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SEISMIC RISK SCENARIOS FOR THE CITY OF SANTA TECLA, EL SALVADOR

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Abstract

El Salvador is struck by a destructive earthquake or earthquake sequence, once per decade on average. The capital city San Salvador is probably the city in the Americas that has been most frequently damaged by earthquakes. The city of Santa Tecla was founded on 1854 with the goal to build a new capital for El Salvador after San Salvador was completely destroyed by an earthquake, objective which did not materialized after all. Santa Tecla has experienced the same fate of its neighbors, partially attributed to the local soil condition, with dominant periods in the same range as the typical infrastructure in the city. Therefore, Santa Tecla has been identified as one of the most critical areas in terms of seismic risk, and has been selected to conduct this research. The project comprised four main activities: calibration of a national seismic hazard model, appraisal of the site effects for the San Salvador Metropolitan Area (AMSS), estimation of the exposed assets in the study area and quantification of the structural vulnerability. The probabilistic seismic risk analysis considered 24,966 probable seismic scenarios and 16,444 buildings belonging to Residential, Commerce, Industry and other Portfolios with an exposed value around 963,414 million dollars. The expected annual loss confirms the high level of seismic risk in the study area.

Keywords: Seismic risk; earthquake scenarios, site effects; Santa Tecla; annual loss

1. Introduction

El Salvador is the smallest country of Central America, with just 21,040.79 km^2, and a population of approximately 6.227 million inhabitants [1], resulting in an average density of 296 inhabitants per km^2. The Metropolitan Area of San Salvador (AMSS) is the most populous area in the country and is composed by 14 municipalities, including San Salvador and Santa Tecla. The Metropolitan Region is set as the directional center of the country in political, financial, economic and cultural matters, concentrating 27% of the population and 70% of public and private investment, in an area equivalent to 3% of the national territory [2]. Its location in the Great Interior Valley, and the constant seismic activity, got the city its nickname “The Valley of the Hammocks”.

The 2001 earthquakes (13.01.2001 Mw 7.7 off the Coast of El Salvador, and 13.02.2001 Mw 6.6 in San Vicente) caused serious damage along the country. At least 944 people were killed, 252,600 people were affected, and economic losses were in the order of $1,600 Million. Santa Tecla was one of the most affected cities in the country, effect that has been attributed to the local site conditions and the seismic vulnerability of its typical building types. Located in the Central Graben on the southern flank of the San Salvador Volcano, and just about 16 km away from the Ilopango Caldera, Santa Tecla is greatly affected not only by the seismic activity that occurs along the subduction zone, but from nearby geological faults and volcanic activity, and the amplification effects associated to the deposits of both eruptive centers (lava flows and volcanic ash).

In order to analyze the seismic risk of the city and establish risk reduction measures, probabilistic modeling of seismic risk scenarios was performed using the CAPRA (Comprehensive Approach to Probabilistic Risk Assessment) platform. Seismic hazard was assessed in terms of spectral accelerations and considering an empirical estimation of the amplification effects due to local site conditions. Exposure information was gathered and the structural vulnerability was evaluated and represented in terms of vulnerability functions.

2. Seismic Hazard Scenarios

It is well known, that the intensity and duration of the strong motion on a particular site depends on the size and location of the earthquake relative to the site (source characteristics and attenuation models), and the geological and topographical site conditions (site effects). The seismic hazard model was constructed on the basis of strong motion parameters, characterized in terms of both amplitude and frequency.

2.1 Methodology for the determination of the Seismic Hazard Map and Scenarios Hazard Scenarios (Rock sites)

Following the guidelines presented in the RESIS II project [3] and using the strong motion database belonging to the Ministry of the Environment and Natural Resources of El Salvador (MARN) and the Central American University, ground motion prediction models (GMPE) were selected. The analysis was based on the direct comparison of the values of the horizontal peak ground acceleration (PGA) and spectral accelerations SA(T) for periods of 0.3 and 1.0 sec, with respect to the values estimated by GMPEs for similar magnitude, distance and site conditions, Eq. (1).

$$R = \ln(Y) - \ln(Y^*) \quad (1)$$

Where R is the residue, Y is the observed value of PGA or SA and Y* the predicted value for similar conditions of magnitude, distance and soil.

Considering the seismogenic zonation defined in RESIS II [4], the typical earthquake characteristics and focal mechanisms, three different seismogenic zones were considered, and a GMPE was selected for each one. The seismicity has been associated as follows: surface seismicity (h< 25 km) to crustal zones; intermediate seismicity (25 km< h< 45 km) to interface zones and deep seismicity (h> 45 km) to subduction inslab zones.

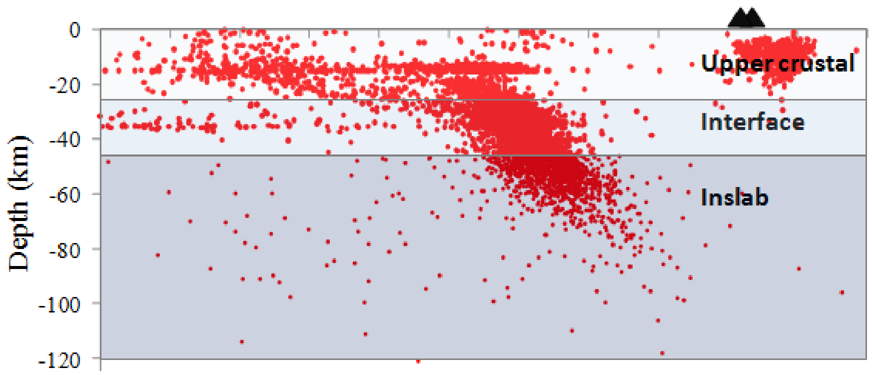


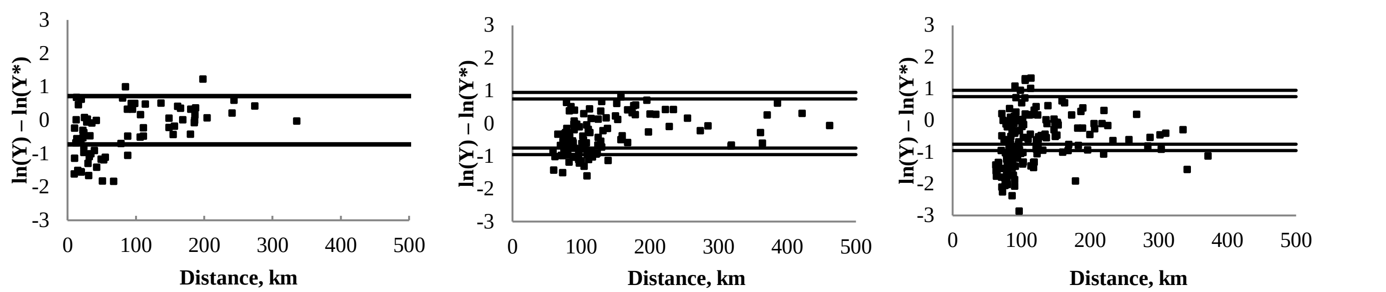
Fig. 1 – In Depth profile of El Salvador´s earthquake hypocenters from 1992 to 2012 and seismogenic zonation adopted for the seismic hazard assessment, with three tectonic regimes: upper crustal (<25 km), subduction interface (25<h<45) and subduction inslab (>45 km).

2.2 Results

The analysis shows best fit using the model proposed by Zhao et al. (2006) [5] for upper crustal earthquakes and Youngs et al. (1997) [6] for interface events and inslab earthquakes. Table 1 shows the percentage of R within the interval μ ± σ established by each model for models that show the best fit, highlighting the selected GMPEs for each source. Fig. 2 shows the distribution of R against distance for PGA for the selected models for crustal, interface and inslab zones.

Table 1 – Percentage of R within the interval μ ± σ established by each model for models that show the best fit.

GMPE	Upper crustal			Interface			Inslab		
	PGA	**SA (0.3 s)**	**SA (1.0 s)**	**PGA**	**SA (0.3 s)**	**SA (1.0 s)**	**PGA**	**SA (0.3 s)**	**SA (1.0 s)**
Zhao et al. 2006 [5]	70	58	54	75	65	59	55	51	48
Youngs et al. 1997 [6]	--	--	--	86	77	49	58	63	37



a) *Model proposed by [5] for upper crustal earthquakes*

b) *Model proposed by [6] for Interface earthquakes*

c) *Model proposed by [6] for Inslab earthquakes*

Fig. 2 - Distribution of R against distance for PGA for the models that show the best fit. The dots represent R and the solid lines represent the standard deviation established by each model

The combination considered most suitable was selected, using the model proposed by [5] for upper crustal source and the model proposed by [6] for Interface and Inslab subduction. The seismic hazard map and respective seismic hazard scenarios were obtained using CRISIS2007 Vr. 5.1 [7] using the seismogenic zonation and seismic zone parameters defined in RESIS II [3], and the ground motion models selected in this study (Fig. 3). 24,966 seismic scenarios, each associated to a specific probability of occurrence, were obtained and used in the seismic risk analysis.

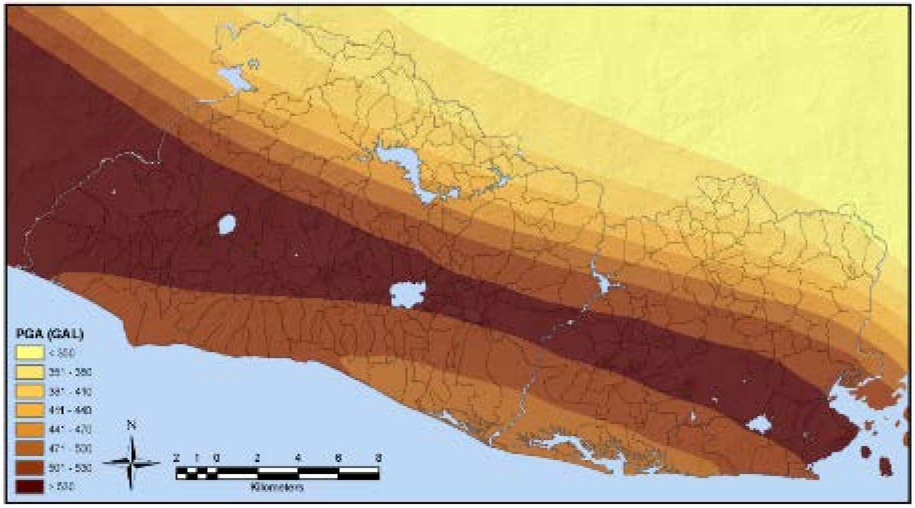


Fig. 3 – Seismic Hazard map of El Salvador, in terms of PGA (gal) for a return period of 500 years obtained in this study.

2.3 Methodology for Site Effects estimation

Site effects in the AMSS are mainly influenced by the presence of lava flows and volcanic ash (locally known as Tierra Blanca), from recent eruptions of San Salvador volcano and Ilopango Caldera. The volcanic ashes are thinned hillside above San Salvador volcano (3 m), but to the east of the capital city (Soyapango and Ilopango), they reach thicknesses of over 60 m [8]. When the seismic waves pass through from rock to volcanic ash deposits, with a much lower shear wave velocity - approximately 200 m/s [9], the amplitude is increased. Seismic waves are amplified in a frequency range that depends on the depth and dynamic properties of the deposit. In other words, the soil "filters" the wave and the strong motion is amplified in certain frequencies while in others is attenuated. Resonance may occur when the soil´s and the structure´s dominant frequency coincide, resulting in great damage.

For the Metropolitan Region of San Salvador, there is no detailed microzonation information available and soil dynamic information is limited. For the purpose of this study, and considering time and money constraints, an approximation (PROXI) of the soil response was conducted. Areas of similar seismic response were estimated, using only available information. Their delimitation was based on dominant frequencies obtained from strong motion records and previous microtremor measurements [10] following Nakamura's H/V technique [11], as well as on the depth of unconsolidated soils over the bedrock (for typical shear wave velocities of ~200 m/s), which was estimated using topographical and geological maps and other geological and geotechnical information available (geotechnical borings, stratigraphic surveys). Amplification functions were determined at specific sites (strong motion stations and monitoring wells) and extrapolated to other sites with similar surface geology.

Typical amplification functions for each area were estimated, following the methodology proposed by Borcherdt [12] when strong motion data at rock sites was available and the distance between the site and the rock site was much less than the hypocentral distance (generally not suitable for upper crustal events, with the exception of monitoring wells). However, strong motion data is scarce in the study area and for some sites only a rough estimation was possible: normalized seismic response spectra for different events at each site were calculated and compared to those derived from the seismic hazard model described in 2.1. The results were then compared to those obtained following the Borcherdt methodology, proving to be a fair estimation for the purpose of this study. The amplification functions represent a transfer or modification function for the response spectrum for rock conditions, obtained from the national seismic hazard assessment (Fig. 4).

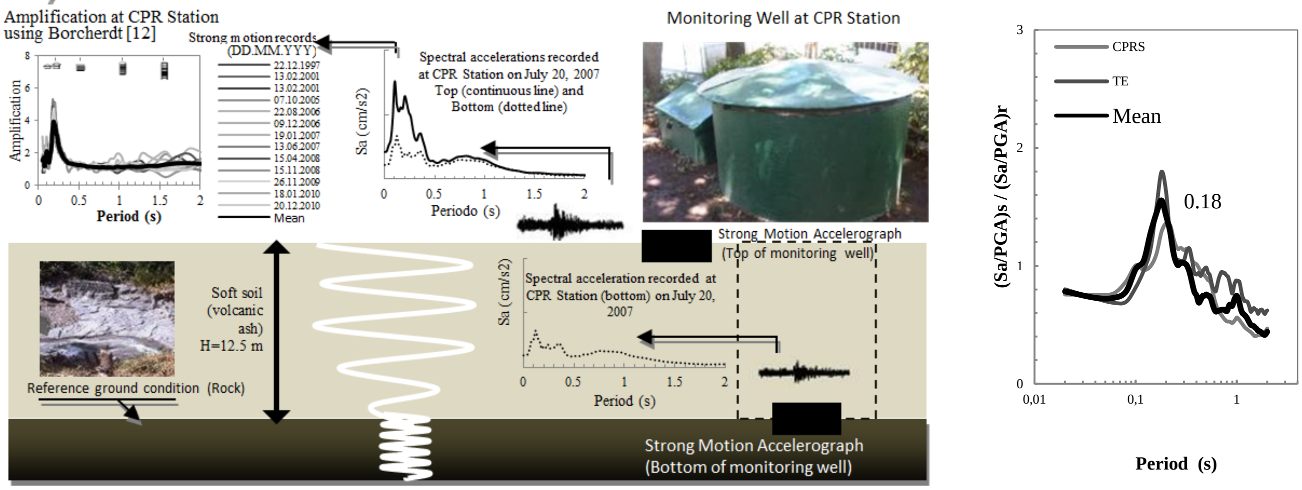


Fig. 4 – Left: Amplification due to local site condition at a Monitoring Well at "Casa Presidencial" Strong Motion Station (CPR) located just outside Santa Tecla) using Borcherdt [12]. Right: Results using normalized response spectrum ratios at sites with similar surface geology: CPR Station outside Santa Tecla and Santa Tecla Strong Motion Station (TE) located in the Santa Tecla City Center.

The analysis was performed using moderate amplitude records (PGA< 100cm/s^2), limiting the results to the elastic range. Although non-linear behavior was identified in some cases, high amplitude records were too limited to conduct a full study. Non-linear effects, as well as the influence of deep soft soil deposits (intercalated lava and ash deposits) should be studied in detail.

2.4 Results

Figure 5 shows areas with similar seismic response for the urban area of Santa Tecla, classified in terms of estimated dominant periods and depth of the soft soil deposits. Table 2 shows the typical soil conditions and amplification functions for areas with similar seismic response.

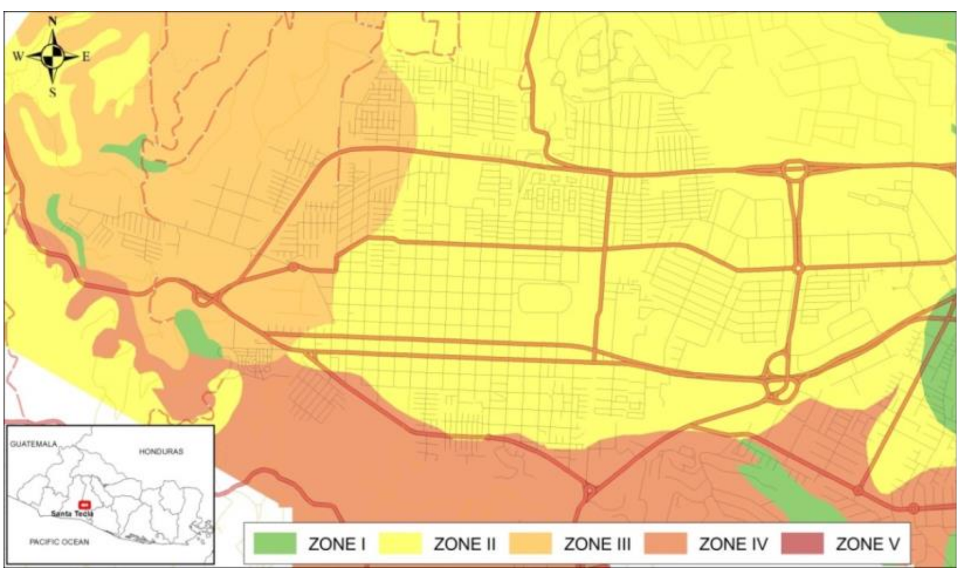
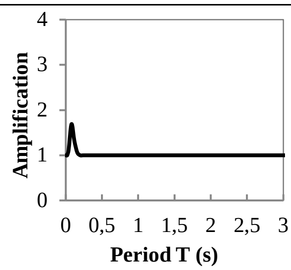
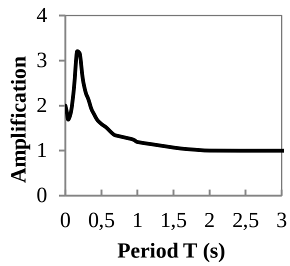
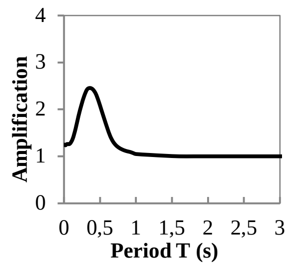
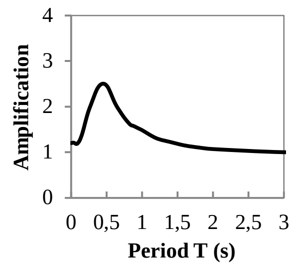


Fig. 5 – Map showing areas with similar seismic response for the urban area of Santa Tecla

Table 2 – Typical soil conditions and amplification functions for areas with similar seismic response.

Z I H soft soil < 5m	**Z II** H soft soil 5-15m	**Z III** H soft soil 15-25m	**Z IV** H soft soil 25-50m
 Colonia Escalón (2010)	 Multiplaza (2007)	 Centro de Gobierno (2010)	 Altos del Boulevard (2008)
			

3. Exposure and vulnerability

3.1 Methodology

Initial activities focused on compiling and classifying different sources of information such as preceding research papers and georeferenced maps of the study area. Important information was obtained from a previous study "Seismic Risk Assessment For The Metropolitan Region Of San Salvador, El Salvador: Educational, Public Health And Governmental Institutions" [13], as well as georeferenced digital maps from Viceministerio de Vivienda y Desarrollo Urbano (VMVDU), Oficina de Planificación del Área Metropolitana de San Salvador (OPAMSS) y Universidad de El Salvador (UES).

Unlike other countries, El Salvador does not possess an organized database, where important information about structural characteristics of buildings is recorded. Therefore, a field work had to be carried out to gather this data. Using a survey sheet, the following information was collected and then input to a georeferenced database:

- General Information: Location, using GPS; cadastral id; area, in m^2; portfolio (Education, Health, Government, Commerce, Industry and Residential); year of construction and usage.
- Technical information: Structural system; geometry; dimensions; number of storeys; storey height; type and material of the roof; type and material of floors.
- Structural defects: Short columns, plan irregularity, elevation irregularity, weak storey, strong beam-weak column, big openings on structural walls and low quality of materials.
- Damages due to previous earthquakes: Date of earthquakes, 1986 or 2001; level of damage and whether damages have been repaired or not.

The study area was divided into seven segments, as shown in Fig. 6, to easily collect and review the field information. The study area had an extension of 5,123,371 m^2 and was set up based on the requirements expressed by the Municipality of Santa Tecla. Taking into consideration the importance and characteristics of the exposed structures, as well as population density, two methods were applied to collect data. The structures located at the three segments belonging to the "Centro Histórico" were surveyed one by one, whilst for the ones situated at the other four segments, some representative structures were sampled and their characteristics were replicated over the urban block where they belong, procedure named from here and on as the homogeneous block method.

Fig. 6 – Study area divided into the seven survey segments.

Following the procedure proposed in [13], buildings were classified into typical structural typologies or building types (Table 5), and vulnerability curves were developed for each typology. The typologies were classified based on the structural system, number of storeys and building height - related to the structural period-, and the level of earthquake resistant design, which was derived from the structures construction year with respect to the years when different building codes were implemented (<1966 Pre code, 1966-1994 Low code, >1994 Med code).

Existing vulnerability functions were analyzed and calibrated, and new curves were developed, based on expert opinions, damage information and numerical models where possible. For each typology found on the field, a vulnerability function was assigned. To develop the vulnerability curves, the multi degree of freedom system is reduced to a single degree of freedom system (SDOF) but, as proposed in [14], the system behaviour is controlled by the interstorey drift instead of the roof displacement of the SDOF system. The capacity curve of the SDOF system is computed and, as an important characteristic of the method, the percentage of damage for the yielding and ultimate stages is assessed. To find out the limit states, the parameters defined in [15] are used. In general, the percentage of damage is around 90% to 100% for the ultimate point; however, a more meticulous approach has to be employed to find out the damage at yielding. The steps to perform this process are presented in Fig. 7.

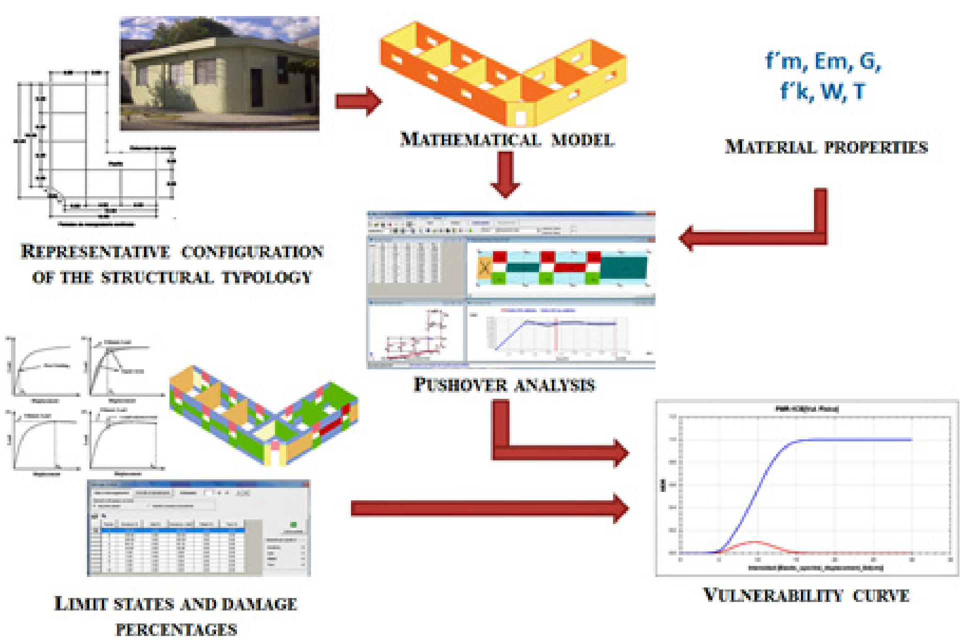


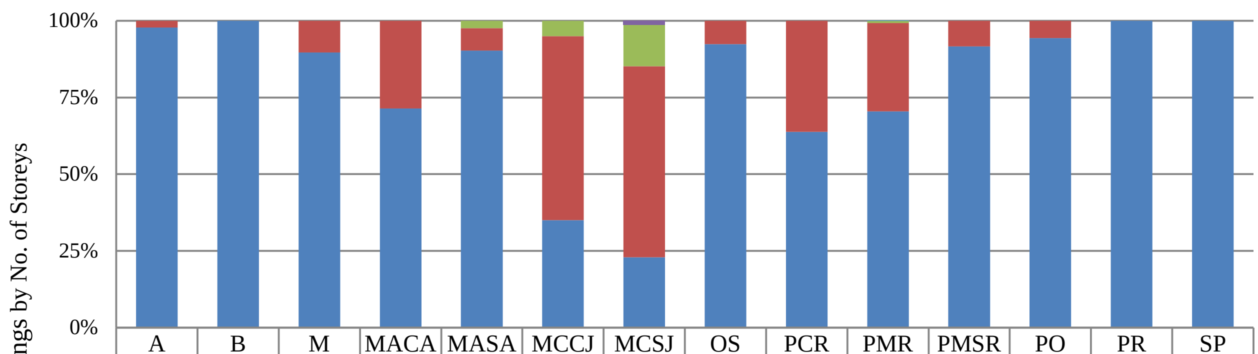
Fig. 7 – Schematic procedure for the development of vulnerability curves.

Based on the field data, typical configurations were selected for each structural typology, and the structures were modelled using a nonlinear analysis program to compute the pushover and capacity curves. In the example in Figure 7, TREMURI [16], is used to study masonry structures. The model is subjected to diverse pushover analysis changing both the shape of the force vector as well as the direction of the application of forces; the analysis which produces the lowest strength value is selected to get the vulnerability curve of the model. Based on the results from the capacity curves, equivalent height and period of the SDOF system, seismic coefficient for which the structure was originally designed, as well as the damage states related to the analysis, the vulnerability curve for each typology can be developed, in Sa (gal) vs Mean Damage Ratio (MDR) format.

3.2 Results

In the "Centro Histórico" area, 1928 structures were surveyed, two third of which belong to the "Residential" portfolio. There is also an important percentage of buildings belonging to the "Commerce" portfolio, since this is the downtown area of Santa Tecla, where the economic activity of the municipality is concentrated. In the suburbs of Santa Tecla, 664 assets were inspected, 90% of which belong to the "Residential" portfolio. Most of the structures are reinforced masonry wall buildings (PMR). A total of 2592 building were surveyed in both sub areas. Fig. 8 shows the structures classified by building type and number of storyes. It can be noticed that most of the constructions are one or two-storey high, a fact which has important consequences when the seismic risk analysis is performed.

Finally, using the procedure previously defined in 3.1, attributes of the structures belonging to the homogeneous block area were replicated into their respective urban blocks, resulting in 16444 edifices. It is worth mentioning that some information, such as number of inhabitant per structure, or their exact replacement cost, could not be collected in many areas, due to lack of access to the dwellings, distrust to the interviewer and lack of personal safety (high crime neighborhoods.)



	A	B	M	MACA	MASA	MCCJ	MCSJ	OS	PCR	PMR	PMSR	PO	PR	SP
5	0	0	0	0	0	0	0	0	0	2	0	0	0	0
4	0	0	0	0	0	0	2	0	0	0	0	0	0	0
3	0	0	0	0	1	1	20	0	0	14	0	0	0	0
2	1	0	3	2	3	12	92	1	17	600	1	4	0	0
1	45	53	26	5	37	7	34	12	30	1470	11	67	3	12

Fig. 8 – Structures classified by Typology and N° of storeys. Structural typologies are described in Table 5

Fig. 9 illustrates a comparison, for the PMR1 and ADOBE typologies, between the curves obtained in previous projects, based on expert criteria mainly, and the one developed in this work, following the procedure described in the precedent section. For the PMR1 typology, only small differences can be observed between the original and the modified vulnerability curves, a result which can be explained considering that the behavior of single-storey, reinforced masonry wall buildings is adequately known. For ADOBE however, the differences between the pre-existing and the newly developed curves are striking.

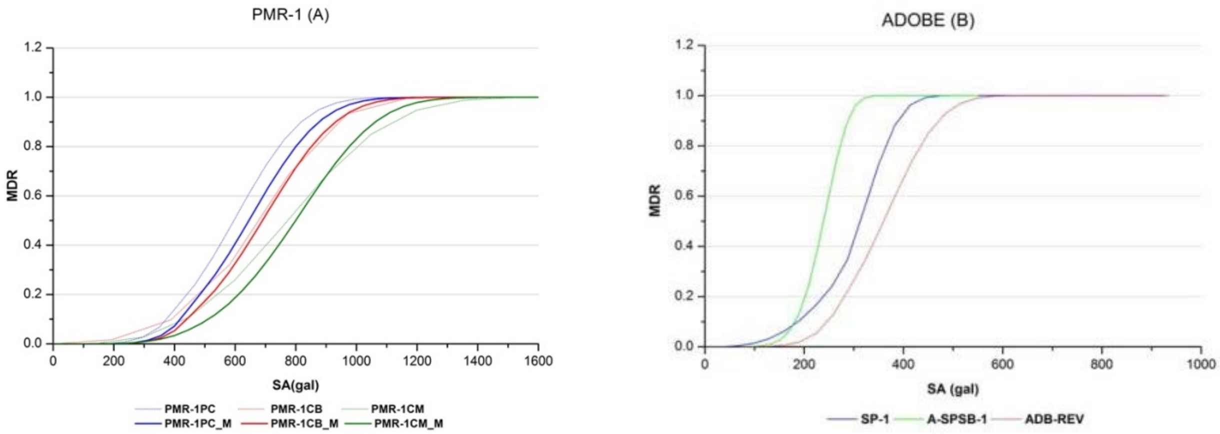


Fig. 9 – Vulnerability curves for: (A) single storey, reinforced masonry wall structure (PMR); PC, CB and CM stand for Pre-code, low code and medium code, respectively; M indicates the vulnerability curves developed in the present work; and (B) Adobe, SP-1 is related to precarious structures and A-SPSB-1 is the curve assigned to single storey adobe structures by a previous project whilst ADB-REV is the adobe vulnerability curve developed in the present work.

The vulnerability curves for any typologies found in the study area were reviewed following the previously described methodology. The main problem faced to perform these analyses was the lack of information that can describe, in an accurate manner, the physical and mechanical characteristics of the materials and the behavior of assemblages; furthermore, tests performed on structural members that actually represent the Salvadoran typologies are limited. For 29 from the 41 structural typologies found in Santa Tecla, new curves were developed, accounting for 98% of exposed assets. 12 curves were been taken from [13] without any modification.

Table 3 – Structural typologies found in the study area.

Main Typology	Code	N° of Storeys
Structural typologies with modified or newly created vulnerability curves		
Steel frames with bracing (MACA)	Pre-code and Low	1
RC Moment resisting frame without seismic gap (MCSJ)	Pre-code, Low and Medium	1, 2-5
Steel frames without bracing (MASA)	Low and Medium	1, 2-5
Bahareque (B)	Low	1
Light steel structure (PO)	Low and Medium	1
RC Structural walls (PCR)	Pre-code, Low and Medium	1, 2-5
Reinforced Masonry walls (including confined masonry walls) (PMR)	Pre-code, Low and Medium	1, 2-5
Wood (M)	Low and Medium	1
Adobe (A)	Low and Medium	1
Structural typologies with originally created vulnerability curves		
Steel frames with bracing (MACA)	Medium	2-5
RC Moment resisting frame with seismic gap (MCCJ)	Pre-code, Low and Medium	1, 2-5
Unreinforced masonry walls (PMSR)	Pre-code, Low and Medium	1, 2-5
Precast structures (PR)	Low	1
Precarious structure (SP)	Low	1

4. Risk

The probabilistic seismic risk calculation procedure consists in evaluating the losses caused by each of the scenarios that represent the seismic hazard, and integrate in a probabilistic way the results using as a weighting factor the frequency of occurrence of each scenario [17].

4.1 Methodology

The probabilistic seismic risk evaluation was performed using the analytical procedure proposed in [18] and implemented in the risk module of CAPRA platform [18]. The risk module of CAPRA evaluates the potential effects of the natural hazardous events (earthquakes) by means of the convolution of the hazard with the vulnerability of the exposed elements. It expresses risk in terms of physical damage, absolute or relative economic loss and/or affected population, allowing the calculation of: Loss Exceedance Curve, LEC; Average Annual Loss, AAL; and *Probable Maximum Loss*, PML [19]. Risk is normally measured using the exceedance rate of loss values and is calculated as:

$$v(p) = \sum_{i=1}^{Events} \Pr(P > p|Event\ i) \cdot F_A(Event\ i) \tag{2}$$

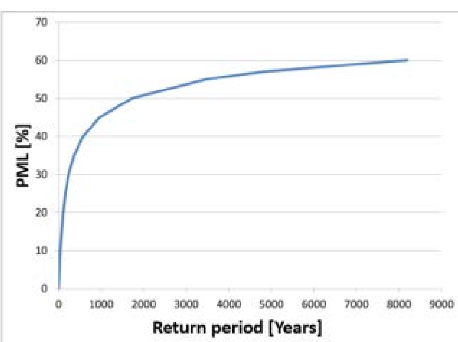
Where $v(p)$ is he excess rate of p loss, Pr ($P>p/Event\ i$) is the excess probability of p loss, since event I occurred, and F_A(*Event i*) is the annual occurrence frequency of event i [19].

The probabilistic seismic risk assessment developed in this work took into account 24,996 possible seismic scenarios and 16,444 buildings, form portfolios of Residential, Commerce, Industry and Others. The exposure value of the assets has been estimated at 963.414 million of American dollars. Physical losses are related only to the replacement value of the infrastructure. The probabilistic seismic risk analysis scenarios were calculated for each building in the city of Santa Tecla, and for two general conditions: 1) without considering the site effects, and 2) with site effects consideration.

4.2 Results

The Average Annual Loss (AAL) for physical assets, without considering site effects, is 10.876 million dollars, representing 1.13% of the total value of assets. Considering site effects, AAL is 52,573 million dollars, representing 5.46% of the total value of assets. The variation of the maximum probable loss in comparison to the return period and the variation in the rate of loss exceedance are presented in Figure 10a and 10b, respectively.

(a)



(b)

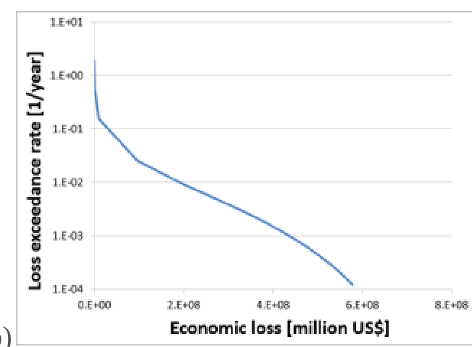


Fig. 10 – (a) Probable Maximum Loss (PML), (b) Loss Exceedance Curve

The spatial distribution of expected annual economic losses in the city of Santa Tecla, are presented in Figure 11. The highest losses are located in the “Centro Histórico”, mainly due to structural types consisting of flimsy materials such as adobe and bahareque; as well as assets mainly built with precarious materials located in areas with limited resources. Buildings with fewer losses are located west of the city, coinciding with the variation of the underlying soil, which produces lower amplification effects to structures located there. The results show that the highest losses are concentrated in a small percentage of exposed buildings, and physical relative losses helped identify systems that may be more affected, without necessarily represent significant economic or human losses.

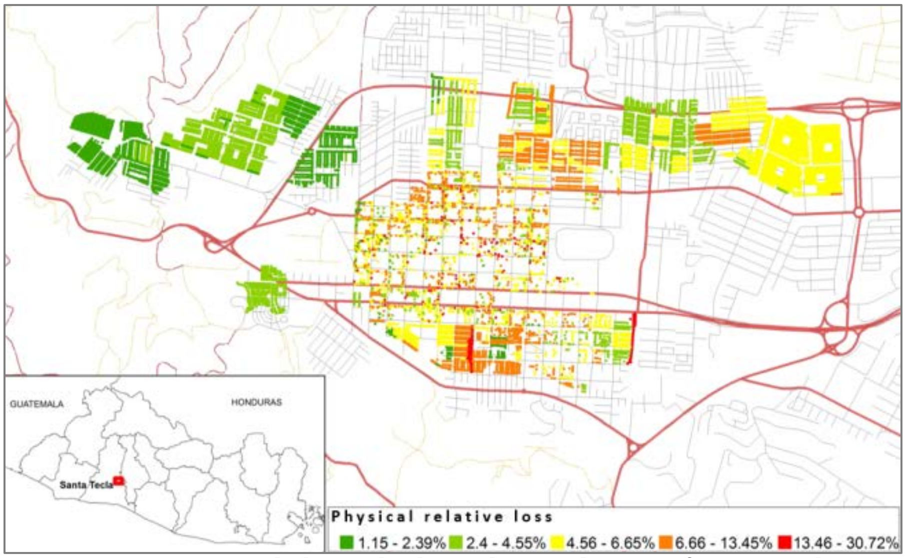


Fig. 11 – Expected physical relative loss in the city of Santa Tecla.

5. Conclusions

A probabilistic risk assessment was performed for the City of Santa Tecla, considering the seismic hazard assessed in terms of spectral accelerations and a preliminary estimation of the amplification effects due to local site conditions. The probabilistic seismic risk analysis considered 24,966 probable seismic scenarios and 16,444 buildings belonging to Residential, Commerce, Industry and other Portfolios with an exposed value around 963,414 million dollars.

The expected annual loss of 5.46%, confirms the high level of seismic risk in the study area. The high seismicity affecting Santa Tecla, controlled by upper crustal earthquakes with relatively short return periods, the particular site conditions, as well as the vulnerability of the building types, contribute greatly to the high level of risk. The significant consequences of soil behavior on the result of seismic risk analysis are confirmed, mainly because the range of periods for which amplification effect is produced is highest for periods in the same range as the most typical building types in Santa Tecla, which consist of reinforced masonry buildings with 1-3 storeys.

Maximum losses are concentrated in a small amount of buildings, thus allowing a prioritization of critical infrastructure for future intervention, which will need detailed studies to further identify feasible mitigation measures. The influence of local soil conditions on earthquake damage potential for different types of buildings should be considered in development plans and land use planning and regulations for earthquake resistant design (i.e. building codes). The results may also contribute to the development of preparedness plans, including the development of a financial optimal structure for risk retention and transfer.

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