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SEISMIC EVALUATION OF NON-DUCTILE REINFORCED CONCRETE SMALL HOUSES

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Abstract

Ecuador's active tectonics, historic seismicity, and socio-economic situation leave the country increasingly vulnerable to seismic activity. In an effort to continue the goals of the United Nations (UN) Secretariat of the International Decade for Natural Disaster Reduction (IDNDR), researchers at Escuela Superior Politécnica del Litoral (ESPOL) partnered with the University of Colorado, Boulder to investigate the seismic risk in the city's poor and vulnerable neighborhoods, known as popular areas. This study employs the Seismic Vulnerability Index (SVI) method, originally developed by Italian researchers in 1984, to develop a structural survey methodology and a Seismic Vulnerability Assessment Scoring Matrix (SVASM) suitable for the informally constructed, popular areas in Guayaquil. A structural survey was conducted on approximately 200 buildings at two different sites: one soft soil, flat terrain area (Trinitaria) and one sloped, hill area (Bastión Popular). The structural survey evaluated several building parameters such as the structural resisting system, irregularities, structural deficiencies such as soft stories, existing damage, and quality of construction. An SVI was then calculated for each structure and used to estimate expected damage. Damage predictions were calculated for earthquake intensities ranging from VII-IX on the Modified Mercalli scale. The Risk Assessment Tools for Diagnosis of Urban Areas against Seismic Disasters (RADIUS) initiative established the design earthquake for Guayaquil as a magnitude 8.0 event on the Richter Scale with a epicenter at about 200 km north-east of the city. The design earthquake results in an Intensity VII and VIII event in Bastión and Trinitaria, respectively. The study found that the surveyed areas are at significant risk to loss of life and property with the majority of the structures experiencing damage or collapse during the design earthquake especially those located in the Trinitaria area. Local authorities can play two roles in reducing risk. First, they could provide resources and expertise for the rehabilitation of existing houses, starting with the most vulnerable. Second, they could provide education and training to homeowners and informal builders to improve the quality of future construction. The findings presented in this study could also be expanded in future research to develop a fully formed plan for improving seismic resilience in Guayaquil.

Keywords: Seismic Risk Assessment; Structural Vulnerability; Ecuador; Informal Construction; Housing

1. Introduction

Ecuador is a country that is exposed to a high seismic hazard, produced by the subduction of the Nazca Plate beneath the South American Plate. Most of its inhabitants are moving to the main cities, increasing its population and concentrating in urban poor areas, becoming more vulnerable to disasters, such as earthquakes. As a result, seismic vulnerability has been growing rapidly especially in urban poor areas where design codes are not generally used and informal construction is very common.

The RADIUS project [1] was launched in 1996 by the Secretariat of the International Decade for Natural Disaster Reduction (IDNDR) of the United Nations (UN) to reduce the disasters caused by earthquakes in urban areas and raise public awareness. Guayaquil, Ecuador was one of the nine case cities selected for this initiative, to make a comparative study of seismic risks.

Researchers at Escuela Superior Politécnica del Litoral (ESPOL) partnered with the University of Colorado Boulder to investigate the seismic risk in two areas of Guayaquil. A structural survey and seismic assessment were conducted on approximately 200 buildings at two sites with different soil profiles: one on a flat terrain area with soft clayey soil, and one on a hillside sloped area. The structural survey consisted in the evaluation of several building parameters such as the structural resisting system, irregularities, structural deficiencies, existing damage and quality of construction. The methodology used for this study focused on determining the Seismic Vulnerability Index (SVI) of the structure. This method was originally developed by Italian researchers in 1984 to perform a structural survey methodology and a Seismic Vulnerability Assessment Scoring Matrix (SVASM) suitable for the informally constructed areas in Guayaquil.

The main objective of this study is to make a seismic risk assessment by obtaining the SVI and estimating the expected damage for different earthquake intensities on the modified Mercalli scale, according to each area. This information will be helpful for local authorities in order to establish a program of rehabilitation of existing structures, set new guidelines for future design and construction, and raise public awareness to reduce disasters.

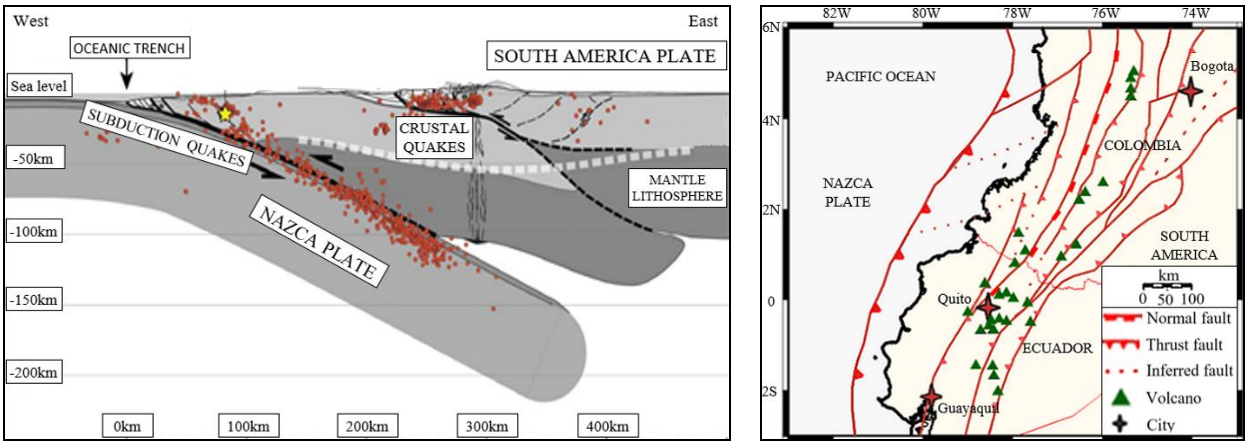
2. Background

2.1 Guayaquil Seismic Hazard Description

Guayaquil city is located on Ecuador's coast, and is considered vulnerable to seismic movement by subduction. Fig. 1(a) shows the subduction mechanism of the Nazca and South America plates, while Fig. 1(b) shows the different seismic sources of subduction across Ecuador [2, 3]. The most recent big seismic event at Ecuador (Pedernales, 2016) highlighted the seismic hazard of Guayaquil, where the earthquake caused some damage to buildings and the collapse of the "Universidad Laica" overpass [4]. The collapse of this overpass caused the death of two people.

2.2 Radius Project

The RADIUS Project [1] was a study sponsored by the United Nations which aimed to gain understanding about seismic risk in urban areas. RADIUS selected 9 cities across 4 continents to participate in the study, including Guayaquil. The RADIUS Project was implemented in Guayaquil in 1999 with the objectives of completing a seismic risk assessment, estimating the damage that a design earthquake could cause, developing an action plan to address risk, and spreading public awareness about the issue. To achieve these objectives, the RADIUS Project collected data from prior catastrophes, building appraisals, population distribution, and soil types, among other information.



(a) Subduction mechanism [2]

(b) Seismic source of subduction [3]

Fig. 1– Guayaquil Seismic Hazard

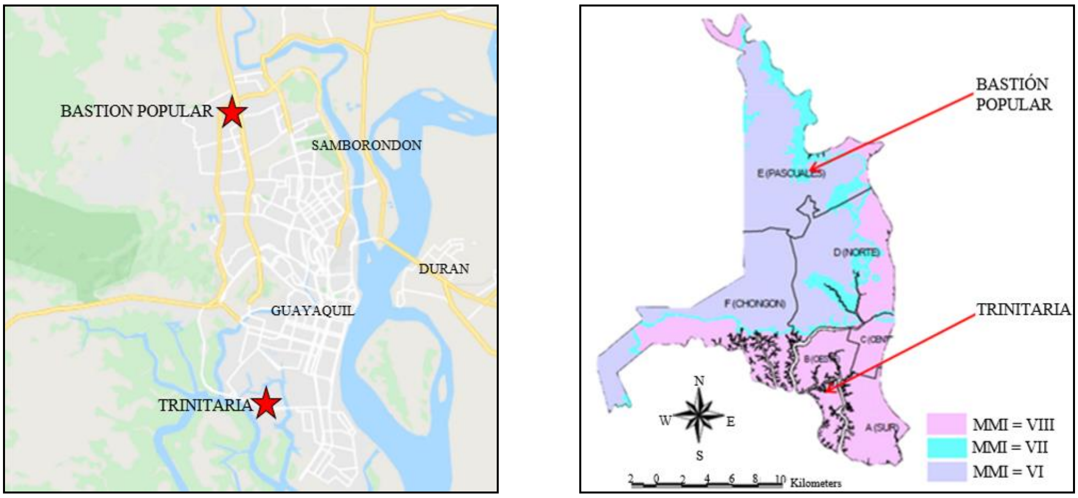
The design earthquake used in this document was based on the design earthquake established by the RADIUS Project, which is a magnitude 8 ground motion on the Richter scale 200 km northwest of the city of Guayaquil. This earthquake triggers different intensities according to the type of soil of the sector studied. Therefore, in soft soil sectors near rivers or estuaries of downtown and south of the city corresponds to VIII Mercalli intensity scale while in the areas of the hills corresponds to VII Mercalli intensity scale. The total losses estimated by RADIUS according to the design earthquake is about US$ 1000 million dollars which includes direct losses of the damaged buildings and indirect losses caused by suspension of functions or services provided by the affected buildings.

2.3 Selection of Popular Areas

Guayaquil is approximately 4 meters above sea level and has varied topography which increases seismic risk. Due to the presence of the Guayas River and the Salado Estuary and the tendency to build atop former landfills, a large portion of the urban area settles on soft soils. Additionally, the city of Guayaquil has several areas built on steep slopes, which put structures at additional risk of landslide. In accordance with these two major types of sites, the popular areas selected for this study were chosen to represent soft soils and hills. Moreover, in these urban poor areas design codes are not generally used and informal construction is very common. Trinitaria, located in the south of the city, was selected as the soft soil area, while Bastión Popular, located in the north of the city, was selected as the hill area. Fig. 2(a) shows the location of Bastión Popular and Trinitaria. Fig. 2(b) shows the Mercalli modified intensity (MMI) for the design earthquake for each sector analyzed. Trinitaria corresponds to a VIII MMI and Bastion Popular corresponds to VII MMI, according to [1].

Bastión Popular was selected from other alternatives due to its steep slopes, presence of natural terrain that facilitates soil borings, and prior landslides. At noon of March 13, 2019, a covacha was buried with two people inside due to a landslide caused by the heavy rain that fell in Guayaquil on the night of Tuesday the 12th [6]. The landslide occurred in Block # 11 of the Floor de Bastion area very close to the selected zone. Bastión Popular area selected for the study has 5 blocks, and a total of 109 houses. Fig. 3(a) shows the aerial view, while Fig. 3(b) shows a close-up view of the common houses found on inspection.

Trinitaria was selected due to the presence of soft soil and proximity to the estuary. This area has 4 blocks, and a total of 111 houses. Fig. 4(a) shows the aerial view, while Fig. 4(b) shows a close-up view of the common houses found on inspection.



(a) Plan view of the selected areas [5]

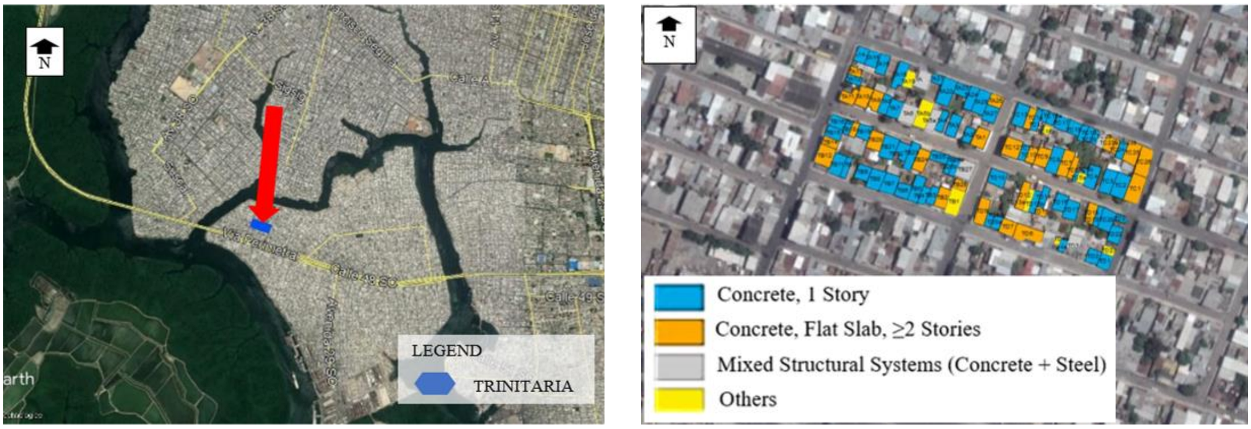
(b) Seismic Intensity according to the design earthquake [1]

Fig. 2 – Selected popular areas

(a) Aerial view [5]

(b) Close-up view of the selected study area [5]

Fig. 3 – Bastión Popular



(a) Aerial view [5]

(b) Close-up view of the selected study area [5]

Fig. 4 – Trinitaria

3. Survey, Visual Inspections, and field testing

3.1 Methodology

Data was collected from the survey areas using visual inspection, photographs, homeowner interviews, and material tests. Before data collection began, researchers used aerial and street views publicly available through Google Maps [5] to map the neighborhoods and number each structure. A block-by-block numbering system was created to organize the surveys, photos, and geographic locations of each structure. Teams of two researchers were deployed to each area over a period of about two weeks to complete a visual inspection. Each house was inspected individually.

During a typical house inspection, one researcher completed a survey form, classifying the building type and material along with noting any irregularities or structural deficiencies. The other used a smart phone to photograph the structure, beginning with a summary photo of the entire building and then including detailed images of irregularities and damage. When possible, both researchers walked along the sides of the house to observe all visible exterior walls. In many cases, shared walls or fencing prevented this. Since limited information is available from the exterior, researchers knocked on most doors to request an interior tour and interview with the homeowner. Many homeowners were not present or did not wish to partake in the survey, so the data collected from their homes was limited to what was visible from the exterior. If an interview could be completed, it focused on the history of the building and the structural details not visible to the naked eye. Questions included the age of the building, the timeline of any expansions or major alterations, and its behavior during recent earthquakes. Since many homeowners in the area built their own homes, they also offered insight about the foundation type and rebar placement.

After the conclusion of the visual inspections, researchers returned to the survey areas to collect material data from a limited number of structures. A Schmidt rebound hammer was used to approximate the compressive strength of concrete in beams, columns, and stairs. Researchers identified flat areas of concrete without any decorative cover for testing. The concrete surface was smoothed with a piece of pumice stone, and the rebound hammer was deployed perpendicular to the surface in accordance with manufacturer guidelines. Each location was tested ten times, the outliers were automatically removed by the device, and an average R value was calculated. Each R-value was then converted to an approximate compressive strength using manufacturer-provided conversion tables. A soil boring exploration program was also executed but the results will not be discussed in this paper.

3.2 Survey Form

The survey form used for this project was designed to collect as much seismic vulnerability information as possible without necessarily entering the structure. Form subsections include General Information (building height, use, and material), Structural System, Irregularities, Construction Quality, Existing Damage, and Observations. Multiple-choice options were used whenever possible to keep the results consistent across all houses. The questions within each subsection were simplified to allow each house to be surveyed within 10-15 minutes. For example, in the survey form, openings were assessed with a series of simple observations: approximate percent by area (with provided ranges), presence of lintels (yes or no), minimum distance between openings (above or below Ecuadorian code), and alignment of openings (yes or no). Each of these observations was intentionally simplistic and binary in nature to encourage rapid sampling and consistent assessment. Qualitative factors like construction quality were assessed using Class A, B, C, and D, as determined by the researchers' judgment.

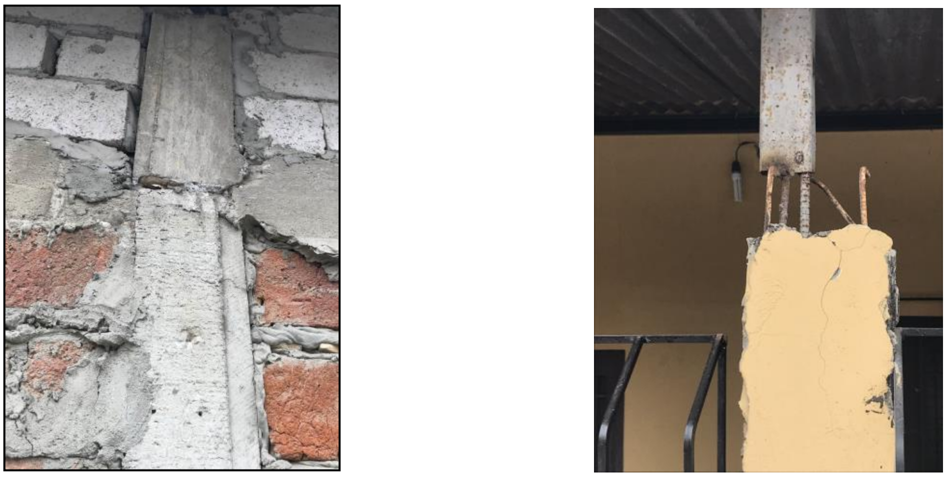
In addition to the multiple-choice portions, there was space for additional comments in each section, along with extensive space for notes in the Observations section. For houses with unusual features or additional information provided through interviews or interior tours, these notes sections were important to capture all available details.

4. Structural deficiencies, Deterioration, and Damage found

Some houses had unique issues, but many deficiencies in design and construction were common throughout the survey sites. Some of the most common structural deficiencies, examples of deterioration, and existing damage are described below.

4.1 Inadequate Connections

The beam-column connections were typically poor as seen in Fig. 5(a). It was often obvious that a beam was not poured continuously, which can produce a weak point in the connection. Fig. 5(b) shows an example where a steel purling is connected inadequately to a reinforced concrete column by a steel shape welded to the reinforcing steel bars of the column. Frequently, the first story column and second story column did not line up.



(a) Inadequate connection column - beam (b) Inadequate connection column - roof

Fig. 5 – Examples of inadequate connections

4.2 Mixed Structural Elements

It was common to see buildings constructed progressively over time. Expansions included the addition of a second story above the first, the expansion of a second story into a cantilever, and outward expansion. In Bastion, the addition of basements built into the hillside was also common. All expansion types exhibited similar issues, including mixed material elements, missing structural elements, and poor connections. The buildings shown in Fig. 6 are examples of expansions with mixed materials and poor connections.

(a) Google Earth, March 2015 (b) Survey Photo, June 2019

Fig. 6 – Examples of multiple additions and expansions with different elements (cont.)

(c) Google Earth, March 2015

(d) Survey Photo, June 2019

Fig. 6 – Examples of multiple additions and expansions with different elements

4.3 Missing Confinement Elements in Unreinforced Masonry Walls

In many houses, especially those built progressively over time, structural elements were missing. The buildings shown in Fig. 7 are examples of these observations. These missing elements were sometimes only visible from the side of the structure. The front of the house was often covered in a thin layer of cement, plaster, paint or tile for aesthetic purposes concealing the presence or absence of structural elements from view. Fig. 7(a) shows an example where a cantilever slab is deflecting excessively and the owner decided to support it using a provisional bamboo strut. Fig. 7(b) and 7(c) show examples where a column and a beam confinement elements are missing.

(*a*) Missing structural element

(b) Column absence

(c) Ring beam absence

Fig. 7 – Examples of unreinforced masonry walls with missing confinement elements

4.4 Intentional Concrete Removal

It was very common to see concrete elements which had been intentionally removed by homeowners (see Fig. 8) for different reasons. It was especially common to see columns adjacent to door openings demolished locally to provide a connection point for door frame welding. In one house, the opening and closing of a door frequently caused pieces of the adjacent column to crumble and fall. The owner realized the concrete was poor quality, so he demolished the column without a plan to replace it (Fig. 8b). Columns and beams were also demolished partially in several houses to accommodate changing door and window openings (Figure 8c), destroying their structural integrity.

(a) Portion of column removed

(b) Structural element demolished to welding a door frame

(c) Portion of beam removed

Fig. 8 – Examples of removal of concrete of structural elements

4.5 Inadequate Cover

Adequate cover is important to fully integrate the reinforcing steel into a beam or column and to protect it from potential corrosion. In a large number of houses, cover was so thin that the concrete is crumbling, exposing the rebar, leaving it susceptible to corrosion as seen in Fig. 9.

(a) Inadequate beam cover and exposed rebar

(b) Inadequate cover of a column and exposed rebar

Fig. 9 – Examples of inadequate concrete cover

4.6 Existing Damage

Some of the most common damage observed was cracking of unreinforced masonry walls, mortar failure, and cracked or spalling structural elements. In some houses, damage was obvious to both researchers and the homeowners. Unfortunately, due to logistical and financial concerns, residents are often unable to repair the damage. The house shown in Fig. 10(a) has a failed masonry wall due to tree growth, which was exacerbated by the 2016 earthquake while Fig. 10(b) shows some masonry wall cracking between openings. These damages put the structures at additional risk in a future earthquake event.

(a) Non Structural damage caused by a tree (b) Non Structural damage between openings

Fig. 10 – Examples of existing damage

5. Seismic Vulnerability Assessment

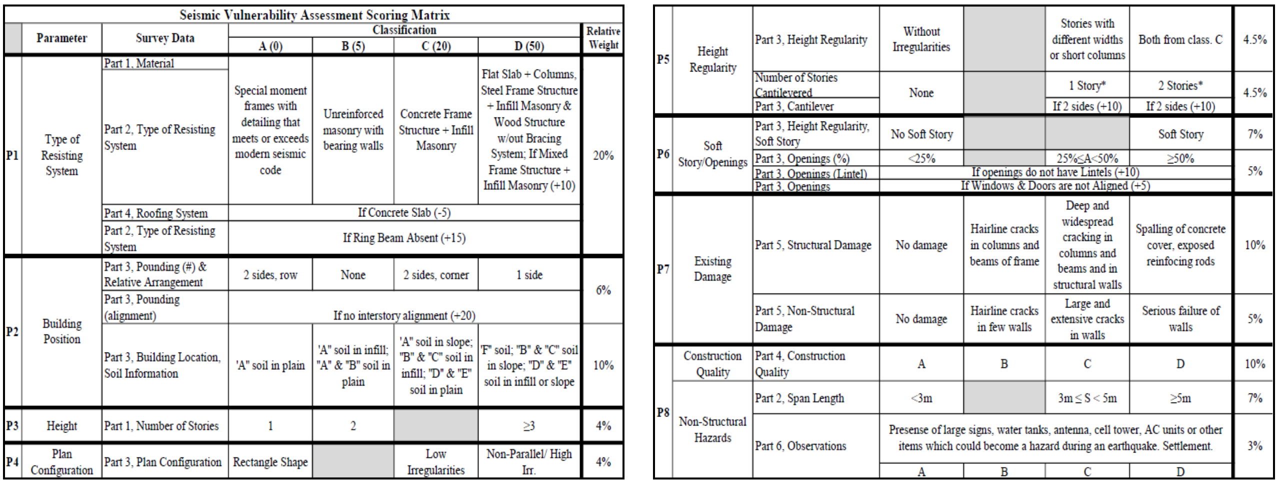
5.1 Methodology

Researchers around the world have been assessing seismic vulnerability for decades, using slightly varying methodologies. One common approach is the Seismic Vulnerability Index (SVI), originally developed by Italian researchers in 1984. This method involves collecting information about various vulnerability parameters and using a weighted average to calculate the SVI [7]. SVI is useful in quantifying vulnerability and interpreting that information into expected damage. Their approach has been modified and adapted in several subsequent papers, as the categories and weights are slightly adjusted to better suit different locations and building typologies [8, 9, 10, 11].

5.2 Seismic Vulnerability Assessment Scoring Matrix (SVASM)

The team combined parameters from prior research to create a SVASM applicable to Guayaquil. The list was narrowed to 8 parameters: type of resisting system, building position, height, plan configuration, height regularity, soft story/openings, existing damage, and additional hazards. To decide on importance weights, the team first prioritized the parameters that previous researchers reached consensus were important (resisting system and building position). There was also significant weight dedicated to the parameters which most affect informally constructed buildings (quality and damage). The SVASM is provided in Figure 11.

Each building surveyed is classified as A, B, C or D within the parameters. Each classification level has an associated score (0, 5, 20, 50). Class A is the least vulnerable (0) and Class D is the most vulnerable (50). Several parameters also have score modifiers to increase or decrease vulnerability relative to the standard classifications. The weights and score modifiers were tested on a sample of buildings from the field surveys and adjusted to accurately capture observations from the field.



Seismic Vulnerability Assessment Scoring Matrix

	Parameter	Survey Data	Classification				Relative Weight
			A (0)	B (5)	C (20)	D (50)	
P1	Type of Resisting System	Part 1, Material Part 2, Type of Resisting System	Special moment frames with detailing that meets or exceeds modern seismic code	Unreinforced masonry with bearing walls	Concrete Frame Structure + Infill Masonry	Flat Slab + Columns, Steel Frame Structure + Infill Masonry & Wood Structure w/out Bracing System; If Mixed Frame Structure + Infill Masonry (+10)	20%
		Part 4, Roofing System	If Concrete Slab (-5)				
		Part 2, Type of Resisting System	If Ring Beam Absent (+15)				
P2	Building Position	Part 3, Pounding (#) & Relative Arrangement	2 sides, row	None	2 sides, corner	1 side	6%
		Part 3, Pounding (alignment)	If no interstory alignment (+20)				
		Part 3, Building Location, Soil Information	'A" soil in plain	'A" soil in infill; "A" & "B" soil in plain	'A" soil in slope; "B" & "C" soil in infill; "D" & "E" soil in plain	'F" soil; "B" & "C" soil in slope; "D" & "E" soil in infill or slope	10%
P3	Height	Part 1, Number of Stories	1	2		≥3	4%
P4	Plan Configuration	Part 3, Plan Configuration	Rectangle Shape		Low Irregularities	Non-Parallel/ High Irr.	4%

(a) Parameters P1 to P4

P5	Height Regularity	Part 3, Height Regularity	Without Irregularities		Stories with different widths or short columns	Both from class. C	4.5%
		Number of Stories Cantilevered	None		1 Story*	2 Stories*	4.5%
		Part 3, Cantilever			If 2 sides (+10)	If 2 sides (+10)	
P6	Soft Story/Openings	Part 3, Height Regularity, Soft Story	No Soft Story			Soft Story	7%
		Part 3, Openings (%)	<25%		25%≤A<50%	≥50%	5%
		Part 3, Openings (Lintel)	If openings do not have Lintels (+10)				
		Part 3, Openings	If Windows & Doors are not Aligned (+5)				
P7	Existing Damage	Part 5, Structural Damage	No damage	Hairline cracks in columns and beams of frame	Deep and widespread cracking in columns and beams and in structural walls	Spalling of concrete cover, exposed reinfocing rods	10%
		Part 5, Non-Structural Damage	No damage	Hairline cracks in few walls	Large and extensive cracks in walls	Serious failure of walls	5%
P8	Construction Quality	Part 4, Construction Quality	A	B	C	D	10%
	Non-Structural Hazards	Part 2, Span Length	<3m		3m ≤ S < 5m	≥5m	7%
		Part 6, Observations	Presense of large signs, water tanks, antenna, cell tower, AC units or other items which could become a hazard during an earthquake. Settlement.				3%
			A	B	C	D	

(b) Parameters P5 to P8

Fig. 11 – Seismic Vulnerability Assessment Scoring Matrix

5.3 Data Processing and Vulnerability Index Calculations

After the surveys were completed, the matrix was used to calculate a Seismic Vulnerability Index (SVI) for each house. The SVI was then used to predict damage in earthquakes of different intensities, using the methodology outlined by Ferreira et al. in 2016 [11]. The damage grade μ_D was calculated for each structure based on Modified Mercalli Intensities [7-11]. Eq. (1) below has input variables I (intensity), V (related to SVI), and Q (ductility). The factor *f(V, I)* in Eq. (1) is computed using Eq. (2).

$$\mu_D = 2.5 + 3\tanh\left(\frac{I + 6.25V - 12.7}{Q}\right) \times f(V,I) \qquad (1)$$

$$f(V,I) = \begin{cases} e^{\frac{V}{2}(I-7)}, & if\ I \leq 7 \\ 1, & if\ I > 7 \end{cases} \qquad (2)$$

Considering the poor connection quality of the houses in the survey areas, the lowest available ductility value of Q = 1.5 was used for all calculations. The calculation was completed five times, using I = 6, 7, 8, 9, and 10. V is a vulnerability parameter linearly related to SVI via Eq. (3):

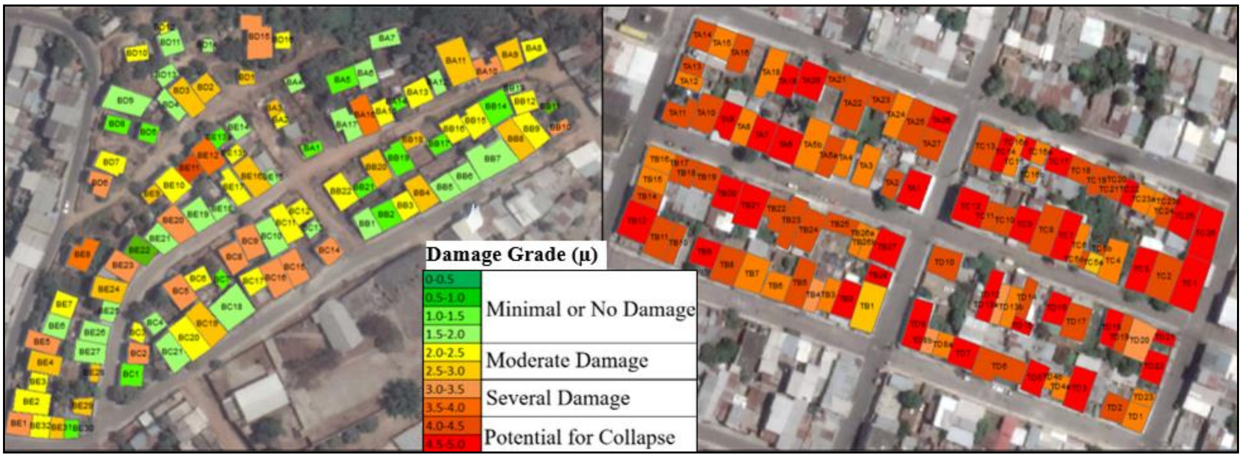
$$V = 0.592 + 0.0057 \text{ x } SVI \qquad (3)$$

Ferreira, et al. 2016 [11] postulates that damage grades 3 - 4 will produce severe damage, while damage grades greater than 4 will have a potential for local collapse. It was also assumed that damage grades 2-3 will produce moderate damage, while buildings with a damage grade below 2 will have no damage or minimal damage. These expected damage grades were used to consider the overall predicted damage at each site, and to produce maps showing the conditions of each neighborhood.

5.4 Damage Grades based on RADIUS Design Earthquake

Based on the RADIUS design earthquake, a subduction earthquake of magnitude 8.0 on the Richter Scale, located approximately 200 km from Guayaquil, the areas of Bastión and Trinitaria will experience seismic intensities of VII and VIII (Modified Mercalli Scale) respectively. Given these intensities, the expected damage in Bastión and Trinitaria for the design earthquake is shown in Figure 12.

Fig. 12(a) shows the Bastión level of damage for a VII seismic intensity. 1% and 17% of the houses may experience potential for collapse and severe damage, respectively. 42% and 40% of the houses may experience moderate or minimal (or no) damage, respectively. Fig. 12(b) shows the Trinitaria level of damage for a VIII seismic intensity. 70% and 28% of the houses may experience potential for collapse and severe damage, respectively. 2% of the houses may experience moderate damage. Therefore, it can be concluded that for the RADIUS design earthquake, the Trinitaria area is more likely to experience significant damage compared to the Bastión area.



a) Bastión Popular: Intensity VII

b) Trinitaria: Intensity VIII

Fig. 12 – Damage Based on RADIUS Design Earthquake

6. Summary, Conclusions, and Recommendations

6.1 Summary

Ecuador's active tectonics, historic seismicity, and socio-economic situation leave the country increasingly vulnerable to seismic activity. In an effort to reduce the potential losses that may be caused by a severe earthquake in Guayaquil poor areas and raise public awareness, researchers at Escuela Superior Politécnica del Litoral (ESPOL) partnered with the University of Colorado, Boulder to investigate the seismic risk in the city's poor and vulnerable neighborhoods. The study presented in this paper employs the Seismic Vulnerability Index (SVI) method to develop a structural survey methodology and a Seismic Vulnerability Assessment Scoring Matrix (SVASM) suitable for the informally constructed popular areas in Guayaquil. A structural survey was conducted on approximately 200 buildings at two different sites: one soft soil, flat terrain area (Trinitaria) and one sloped, hill area (Bastión Popular). In these urban poor areas design codes are not generally used and informal construction is very common.

The structural survey evaluated several building parameters such as the structural resisting system, irregularities, structural deficiencies, existing damage, and quality of construction. A Seismic Vulnerability Index was then calculated for each structure and used to estimate expected damage considering earthquake intensities from VII-IX on the Modified Mercalli scale.

6.2 Conclusions and Recommendations

The study found that the surveyed areas are at significant risk to loss of life and property with the majority of the structures experiencing damage or collapse during the design earthquake especially those located in the

Trinitaria area. Local authorities can play two roles in reducing risk. First, they could provide resources and expertise for the rehabilitation of existing houses, starting with the most vulnerable. Second, they could provide education and training to homeowners and informal builders to improve the quality of future construction. The findings presented in this study could also be expanded in future research to develop a fully formed plan for improving seismic resilience in Guayaquil.

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