributed to each wall in proportion to their rigidities. Walls at the second floor must be designed using the procedure and seismic coefficient for one floor houses with flexible diaphragms.

Lateral force for each case can be calculated as:

$$V = Cs\ W$$

The different values of Cs are described in Table 3

Table 3. Values of Cs to estimate design lateral forces

	Zone 1	Zone 2
Rigid diaphragm	0.20	0.15
Flexible diaphragm	0.30	0.22

2.3.1.3 Design requirements

All the values described in this special guideline can be increased by 33% when gravitational and lateral analysis is conducted.

Shear contribution of walls which aspect ratio (Height/Length, H/L) exceeds 1.33 must be reduced by the factor $1.33\ (L/H)^2$.

Table 4. Allowable stress for steel reinforcement

Steel with yield strength ≤ 350 MPa	140 MPa
Steel with yield strength > 350 MPa	170 MPa

2.3.1.3.1 Concrete walls

- Minimum thickness 10 cm
- Minimum compressive strength of concrete 14 MPa
- Concentrated loads on walls must be considered as distributed loads acting on an effective length equal to 6 times the thickness of the wall.
- Horizontal and vertical reinforcement must be individually at least 0.025 times the transversal area of the wall.
- Maximum separation of horizontal and vertical reinforcement is 30 cm.
- In openings on walls, extra reinforcement (a bar of diameter 9mm) must be included (no details are described about its positioning on the wall).

Table 5. Allowable stress recommended for concrete walls

Axial compressive strength	0.20 f'c
Flexural compressive strength	0.45 f'c
Shear strength	0.29√ f'c

2.3.1.3.2 Reinforced masonry (hollow concrete block)

- Minimum thickness for two floor houses 15 cm
- Minimum thickness for one floor houses 10 cm
- Concentrated loads on walls must be considered as distributed loads acting on an effective length equal to 4 times the thickness of the wall.
- Independently of the yield strength of reinforcement, the total amount of vertical and horizontal reinforcement in a wall must be at least 0.0013 times the gross area of the wall.
- In any case, the amount of horizontal or vertical reinforcement individually must be at least 0.0005 times the gross area of the wall.
- Minimum diameter of vertical reinforcement is 8mm and for horizontal reinforcement, 6.4 mm.
- Separation of vertical reinforcement must be selected as the minimum between 6 times the thickness of the wall or 80 cm.

- Horizontal reinforcement must be included each 40 cm.
- Vertical reinforcement must be included on the blocks adjacent to openings of walls and windows. Minimum diameter of bars is 9mm.
- In order to join the vertical reinforcement included on the borders adjacent to openings, on each window ledge must be constructed one concrete element, which height must be at least 10 cm and similar thickness of wall, reinforced longitudinally with 2 bars of diameter 9mm and transversal reinforcement wit bars of diameter 6mm separated each 20 cm. A reinforced lintel block can be used instead the concrete beam.
- On the top of the openings the lintel must be designed to resist the correspondent gravitational loads.
- At the top of the wall must be constructed one continuous beam, which height must be at least 20 cm, with similar thickness as the wall.
- Reinforcement of this element must be designed, using as a minimum longitudinal reinforcement two bars of diameter 9mm. Transversal reinforcement must be at least bars of diameter 6mm separated each 20 cm.

Table 6. Allowable stress for hollow concrete blocks with f'm = 9.5MPa
(In case of a different f'm, the expressions can be evaluated)

Axial compressive strength	2.0 MPa	0.20 f'm
Flexural compressive strength	3.0 MPa	0.45 f'm
Shear strength	0.2 MPa	0.23√ f'm

2.3.1.3.3 Confined masonry

- Minimum thickness for bearing walls 14 cm
- Minimum thickness for non bearing walls 10 cm
- Concentrated loads on walls must be considered as distributed loads acting on an effective length equal to 4 times the thickness of the wall.
- Walls must be confined by vertical and horizontal concrete elements, having these concrete elements at least the same thickness of the wall.
- Vertical concrete elements must be connected to the foundation

and to the top beam of the wall, which must be continuous over the length of the house.

- Height (dimension measured over the plan of the wall) for vertical and horizontal concrete elements must be at least 15 cm. In case of intermediate elements, height can be 10 cm as minimum.
- Reinforcement of vertical and horizontal elements must be at least 4 bars of diameter 9mm. Transversal reinforcement will consist of bar of diameter 6mm separated each 15cm over the length of elements.
- Only in case of intermediate elements reinforcement to confine walls can be at least 2 bars of diameter 9mm. Transversal reinforcement will consist of bars of diameter 6mm separated each 15cm over the length of elements.
- Confining elements must be included in:
  - Intersection of walls and corners
  - In both extremes of isolated walls
  - Around openings of walls and windows
- Maximum separation for vertical concrete elements must be 2.5m
- Maximum separation for horizontal concrete elements must be 2.4m

Table 7. Allowable stress for confined masonry with solid units

Flexural compressive and axial compressive strength	1.00 MPa
Vertical flexural tensile strength	0.07 MPa
Horizontal flexural tensile strength	0.14 MPa
Shear strength	0.10 MPa

Table 8. Allowable stress for confined masonry with hollow units

Flexural compressive and axial compressive strength	1.00 MPa
Vertical flexural tensile strength	0.04 MPa
Horizontal flexural tensile strength	0.08 MPa
Shear strength	0.08 MPa

2.3.2 Special requirements for adobe constructions

2.3.2.1 Stability of walls

Stability of adobe walls against lateral loads depends on geometric properties of walls and buttresses.

- Wall dimensions
  - Maximum height (h) of walls 3.00 m.
  - Thickness (e) of walls h/8, but not less than 30 cm.
  - The maximum length of a wall, measured between two consecutive walls must be equal or less than 10 times the thickness (e) of the wall.
  - To ensure out of plane stability, in a case of any wall, if the separation between two connected orthogonal walls is larger than 10 times the thickness (e) of the wall, buttresses must be provided at the center of the wall.
- Openings
  - Maximum width of openings (windows and doors) 1.20m.
  - Minimum separation between borders of openings to wall corners or buttresses 1.20m.
  - Area of openings in a wall must be less than 0.3 times the area of wall between two consecutive walls or buttresses.

2.3.2.2 Design requirements

Specific weight of adobe walls can be taken as 16 kN/m^3.

Shear force can be calculated as

$$Vs = Cs\ W$$

The different values of Cs are described in Table 2

Table 9. Values of Cs to estimate design lateral forces

	Zone 1	Zone 2
Adobe construction	0.50	0.40

Table 10. Allowable stress for adobe constructions

Average shear strength	0.025 MPa
Flexural strength	0.05 MPa

3 Outline of construction practices

3.1 Type of constructions

Low rise constructions in El Salvador are typically one or two floor buildings. The category of mid or high rise construction can be considered for three or more floors buildings. These are not commonly designed for residential use except for some apartments constructed by the government or private companies. Buildings with three or more floors are usually constructed using reinforced concrete or steel frames.

For low rise constructions, masonry is the most typical material for construction in El Salvador. At the roof level, the use of flexible diaphragms is the most common constructive practice. Except for urbanizations, individual constructions are carried out by local workers specialized in constructions. Only for very exceptional cases, the house construction is carried out with the design or supervision of civil engineers or architects. The most common type of constructions used by workers can be summarized as:

3.1.1 Earthen construction (adobe and bahareque)

Based on the census conducted on 2007, this type of constructions represents almost 20% of the total number of houses in El Salvador. Some of the Mayan cities buried during volcanic eruptions shown the use of bahareque (named as quincha in Peru) previous to the arrival of the Spaniards. The term bahareque is used for any construction which has a series of internal struts (traditionally wood or cane) and is filled with soil or bricks.

Traditional adobe houses are constructed without including external or internal reinforcement. Some NGO’s have tried to implement the inclusion of reinforcement and additional geometrical features for adobe constructions. The oldest adobe constructions can be found at the north region of the country. Most of the adobe houses are located in the rural areas of every city. Except for some older constructions (as churches and post-Hispanic buildings), the common practice for adobe and bahareque is limited only for one floor dwellings.

3.1.2 Fired clay brick confined masonry

Besides earthen construction, confined masonry using fired clay bricks is one of the most typical constructions used in the rural areas. However this type of constructions can be found spread throughout urban areas. The practice of fire clay bricks is to be modified in the near future due to the impact to the environment. Artisanal ovens are used to fire the bricks during three or four days, requiring big amounts of wood and polluting the air with considerable amounts of smog. Instead the use of sun dried bricks constructed with soil and cement is enforced. Soil called "tierra blanca" is basically volcanic ash consisting on different percentages of silt and sand. The common practice used by laborers for confined masonry is not reflected in the current guidelines. In El Salvador, the common practice for single floor houses is to add an extra horizontal concrete element at the center of the walls (Figure 6). This element is known as "solera intermedia" (intermediate beam).

Figure 6. Intermediate beam used in confined masonry in El Salvador (Photo by Edgar Peña)

3.1.3 Hollow concrete block.

The most common material used by companies to construct urbanizations. Concrete blocks follow the specifications described by the ASTM, although low quality blocks can be found, due to the existence of small local companies which produce blocks. Depending on the experience of workers, the construction of concrete block houses is similar to the construction of confined masonry, using intermediate concrete elements to confine the concrete blocks (Figure 7).

Figure 7. Intermediate beam used in hollow concrete block construction in El Salvador (Photo by Edgar Peña)

3.2 Urban development law

The main governmental institution related to approve permission of construction is a dependence of the Ministry of Public Constructions (MOP). The actual dependence is named Vice-Ministry for Housing and Urban Development (VMVDU). This institution is in charge to ensure that all constructions are in compliance with the local plans of each municipality and the regulations described in the urban development law of the country. The local development plans must be supervised by the VMVDU and must comply at least the minimum requirements established by the urban development law.

Considering the extension of constructions around the capital city, in 1990 a special office was created to attend the metropolitan area. This special office is named Office for Urban Planning of the San Salvador Metropolitan Area (OPAMSS). Besides the capital city, San Salvador, OPAMSS regulates the permission of construction of 13 more municipalities which surround the capital city. Around 2 million people are living in these 14 municipalities, which represent almost 30% of the total population of the country. These municipalities are not inspected by VMVDU.

Regarding the official procedure for low rise constructions, the owner of the building must inform to the respective municipality about the construction plan. Depending on the area of construction, the local government will ask to the owner to legalize the construction following the procedure indicated by the VMVDU. In case of OPAMSS, the procedure is obligatory for any construction.

In both cases, first step consists to submit the drawings and deeds of the land where the building(s) will be constructed. Depending on the area of construction and its location in the country, some extra permission can be required by VMVDU (environmental permission, cultural heritage permission, etc). The owner must fulfill the requirements established during the first step.

Second step consist to submit the technical information related to the construction site, including constructive drawings, structural analysis and design memory of calculations, permission (feasibility) for water supply, electricity, and extra requirements established on the first step.

The permission for construction is granted for the VMVDU or OPAMSS. At least three copies are required, one copy for the owner, one for the municipality and one for VMVDU. Depending on the magnitude of the construction, a certificate of reception must be submitted to the respective institution and municipality.

3.2.1 Engineered constructions.

In this category can be included all the constructions which followed the procedure established by the urban development law. Legal documentation includes the structural revision of the houses following the minimum requirements described previously.

Most common case of engineered construction is the case of urbanizations, where multiple individual houses are constructed. For this case, hollow concrete block is the most typical material used for construction. Most of these urbanizations are limited to constructions up to 2 floors, following the regular geometric characteristics described by the guideline. In case of residential apartments (between 3 and 5 floors), in most of the cases buildings are constructed using reinforced concrete or steel frames. Masonry is only used as infilled wall, avoiding the wall to be in contact with columns or the upper beam.

As mentioned before, depending on the area of construction, some of the individual projects are required to follow the procedure established by the law. The owner usually contracts architects or engineers to carry out the legal process.

3.2.2 Non-engineered constructions.

If one construction did not follow the procedure established by the urban development law is considered as non-engineered. These constructions are more related to individual houses, which construction start or even are finished before obtaining the permission of construction (if it is ever submitted). Construction of a second floor, construction of appendices, change of use or even new constructions have been detected by the land registry office of each municipality. These are required by the municipality to follow the legal procedure, applying in some cases fines to the owner.

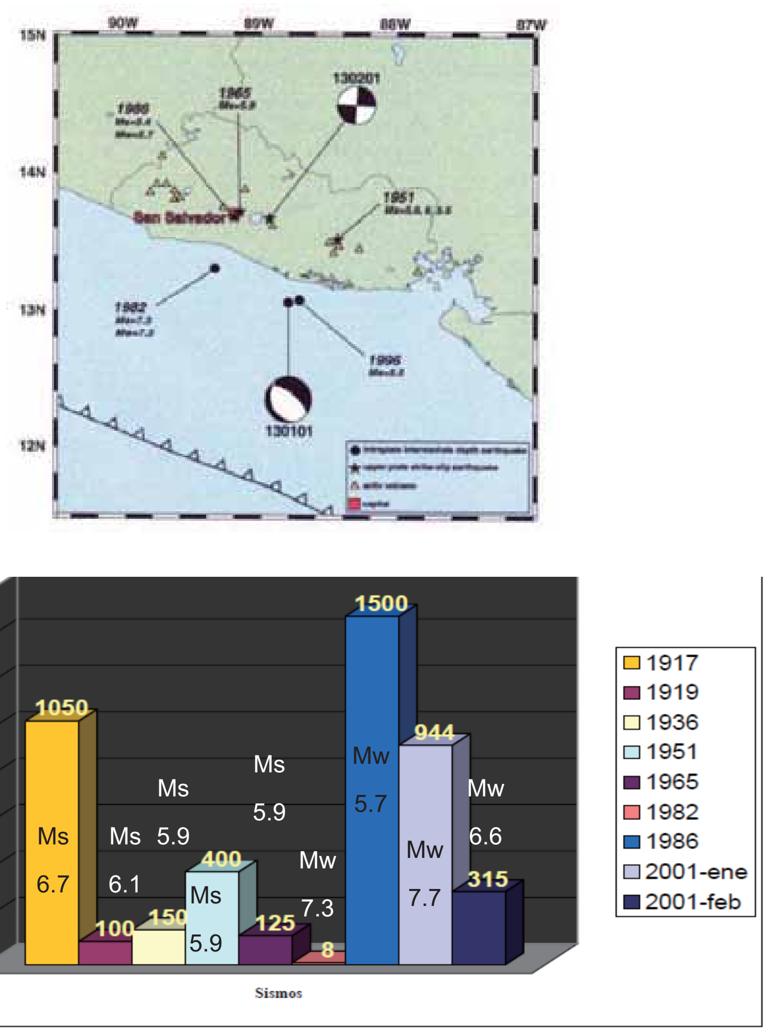
3.2.3 Special constructions (social housing, as NGO's projects).

In case of emergency (after earthquakes, floods or other disasters) or using the support of international agencies, some non governmental institutions provide houses for communities. Some of the houses are constructed using the self construction modality. In some cases, prefabricated houses are provided, which are not required to fulfill the requirements established by the special guideline for houses (especially during disasters). Some of the NGO's provide some calculations regarded to the stability of the constructions.

4 Earthquake damage of low rise constructions

4.1 History

In the last century, nine important earthquakes have caused destruction of cities in El Salvador. Death toll registered and the location of earthquakes are shown in Figure 8.



Fuente: SNET

Figure 8. Death toll and location of earthquakes in El Salvador (*SNET*)

Most destructive earthquakes are related to local failures as 1986' earthquake in San Salvador and 1951' earthquake in Jucuapa at the east side of the country. The local failure earthquakes epicenters are aligned with the volcanic chain of the country. Local earthquakes have low magnitudes (Mw 5 to Mw 6.5), however the depth of these are located 10 km or less under the surface.

Earthquakes originated at the costal area with magnitude 7 or stronger, have produced landslides along the country. These are usually located 45 km far from the coast and their focus can be located as 60 km.
Related to constructions, after the 1986' earthquake in San Salvador, adobe construction was banned in the capital city. Old adobe constructions are typical at the north region, where seismicity is less than the central and south region. However, this practice remains at the central and south region after earthquakes due to economical and cultural condition of the population.

4.2 Recent experiences[4]

Figure 9. Landslide in Las Colinas (south of San Salvador) during January 2001 (Report CEPAL, UN).

During 2001, two strong earthquakes hit El Salvador. First earthquake (Ms 7.7) occurred on January 13th at 11:33 am (local time). Its epicenter was located on the Pacific Ocean, 45 km far from the coastal area of El Salvador. The focus of the earthquake was estimated as 45 km. Main characteristic of the effects of this earthquake was the large number of landslides through the country. The main concentration of death tolls due to this earthquake was registered in Las Colinas (Figure 8), where hundreds of residents died buried during the landslide of the adjacent hill.
Second earthquake (Ms 6.6) occurred at February 13th at 8:22 am (local time). Its epicenter was located in San Vicente, 30 km south east of San Salvador. The focus of the earthquake was estimated initially as 15 km. The second earthquake caused the collapse of many houses damaged during the first earthquake,

especially on the central region of the country[4].

According to the Ministry of Public Works, 163,866 houses (11.68 percent of total number of houses in El Salvador) collapsed while 107,787 (7.68 percent) were seriously damaged. 100 municipalities were affected, some of them reporting 70% to 100% of collapsed constructions.

Figure 9. Region affected by earthquakes during 2001 (Report CEPAL, UN)

5 Current research outputs

5.1 Existing research

Technical research about low rise constructions is basically conducted by Universities through the development of graduation theses. Some other researches about quality control during constructions or development of new constructive techniques have been undertaken by some NGO's and private companies.

Most of the theses related to masonry construction developed by Universities are related to constructive details, as mortar or brick quality using local materials.

5.2 TAISHIN project.

The Project "Enhancement of Technology for the Construction and Dissemination of popular Earthquake-resistant Housing" (known as TAISHIN project) is a trilateral technical cooperation project jointly undertaken by the governments of Japan, Mexico and El Salvador in accordance with an exchange of agreements signed in November and December, 2003. The main objective of this project is to develop and disseminate enhanced materials and construction methods to strengthen the seismo-resistant capabilities of low-cost popular housing in El Salvador. The Government of Japan through the Japanese International Cooperation Agency ("JICA") contributed with equipment, tools and necessary infrastructure for Universities for the implementation of the project. The main technical issue of the project is the investigation of housing materials and structures used in El Salvador.

Two main facilities have been constructed in El Salvador: one laboratory to conduct tests on walls (in plane behavior of walls) and one tilting table to evaluate the out of plane behavior of houses (especially for earthen constructions or brittle materials).

Figure 10. Experimental facilities donated by Japan to El Salvador through JICA (available in http://taishin.mop.gob.sv).

5.3 Future works

Currently the 2nd phase of TAISHIN project is under execution. Main objective of this phase consists checking and improving of the provisions described on the special guidelines for construction of houses. The improvement of laboratories in Universities allows establishing a permanent research on these types of constructions and the improvement on the educational background of students. Universities involved are Universidad de El Salvador (national university) and Universidad Centroamericana "Jose Simeon Cañas" (private university).

Current research is focused on:

- Reinforced adobe construction, where thin bamboo is included as horizontal and vertical reinforcement in new constructions. Besides, out of plane effects and the effectiveness to avoid those using wire meshes as reinforcement for existing constructions are being studied.
- Confined masonry construction using soil cement bricks as a substitute for clay fired bricks. The research is planned to start at the end of 2010.
- Evaluation of design parameters for reinforced hollow concrete block

construction. The research is planned to start at the end of 2011.

The project will be finished at the end of 2013. Results are expected to contribute improving the current guideline provisions. The technical information will be disseminated trough the guideline and manuals of construction for workers.

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