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Seismic vulnerability in guatemala city considering the urban planning

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Abstract

This paper proposes a list between the different variables that affect the vulnerability of a building after an earthquake. The significance of urban planning and other urban factors affecting the vulnerability of buildings have not received special attention either from the government or researchers. The lasts research of the vulnerability of buildings are Benedetti and Petrini (Inf Constr 18:66-78, 1984), the EMS-98, the Risk-EU project (2003) and Martínez-Cuevas (2020). The proposed methodology was applied to a database with information about buildings and hypothetical damage grade in Guatemala City. Guatemala City is in a high seismic hazard in the Caribbean plate and surrounded by the North American and Cocos plates (B. Benito 2012). Three main tectonic features have been distinguished around Guatemala: The subduction zone in the plate boundary Cocos-Caribbean; the local faults situated in the volcanic chain; and the Polochic-Motagua in the North America-Caribbean plate boundary. The Guatemala case is unique due to these three seismic origins: Interphase subduction related to the volcanic chain; In-slab subduction related to the Cocos-Caribbean boundary; and Crustal Zone related to the North America-Caribbean boundary. The most destructive event in the last decades in Central America was the earthquake associated with the Motagua fault, Mw 7.6, causing 22,000 deaths in Guatemala City in 1974. The most recent destructive earthquake in Guatemala was associated with the Cocos-Caribbean boundary in San Marcos, Mw 7.4, causing 45 deaths in Guatemala. The San Marcos earthquake reminds Guatemala of the importance of the earthquake code and the seismic hazard evaluation of the country. The results of the described analysis will provide useful insights for areas with seismic risk.

Key words: seismic vulnerability, seismic hazard, urban planning, earthquake lessons, Guatemala City

1 Introduction

The seismic vulnerability can refer to specific structures, whose behaviour in an earthquake is evaluated individually, ranging the entire cities or towns to tiny buildings. However, for each case, the behaviour considering the interactions between the elements that surround it must be studied. At the city level, seismic vulnerability refers to the inability to provide an adequate response and the lack of resilience of some urban components of the city when exposed to earthquakes for a certain period. In the building level, it is important to analyse all the components of the structural design and are critical tasks the classification by type and assignment of the vulnerability class.

Various authors have proposed many techniques and methodologies for assessing vulnerability, principally based on studying the seismic performance of structures corresponding to their structure and construction. Some of these methodologies include empirical, analytical, or theoretical methods. For example, empirical methods are based observing the types of performance for different buildings during earthquakes and characterizing potential seismic deficiencies (Benedetti and Petrini 1984). Empirical methods take behaviour modifiers into account. For example, it is possible to use the vulnerability index proposed by Benedetti and Petrini and use the Risk-UE (2003) to identify the regularity of the building plan and the position of the building. And finally, the analytical methods evaluate the resistance of structures to ground motion using mechanical models (Pagani et al. 2014).

In the present study, the use of parameters referred to as "urban modifiers" [1] and their application to a hypothetical earthquake is proposed (RESIS II) [2].

A proposal to classify damage to inform seismic design for high buildings in different places in Guatemala City is given. The objective is to consider the different independent variables, structural and non-structural damage (Fig. 1).

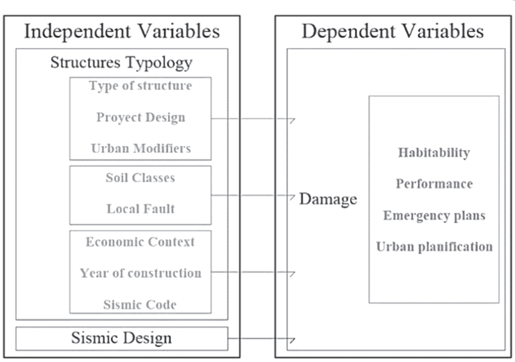

Figure 1. Variables in the present study

The damage is related to the results from the 3D studio on SAP2000. This classification intends to make an index and a damage scale which are then used to create a table of building typologies on different types of urban morphology's, soil and high. The principal contribution is a procedure to determinate the variables of the structure in an earthquake situation taking into account different parameters, such as the type of structure, the urban configuration, and the soil condition of the new building location. Besides, a spatial analysis of Guatemala City to identify the non-habitable areas and to project new zones of urban development could generate. This information could be valuable for CONRED (National Coordination for Disaster Reduction) and Municipality of Guatemala to help to device contingency plans, and to identify those areas that should be rebuilt according to seismic risk.

2 Vulnerability

The principal objective of any seismic vulnerability classification for buildings is to describes the types of building or set of buildings which may be susceptible to suffering damage after a certain type of earthquake. In this way, their structural response, and an estimation of the magnitude of the resulting losses may be gathered. Also, the response of the building is affected by the distance between the structure and the epicentre of the earthquake or the geology. Structure typology depends mainly on local building materials, climatic condition, the socioeconomic status, as well as the geology and geography factors [3]. In Guatemala City, it is very important to describe the earthquake, as it is not the same an interphase subduction earthquake than an in-slab subduction or a crustal zone (Benito et al. 2012).

3 Application Earthquake in Guatemala City

Guatemala City is in the middle of Guatemala, located in the northern part of Central America (CA). CA is in the western limit of the Caribbean Plate, which plate is surrounded by the South American, Nazca, Cocos, and North American plates. The Nazca and the South American affect principally the southern part of CA (Nicaragua, Costa Rica, and Panamá), and the other two plates affect the Northern Triangle of CA (Guatemala, El Salvador, and Honduras). The principal faults that affect Guatemala area, the Cocos and Caribbean plates, are bounded by the Central American subduction zone and the transcurrent faults of Polochic-Motagua-Chamelecón which are the boundaries of the North American-Caribbean plates. Fig. 2 depicts the described Central America Tectonics.

In this northern region of CA three main tectonic features have been distinguished: (1) the subduction zone in the plate boundary Cocos-Caribbean; (2) the local faults situated in the volcanic chain; and (3) the Polochic-Motagua in the North America-Caribbean plate boundary. In the last 500 years many devastating earthquakes have occurred in these tectonics features with high or moderate magnitudes ($8.0 \leq Mw \leq 6.0$).

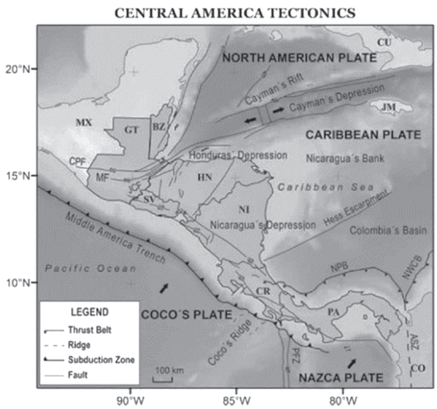

Figure 2. Tectonic map of Central America [4]

The last updated Central America catalogue of regional seismic events was proposed by Benito et al., 2010. CA has been struck since 1522 by numerous earthquakes that caused devastation, both in the subduction zone and in the local faults of the volcanic chain. The first type produced higher magnitudes earthquakes of subduction Mw 8, but these events were less frequent and caused less damage than those originated at the local fault because their epicentres are normally located seaward, and their depths are h ≥ 25 km. In the Volcanic chain, the earthquakes present measured magnitude Mw ≤ 6.7 but caused more damage because there are crustal events with h < 25 km and are frequently located close to the population centres. In Fig. 3 the, different seismogenic zones are shown.

Figure 3. Seismogenic zones adopted for the seismic-hazard assessment: a) Crustal zones superimposed to surface seismicity, b) Interplate zones superimposed to intermediate seismicity, c) In-slab zones superimposed to deep seismicity. [4]

The last evaluation of seismic hazard in CA has been carried out as part of the cooperation project named RESIS II. In this cooperation project participated several seismic-hazard experts from Guatemala, Honduras, El Salvador, Nicaragua, Costa Rica, Panamá, Norway, and Spain. One of the results obtained by this evaluation is a new hazard map with Uniform Hazard Spectra (UHS) for the capital cities of CA. Cooperation project currently continues as KUK ÀPÁN: an integrated regional study of structure and evolution 4D of CA lithosphere, with implications in seismic hazard and risk calculation. The RESIS II project obtained maps of PGA and SA (1 s) for three return periods: 500, 1000, and 2500 years.

Analysis of these figures allows highlighting the following results from Guatemala: the greatest values of PGA are predicted in the south of Guatemala and in some areas of the volcanic chain. For a return period of 500 years, PGA reaches a maximum of 600 cm/s^2 in south Guatemala, and 500 cm/s^2 in some places located in the volcanic chain along Guatemala (Fig. 4). It is found an exception in southern Guatemala, where the isolines are not parallel to the coast as in the rest of CA, and PGA decreases more slowly showing the influence of the Motagua fault. Also, similarities in the PGA isolines for the return periods of 1000 and 2500 years can be observed, being the greatest values entirely located in southern Guatemala.

Figure 4. Seismic-hazard maps of Central America in terms of PGA for return periods of: a) 500 years, b) 1000 years, and (c) 2500 years [4]

Table 1. Control Earthquake [4]

Control Earthquake	**Peak Ground Analysis** [cm/s^2]		**Spectral Acceleration** [1 s, cm/s^2]		**Peak Ground Analysis** [cm/s^2]		**Spectral Acceleration** [1 s, cm/s^2]	
	Mw	**Rhyp** [km]	**Mw**	**Rhyp** [km]	**Mw**	**Rhyp** [km]	**Mw**	**Rhyp** [km]
Guatemala City								
CE1	6.5	15	6.5	15	6.5	15	6.5	15
CE2	7.0-7.5	135-150	7.25-7.5	135-150	7.25-7.5	150-180	7.25-7.5	135-180

Also, the RESIS II project obtained hazard results for Guatemala City and the other capitals of CA (Table 1). As expected, the greatest hazard level corresponds to Guatemala.

The RESIS II reviewed the seismic hazard for each capital. In the case of Guatemala City, the pair Mw 6.5 and Rhyp = 15 km stands as a clear control earthquake. This event predominates in all the analyzed return periods. Also, but with a lower probability density, an earthquake with Mw 7-7.5 and distance Rhyp = 135-150 km for 500 years return period and another with Mw 7.25-7.5 and distance Rhyp = 150-180 km for a return period of 2500 years are found. The most important conclusion is that for all cases the hazard is dominated by nearby faults, although there is also a contribution from a more distant subduction event. This new control earthquake provides new information to be considered in the future revision of the national seismic code in Guatemala. This difference between the new control earthquake and the seismic code in Guatemala is because the RESIS II studio include the smaller seismogenic zones with greater detail, and also because it uses a combination of different attenuation models for crustal, subduction interface, and in-slab events previously calibrated with local data.

4 Guatemala City typology

Guatemala City is in the “Valle de la Ermita” at an altitude of 1.500 mts above sea level. The city is the economic, governmental, and cultural center of the nation. It is estimated that the population of Guatemala City is about 2.5 million, but when considering the metropolitan zone, it increases to almost 5.1 million. The current city is the fourth site of the capital of Guatemala Kingdom. The reason for the last movement of the capita was the Santa Marta earthquake that destroyed Santiago de los Caballeros, today Antigua Guatemala, in 1773.

The Valle de Guatemala is an active geologic graben, whose trench is 12-15 km wide and about 30 km long. It literally splits the main Guatemala mountain chain [5]. The Guatemala City area is under the threat of local, active geologic faults and major, regional active faults. Local earthquakes are a major source of seismic hazard, which may be accompanied by landslides, passive ground cracking and very possibly, active fault rupturing. In the Fig. 5, the most important volcanoes are marked in red, the volcanic chain (NW-SE) and the important fault in blue (Polochic, Motagua, Jocotán, and Jalpatagua), in light green Guatemala City, in dark green the near towns, and in yellow the secondary faults.

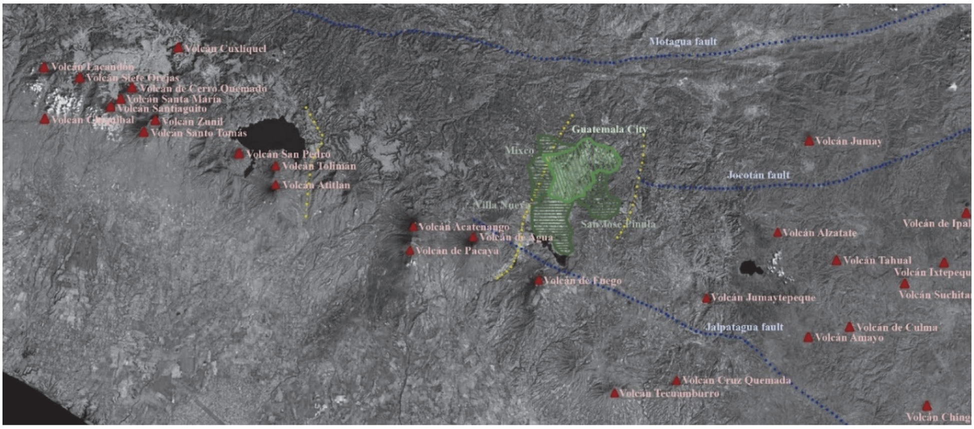

Figure 5. South of Guatemala

Guatemala is located on an important seismic active zone, as shown by the list of the most recent earthquakes in the country given in Table 2. The real dimension of the seismic hazard was to become apparent only after the 1976 earthquake. Before then, the construction was divided into three main categories: housing, commercial and office buildings, and industrial. Most of the housing in Guatemala City are single-family, and almost half units are reasonably reinforced masonry; a quarter is adobe; and the remainder is shacks built from a variety of materials, from wood boards to scrap material. Commercial and office buildings are usually reinforced concrete frames, and the industrial buildings are usually steel frames.

Table 2. Earthquakes $M_M \geq 7$ or $I_{MM} \geq$ VII in Guatemala [7]

Date	Hour			Depth[km]	Imax population	I0	Imax	M
29/07/1773		14,66	91,16	Cortical	Antigua Guatemala		IX	7,5 (M_M)
22/07/1816		15,45	91,50	Subduction	Soloma, Jacaltenango	IX	IX	7,5 (M_M)
06/05//1821		15,33	90,75	Cortical	Sacapulas, Quiché	VIII	VIII	6,2 (M_M)
21/04/1830		14,47	90,60	Cortical	Amatitlán	VIII	VIII	6,0 (M_M)
03/05/1830		14,33	90,42	Cortical	Cuilapa, Sta. Rosa	VIII	VIII	6,0 (M_M)
X/03/1845		14,42	90,62	Cortical	Amatitlán	VIII	VIII	6,0 (M_M)
17/05/1851		15,08	91,78	Cortical	Tajumulco and S. Marcos		VIII	6,0 (M_M)
09/02/1853		13,50	91,50	Subduction	Quetzaltenango		VIII	7,2 (M_M)
19/12/1862		14,40	90,20	Subduction	Salavador-Guatemala		VIII	7,2 (M_M)
12/05/1870		14,20	90,12	Cortical	Cuilapa, Sta. Rosa	VIII	VIII	6,0 (M_M)
03/09/1874		14,50	90,83	Subduction	S. Miguel D.		VIII	6,5 (M_M)
18/12/1885		14,41	90,62	Cortical	Amatitlán	VIII	VIII	6,0 (M_M)
19/04/1902	02:24	14,00	91,00	Subduction	Quetzaltenango		IX	7,5 (M_S)
08/03/1913	16:05	14,30	90,35	Cortical	Cuilapa, Sta. Rosa	VIII	VIII	5,9 (M_S)
25/01/1918	01:18	14,60	90,53	Cortical	Guatemala	VIII	VIII	6,2 (M_S)
14/07/1930	22:40	14,20	90,15	Cortical	S. Ma. Ixhuatán	VIII	VIII	6,9 (M_S)
06/08/1942	23:36	13,90	90,80	Subduction	Sacatepéquez		VIII	7,9 (M_S)
23/10/1950	16:13	14,30	91,70	65	San Marcos		IX	7,3 (M_S)
04/02/1976	03:01	15,30	89,20	5	S. Juan and S. Pedro		IX	7,5 (M_S)
3/11/1988	14:14	13,88	90,45	69	S. Vicente Pacaya		VI	6,0 (M_S)
10/01/1998	02:20	14,37	91,47	33	S. Domingo S.		VII	6,6 (M_S)
19/09/2011	18:34	14,33	90,14	9	Guatemala City		VII	5,8 (M_S)
07/11/2012	16:35	13,98	91,96	24	Champerico		VII	7,4 (M_S)
06/11/2017	07:29	14,54	92,00	94	S. Pablo, S. Marcos		VII	6,6 (M_S)

During the earthquake, principally the adobe buildings behave quite badly as it is non-cohesive and extremely brittle and supports heavy tile roofs. All of this result in most of this type building collapsing in Guatemala City. The most hazardous buildings in reinforced concrete are the oldest ones, because of their brittleness and the bareness of their frames. None of the larger buildings of this type collapsed, but a few had to be demolished while some other underwent major repairs.

The 1976 earthquakes, which attained a magnitude of 7.5 degrees [6] struck on February 4 at 3:01 am local time when most people were asleep. This contributed to the high death toll of 23,000 people, also approximately 70,000 people were injured, and many thousands left homeless. The epicentre was centred on the Motagua Fault, at 5 km depth, about 160 km northeast of Guatemala City. The earthquake caused visible rupturing over 230 km along the Motagua Fault, being, some places the horizontal displacement 100 cm. In the next days, several aftershocks (10), ranging from 5.2 to 5.8 Mw were measured.

4.1 Selection of samples for the study

The most common types of structures in Guatemala City are very similar to those in the 1970s. The only difference is in the low buildings with adobe construction because many of these buildings collapsed during the 1976 earthquake. Now, many structures correspond to reinforced concrete frames-filled block buildings (Concrete Masonry Unit -CMU-). The problems are the poor quality of materials and bad configuration of the building. Also, the abuse of the construction systems for inadequate situations: the CMU have a good performance in low buildings (2 or 3 floors) but in higher buildings the structural performance in penalized.

In the last years, the pace of construction in Guatemala City has increased due to the social circumstances of the country. One of the largest sectors has been high-rise construction, densifying the most important areas of the city. Fig, 6 shows in red the recent tall buildings and yellow the most important faults.

Most of these new buildings are made of reinforced concrete frames and over 20 stories high. Their greatest limitation is due to their proximity to the airport. Another limitation, recently updated (2015), is the urban planning by the Municipality of Guatemala (POT). And finally, the recent update of the seismic code (2018) must be considered.

However, this recent seismic code (NSE-3 2018) does not contemplate the results of the project RESIS II and KUK ÀPHÁN. One of its main limitations is the use of deterministic results and considering the most unfavorable probabilities of the faults regions [8]. The NSE-3 ignore the probabilities of the local faults.

For these reasons, the study cases were chosen according to their age, their height and the code considered for their design.

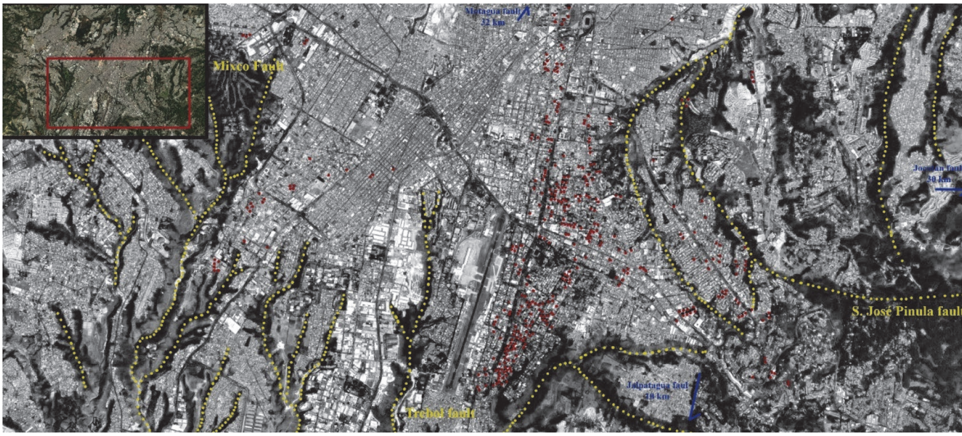

Figure 6. Guatemala City

5 Information Study

This methodology proposes to create a database with information on the variable to be analyzed: the name of the variable, description, levels, and type. Table 3 shows the database structure with four columns corresponding to the most relevant fields. In this case, the only dependent variable was damage. All other variables behaved as independent variables. This methodology allows to predict the damage in case of new seismic design, unlike other studies that began after an earthquake and they have records available of the building damaged.

Table 3. Definition of dependent and independent variables [3]

Variable		Type of variable
Damage		Dependent
Urban Modifiers	Irregular plan	Independent
	Vertical Irregularity	Independent
	Hammering Effect	Independent
	Height Difference, Right Side	Independent
	Height Difference, Left Side	Independent
	Soft Story	Independent
	Short Column	Independent
	Urban Typology	Independent
	Aggregate Building Position	Independent
	Alignments	Independent
	Aggregate Building Elevation	Independent
	Soil Morphology	Independent
	Number of Floors	Independent
Seismic Code		Independent
Year of Construction		Independent

5.1 Case Study

This building is in Avenida Las Americas, 11 calle, zona 13 in Guatemala City. It is randomly chosen. On the left side of Fig. 7, the ubication of the building is given, and urban planning of the area in the POT [9] shown on the right-hand side. Fig. 8 shows the principal plans of the building: urban typology to the right, and the vertical irregularity, the number of floors, and another independent variable to the left. The information is provided by a private company, this facilitates data collection. Other information that was obtained was the construction year, the main use, and the current seismic code.

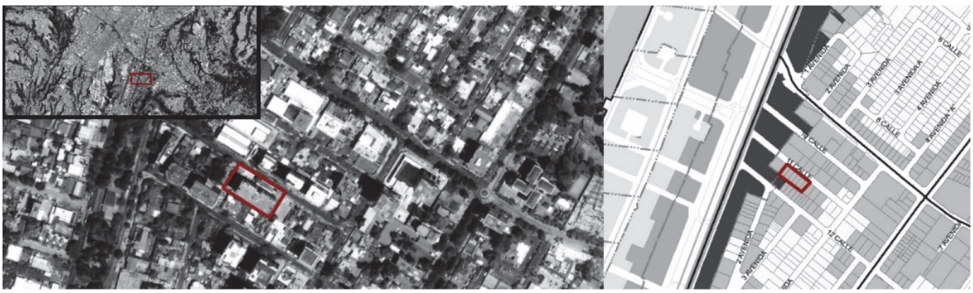

Figure 7. Case ubication

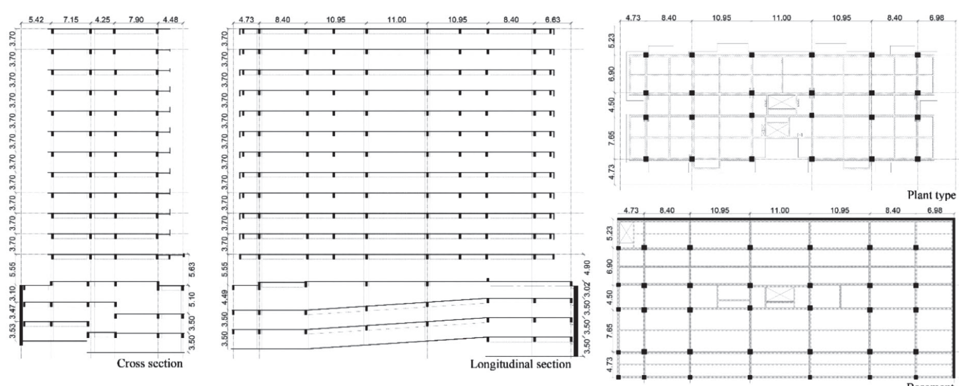

Figure 8. Plans of the case

The next phase has two steps, create database with the different building variables, and the analysis statistical. The missing variables for this study are the most important to evaluate the damage, for example, the soil morphology, the near fault, and other architectural details (urban typology, short Column, soft story, hammering effect…) that the only way to achieve is through an exhaustive fieldwork in Guatemala City. To get a complete database, the sample needs 125 buildings, 25% of the buildings with more than 10 floors in Guatemala City, including the 44 buildings with more than 20 floors. The last variable to introduce is damage after 3D rendering. For this latter, it is necessary to assign the variables that affect the response spectrum, such as soil morphology, nearby faults, and construction details. Statistical analysis needs a complete database first, then it is necessary to assign the type of variable, dependent or independent, nominal polytomous or nominal dichotomous, and the levels of classification; to get the correlative variables, and the variable statistically insignificant. Nominal dichotomous means that only two levels are defined for the variable, for example: present or not present short columns. Nominal polytomous indicates that the variable has more than two levels, for example: regular, irregular closed cantilever or irregular open cantilever for the vertical irregularity.

6 Conclusion

The present example is another step towards identifying which building typologies are used in Guatemala City. It also shows the required study variables and other values that are unknown. For example, soil type, proximity to local faults, and other architectural and urban modifiers.

This study opens a line of investigation for public authorities and experts in seismicity to work together to plan seismically in Guatemala City. This study should be applicated to more buildings to detect some vices in the planning, design and construction process. The results obtained must be conveyed to organizations in charge of city planning and supervising civil and emergency protection so that we develop Guatemala City in a way that minimizes seismic risk and organize viable emergency plans.

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