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Abstract

This study evaluates the seismic vulnerability of buildings in Guayaquil, a city located on the Pacific Ring of Fire and therefore prone to earthquakes. Using the FEMA P-154 method, 168 buildings in the urban parishes of Pedro Carbo and Rocafuerte were inspected. Most of the structures evaluated (91%) were moment-resisting concrete frames. Older buildings, built before the implementation of modern seismic codes, showed higher vulnerability. The parameters considered included construction material, height, age, structural configuration, soil condition and maintenance. Buildings with S values between 0.3 and 0.7 were found to have a high probability of severe damage. The most vulnerable buildings were the Hotel Patrimonial, Hotel Manso Boutique and Hotel Perla Central. Solutions such as the use of carbon fiber, column jacketing and improved structural connections were proposed to mitigate these risks. Most of the buildings present high seismic vulnerability, with "El Gran Pasaje" being the most vulnerable. It is crucial to perform detailed inspections and reinforce old structures to reduce seismic risks in Guayaquil.

Keywords: Seismic vulnerability, FEMA P-154, Urban parishes, Guayaquil.

Resumen

Este estudio evalúa la vulnerabilidad sísmica de los edificios de Guayaquil, ciudad situada en el Cinturón de Fuego del Pacífico y, por tanto, propensa a los terremotos. Utilizando el método FEMA P-154, se inspeccionaron 168 edificios en las parroquias urbanas de Pedro Carbo y Rocafuerte. La mayoría de las estructuras evaluadas (91%) eran estructuras de hormigón resistentes a los momentos sísmicos. Los edificios más antiguos, construidos antes de la aplicación de los códigos sísmicos modernos, mostraron una mayor vulnerabilidad. Los parámetros considerados fueron el material de construcción, la altura, la antigüedad, la configuración estructural, el estado del suelo y el mantenimiento. Se determinó que los edificios con valores de S entre 0,3 y 0,7 tenían una alta probabilidad de sufrir daños graves. Los edificios más vulnerables fueron el Hotel Patrimonial, el Hotel Manso Boutique y el Hotel Perla Central. Para mitigar estos riesgos se propusieron soluciones como el uso de fibra de carbono, el encamisado de columnas y la mejora de las conexiones estructurales. La mayoría de los edificios presentan una alta vulnerabilidad sísmica, siendo «El Gran Pasaje» el más vulnerable. Es crucial realizar inspecciones detalladas y reforzar las estructuras antiguas para reducir los riesgos sísmicos en Guayaquil.

Palabras clave: Vulnerabilidad sísmica, FEMA P-154, Parroquias urbanas, Guayaquil.

Introduction

The informal constructions that have developed throughout history in the city of Guayaquil seriously affect the citizens living in these seismic hazard zones. "In recent history, most of the high magnitude earthquakes (more than 80%) have been recorded in the Pacific Ring of Fire region, particularly in about 10 countries, mostly located in Asia" .

Figure 1. Building in Guayaquil affected by strong earthquake on March 6, 2023.

Source: (El expreso,)2023

This figure shows the damage caused in Guayaquil after the earthquake that occurred in Pedernales on April 16, 2016.

According to (Moncayo et al., 2017), seismicity in Ecuador is reactivated every 50 years and due to this several earthquakes close to 8 degrees in magnitude occur. The study city was also selected because a large part of its urban area is composed of soft soils, which makes it more vulnerable.

Based on the Ecuadorian construction standard , 6 types of soils are established and in the context of Guayaquil this would be classified as type E, which is categorized as having soft soil.

Type A: Competent rock profile, suitable for construction due to its rock composition.

Type B: Medium stiffness rock profile, moderate for construction.

Type C: Very dense soil profiles or very soft rock, unfavorable because their soil type contains a lot of moisture content.

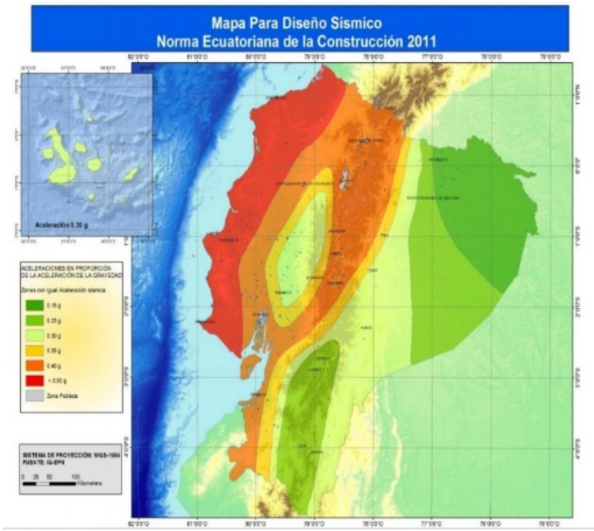
Type D: Stiff soil profiles are highly unfavorable.

Type E: Profile containing a total thickness H greater than 3 m of soft clays, they are expansive soils with the capacity to absorb water and contract upon drying.

Type F: These soils require an on-site evaluation by a geotechnical engineer. It is a special soil with several subclasses.

Within the map of seismic zones for buildings of normal use, the value of Z is used, which represents the maximum acceleration in rock expected for the design earthquake, expressed as a fraction of the acceleration of gravity. The site where the structure will be built will determine one of the six seismic zones of Ecuador, characterized by the value of the zone factor Z, according to the map in Figure.

Figure 2: Map for seismic design and zone factor (Z).



Materials and methods

This research is defined as descriptive with a qualitative approach because, in order to study several buildings quickly, the main thing was to observe and describe the characteristics of the buildings. Because of this, the proposed FEMA P-154 method was used.

According to the rapid visual detection procedure is developed to identify, inventory and examine buildings that are potentially seismically hazardous.

Location and Location

The study site is located in the city of Guayaquil, capital of the Province of Guayas, specifically in the parishes of Pedro Carbo with the following coordinates 2°11'14''S, 79°52'49''W and Rocafuerte with the following coordinates 2°11'41''S, 79°53'05''W. The parishes are two important sectors within the city of Guayaquil, each with distinctive geographic and demographic characteristics.

Figure 3. Location map of Rocafuerte and Pedro Carbo parishes.

Source: Google Earth

The following are some of the tasks to carry out the research:

Create a database describing the characteristics of residential buildings in the urban parishes of Pedro Carbo and Rocafuerte using FEMA P-154.

Define the most vulnerable dwellings based on their age of construction, the presence of irregularities, the S-factor, the condition of their soil and their structural configuration.

Propose solutions for non-compliant housing in accordance with FEMA-154 and propose recommendations on minimum requirements for safe construction.

The seismic vulnerability inspection project was carried out by a research team of the Civil Engineering career, Faculty of Mathematical and Physical Sciences of the University of Guayaquil, as part of the project of linkage with society where 163 buildings were analyzed.

Figure 4. Visual inspection of the Aminco Amaya building, where structural damage was identified

Prepared by: Ubilla Isai and Zambrano Xavier.

The main objective of the project was to evaluate the seismic vulnerability of buildings located in the Pedro Carbo and Rocafuerte parishes of the city of Guayaquil, in order to generate a detailed diagnosis and subsequent report to identify the most vulnerable structures.

The planning and organization of the project included the selection of study areas within the urban parishes of Pedro Carbo and Rocafuerte and the assignment of tasks among the team members, who were divided into groups, each assigned to a specific area.

Field data collection was carried out in several stages. 1) First, a preliminary visual inspection was carried out to identify the most vulnerable structures. 2) Then, using the FEMA method for rapid assessment of buildings with seismic risks , information on the structure of the buildings, construction materials, height, age of construction and any visible damage was recorded. In addition, photographic evidence was taken of each of the inspected buildings and relevant observations were documented.

The data analysis consisted of classifying the buildings according to their level of vulnerability using the criteria established by the FEMA method, which made it possible to identify the buildings with the highest seismic vulnerability in the Pedro Carbo and Rocafuerte parishes.

Analysis parameters

To determine the seismic vulnerability of a residential building, the following parameters and limits are considered in base:

Construction material

Reinforced Concrete: Evaluated for its strength and ductility.

Masonry: Vulnerability due to fragility and lack of flexibility.

Steel Structure: Evaluated for its resistance and capacity to absorb seismic energy.

Wood structure: normally flexible but susceptible to degradation and termites.

Construction age

Pre- and post-code buildings: structures built before the adoption of modern seismic codes are more vulnerable.

Historic Modifications: Any structural changes that may have compromised the integrity of the building.

Structural configuration

Regularity in plan and elevation: regular buildings tend to perform better during earthquakes.

Symmetry: asymmetrical buildings may experience torsional forces, increasing vulnerability.

Vertical irregularities: changes in stiffness or resistance between floors can generate weak points.

Soil condition

Soil type: Soft soils can amplify seismic waves, increasing the movement experienced by a building.

Liquefaction potential: risk of the soil behaving as a liquid during an earthquake, undermining the foundations.

Maintenance condition

Visible deterioration: Cracks, rust and other signs of wear may indicate weakened structural components.

Repairs and upgrades: assess the quality and impact of any repairs or upgrades performed.

Vulnerability classification

Low vulnerability: Buildings that meet all FEMA criteria with significant safety margins.

Moderate vulnerability: buildings that meet most of the criteria but may have some areas of concern that require attention.

High vulnerability: buildings that do not meet several critical criteria and are at significant risk of severe damage or collapse during a seismic event.

Common structural failures

Shear failures in walls and columns: indicated by diagonal cracks and may cause sudden collapse.

Foundation failures: Due to soil liquefaction or inadequate foundation design, causing tilting or settlement.

Connection failures: Weak connections between structural elements can lead to partial or total collapse.

Soft floor collapse: Often occurs in buildings with large open floor spaces.

Results

Of the 168 buildings evaluated in the parishes of Rocafuerte and Pedro Carbo in the city of Guayaquil, using the FEMA format.

Forty-eight percent of the results correspond to buildings for residential use or shared with offices and commercial premises, while 52% of the buildings evaluated correspond to buildings for government, commercial and office use, as shown in Figure 6 below.

Type of structures

Of the 81 buildings analyzed, 74 were Type C1 (91%), 2 were Type C2 (2%) and 5 were Type C3 (6%). The following table defines the characteristics of the buildings of the present investigation.

Table 1. *Structural configuration of the analyzed buildings*

Structural configuration	Percentage
C1: Moment resisting concrete constructions	91%
C2: Concrete structures with slabs	2%
C1: Concrete constructions with unreinforced brick walls	6%

Prepared by: Gladys Castro

The oldest buildings collected from the 81 buildings analyzed are presented below. It was decided to base the information primarily on the older buildings due to the fact that in the old days more informal constructions were built and there were no regulations to regularize the constructions in a safe way.

All 12 buildings have a structural configuration type C1: moment resisting concrete construction, which was the most common type of construction at that time.

Table 2. *Oldest buildings in the study*

BUILDINGS	YEAR OF CONSTRUCTION	AGE
Casa Fantoche "Group Theater".	1940	84
Building 518	1950	74
Aminco Amaya Building	1955	69
Castilla Building	1956	68
Commerce Building	1954	70
Hotel Patrimonial Building	1940	84
Plaza San Francisco Building	1954	70
Residential Building next to Hostal Wilson INN - 212	1956	68
Rosalia Building	1947	77
Manso Boutique Hotel	1954	70
Hotel Pepe's Guayaquil	1954	70
Hotel Perla Central	1940	84

Based on the seismic vulnerability method , vulnerability is classified according to the damage caused. Grades 1 and 2 are considered non-vulnerable. Grade 3 is considered vulnerable. Grades 4 and 5 are considered very vulnerable.

- Grade 1: No structural damage
- Grade 2: Moderate damage
- Grade 3: Significant to severe damage
- Grade 4: Very serious damage
- Grade 5: Destruction

The expected behavior of the buildings is that: If S<0.3 it has a high probability of having damage grade 5. If the value of that S is between 0.3 to 0.7 this means that it has a high probability of having damage grade 4. If the value of S is between 0.7 to 2.00 this means that it has a high probability of having damage grade 3. If the value of S is between 2.00 to 3.00 it has a

Finally, if S is a value greater than 3, it has a probability of having a grade 1 damage.

As shown in the figure, the most demanding range is between 0.3 and 0.7, which means a high probability of having a grade 4 damage. Since we have a high percentage of seismic vulnerability, it was decided to analyze the oldest structures with a lower index according to FEMA.

Table 3. *Vulnerability index of the oldest buildings*

BUILDINGS	S
Casa Fantoche "Group Theater".	0,4
Building 518	0,6
Aminco Amaya Building	0,8
Castilla Building	0,4
Commerce Building	0,4
Hotel Patrimonial Building	0,1
Plaza San Francisco Building	0,4
Residential Building next to Hostal Wilson INN - 212	0,3
Rosalia Building	0,8
Manso Boutique Hotel	0,1
Hotel Pepe's Guayaquil	0,4
Hotel Perla Central	0,2

Prepared by: Aurora Yagual and Gladys Castro

Based on the table we have that the 3 most vulnerable residential buildings are:

Heritage Hotel Building S=0.1

Manso Boutique Building S=0.1

Hotel Perla Central S=0.2

But based on with this final score, the vulnerability of the structure or the probability of collapse can be defined. This being so in level 1:

SL1<Smin High vulnerability

SL1=Smin Median vulnerability

SL1>Smin Low vulnerability

Hotel Patrimonial Building

This 4-story building was built in 1940. It has an E-type floor. The first floor serves as reception, food court and living room. The upper floors are used as living quarters. It has cracks in the interior walls. There is irregularity in the floor plan, soft floor and short column effects can also be generated. A level 2 inspection is required.

This building has an Smin value of 0.3 and a SL1 value equal to 0.1. This means that it has a high vulnerability based on the Ministry of Urban Development and Housing.

Hotel Manso Boutique Building

This 5-story building was built in 1954. It has a type E floor. The building has significant damage due to signs of cracking in pardes, crumbling and moisture stains.

Does not meet minimum requirements and a level 2 inspection is required.

This building has an Smin value of 0.3 and a SL1 value equal to 0.1. This means that it has a high vulnerability based on the Ministry of Urban Development and Housing.

Hotel Perla Central

This 3-story building was built in 1940. It has a type E floor. The building is generally in good condition. There is paint deterioration on the outside of the slab.

It was noted that a level 2 type inspection needs to be carried out.

This building has an Smin value of 0.3 and a SL1 value equal to 0.2. This means that it has a high vulnerability based on the Ministry of Urban Development and Housing.

Most vulnerable building of the 81 buildings analyzed

The building known as "El Gran Pasaje" is the most vulnerable of the entire investigation. It was built in 1965 and has 12 floors. The value of S according to the inspection gives us a value of 0.10.

The building is maintained in optimal condition despite being more than 50 years old, this is due to the constant maintenance performed. It is a modern building with no cracks or fissures. However, based on the FEMA methodology, it does present structural risks to seismic events in the future.

Future solution

A much more detailed inspection of the building is essential in order to analyze the building in a more micro way. Samples of the concrete used can be taken so that the laboratory can determine its actual properties.

Also non-destructive testing such as laser scanning. However, the most economical would be to use structural analysis software to simulate the behavior of the building when subjected to design earthquakes and based on this analyze the most vulnerable areas. All this in order to propose an optimal structural strengthening plan for the structure.

Finally, continuous training of the personnel in charge of building maintenance and monitoring is vital. This ensures that they are kept up to date with the latest techniques and technologies in the field of structural engineering, thus guaranteeing rapid and effective intervention when necessary.

Structural reinforcement

Implementing strengthening methods will allow the most vulnerable buildings in the research to improve their capacity to resist seismic loads and events.

Carbon fiber reinforcement: In recent years, reinforcing structures with carbon fibers has become standardized and common. The application of carbon fiber sheets in structural elements such as columns, beams and walls significantly improves their strength and ductility. This material is lightweight, strong and does not add considerable additional weight to the structure.

Column jacketing: Consists of wrapping the columns with additional reinforced concrete or steel. This increases the column cross-section, improving its load-bearing capacity and resistance to seismic effects

Improving structural connections: Ensuring that joints between columns, beams and other structural elements are robust and well reinforced is crucial. Additional steel connectors can be used or existing joints can be reinforced to ensure better load transfer

Conclusions

Using the FEMA P-154 methodology, an inspection of the buildings analyzed in the parish of Rocafuerte and Pedro Carbo was carried out. The vulnerability of most of these buildings is considered to be high.

The most predominant structural configuration is type C1: moment resisting concrete buildings. Eighty-one residential or Commercial-Residential buildings were analyzed.

Each building was classified in a table together with its main characteristics. Thanks to the filter of the table, the oldest buildings of the parishes under study were found. Several old buildings were analyzed in the study and 3 most vulnerable buildings were determined based on their S-factor.

These 3 buildings were the "Hotel Patrimonial" with an S-value of 0.1; the "Manso Boutique" building with an S-value of 0.1 and the "Perla Central" hotel with an S-value of 0.2. The most vulnerable building was also determined according to the number of floors, the S factor and its soil type. This gave us as a result that the building most vulnerable to earthquakes according to FEMA is the building "El Gran Pasaje".

Thanks to the filter of the table, the oldest buildings of the parishes under study were found. In the study several old buildings were analyzed and 3 most vulnerable buildings were determined based on their S factor. These 3 buildings were the "Hotel Patrimonial with an S value = 0.1; the building "Manso Boutique with a value S = 0.1 and the hotel "Perla Central with an S value = 0.2. The most vulnerable building was also determined according to.

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