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Evaluation of the Seismic Behaviour of a Building for Residential Use Based on a Typical Soil and Implementing the Ecuadorian NEC-SE-DS Standard

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Abstract - The present work allows evaluating the behaviour of a building in the city of Guayaquil built on a soft soil type E, considering the seismic performance based on the last earthquake that hit Ecuador and left irreparable damages. For this reason, the structure was modelled for further analysis using structural analysis software (ETABS) to evaluate and compare the values collected from the measurement in the accelerograph of Guayaquil and Manta, and thus have a reference and knowledge regarding the damage, displacements and deformations presented.

The objectives of this work are to demonstrate the behaviour of the structure, analysing the static level of the infrastructure placed in pseudo-dynamic and dynamic time-history mode; where a redesign of the structure is considered, considering the current regulations regarding stability, drifts, and shear forces. The work provides and expands the data on factors that increase the seismic hazard, which in the future can be contrasted with similar studies within the city of Guayaquil, to analyze the possible variants of how to improve future constructions.

***Keywords*:** seismic behaviour, soil type, structural analysis, damage

1. Introduction

Ecuador is located in the Pacific Ring of Fire, an area with high seismic and volcanic activity, where the Nazca Plate is in the process of subduction under the Continental Plate, it is also located on an area with many geological faults, these being two factors that can give rise to seismic activity in the country [1, 2]. There are different earthquakes throughout Ecuadorian history that have caused serious damage to structures and society in general. The seismic record of Ecuador initiates with the Guayaquil earthquake in 1787, followed by the 1943, and the most recent one in 2016. For instance, the earthquake of April 16, 2016, clearly indicated the deficiency of structural designs that for the most part did not comply with the seismic code, generating that many civil engineers have a greater commitment in terms of earthquake resistant design, especially when considering quantitative parameters such as displacement, speed, acceleration, magnitude, and intensity to generate a risk reduction.

Moreover, existing structures present higher seismic vulnerability, especially the informal constructions which have increased over the last decades in rural areas [3,4]. Generally, these informal constructions consist of reinforced concrete residential houses or buildings (up to four floors) or mixed structures (i.e., timber, masonry, and reinforced concrete) [2-9], which are neither designed nor built by engineers or architects. As a result, the strength of the materials, the structure configuration, and design are empirical; and thereby do not follow any of the seismic requirements established on the local building code. Although Ecuador has standards it has been noticed that most of the constructions do not follow these standards.

1.2 Description of existing residential buildings situation

The earthquakes undoubtedly generate catastrophic damages in structures being an affectation considered by every civil engineer, both in the design and in its construction. The dynamic response, as well as the damages that the structural and non-structural elements may present, depend not only on the characteristics of the seismic action, but also on the behaviour of the entire structural system of the building.

The effects observed during recent seismic events have become a problem for several sectors within the city of Guayaquil, which is the economic capital of Ecuador due to its river harbour, where many of the structures exceeded their admissible stresses, generated by the vibration of the ground, which caused them to fracture. Columns, beams and walls can be found among the structures that collapsed. In the centre of the city, damages were registered due to different faults such as the adjoining buildings, slender columns, columns with changing sections, columns irregularly distributed or omitted in plan, long overhangs, poor foundations, soils with little bearing capacity and poor compaction. by not using the ideal analysis for the type of structure [10-12]. It has been noticed that the informality in housing and settlement has been increasing. These informalities include informal housing which also can include any way of shelter or settlement. Informal settlements can be in urban as in residential areas where the future habitants will not have a security after they start to live in their houses. These settlements generally lack of different urban infrastructure and basic services, while housing may not comply with current regulations, and is often situated in hazardous areas. In addition, informal settlements can be that the owner build their houses with more floors that was permitted or maybe they employ different low-quality materials which probably will have negative results.

Failure to respect what is stipulated in the construction regulations, also carries part of the responsibility, where the buildings do not comply with the regulations to be considered in the assembly of beams and columns in which the stirrups do not have the necessary spacing. Additionally, the lack of confinement and seismic hooks, due to constructive oversights or non-application of the standard, are a probable cause of several failures, which are added to the little use of spiral reinforcement and drop beams to better distribute the drag of the earthquake, in its interaction with the slabs [7].

2. Site Location

The area of seismic engineering is a primary part of the study since it is the one that will define the seismicity parameters of magnitudes, intensities, and accelerations of the ground in the area to be evaluated, the seismic potential and the seismic zones. In addition, it will be possible to learn about how earthquakes have occurred in the place of study throughout history, allowing to generate the dynamic analysis by the spectral modal method with the implementation of the Ecuadorian Construction Standard (NEC-15) [3] in the seismic hazard part.

2.1 Seismicity in the city of Guayaquil

Earthquakes are geological phenomena that have occurred throughout the history of the city of Guayaquil, where none of their aspects can be predicted: neither where they will be, nor size, nor when they will occur. The passage of these seismic attacks generated from the vibration of the earth by the rapid release of energy, occurs due to the movement of the inner layers of the earth where severe damage has been suffered, due to the subduction of the Nazca plate, being the coastal region of Ecuador the most dangerous area for earthquakes. The released energy is transmitted in all directions from its focus or hypocentre through waves. Earthquakes are characterized by having a hypocentre and an epicentre. The hypocentre is the point of origin and is located inside the earth, in turn the epicentre is the point on the surface where the earthquake is seen with the greatest intensity, with surface earthquakes causing the most damage.

Although in Ecuador there are many earthquakes registered in the different regions, in the part of the Coast those that have specifically hit the city of Guayaquil the most are reported in Table 1 which indicate the date of the event, the main characteristics of the earthquake (i.e., epicentre, brief description of the damage caused), as well the moment magnitude [7,12-16].

Table 1. Seismic events with the greatest damage in the city of Guayaquil

Date	Characteristics	Magnitude Mw
13/05/1942	▪ Excessive vibrations ▪ It caused numerous loss of life and serious material damage. ▪ The epicentre of the earthquake was in the Pacific Ocean, near the north coast of the province of Manabí. ▪ The disaster destroyed to a greater extent the reinforced and mixed concrete building in the parishes of Carbo, Rocafuerte, Olmedo, Bolívar, Sucre and October 9.	7.9
18 /08/1980	▪ The epicentre was located near Nobol, just 30 kilometres north of Guayaquil. ▪ The estimated duration was 60 seconds. ▪ It started with a slight vibration and shaking, and after a few seconds it turned into a strong movement ▪ Causes all classes to be suspended. ▪ Commercial and industrial activities and basic services such as transportation, telephony, and electricity. ▪ More than 100 houses and buildings were destroyed or damaged. The greatest loss was the mixed houses in the parishes of Bolívar, Ayacucho, García Moreno, and Sucre.	6.1
04 /08/1998	▪ The earthquake is remembered because it caused great damage in Bahía de Caráquez, Manabí and towns like Canoa. ▪ Despite the distance, he still felt strong in Guayaquil. ▪ In the centre of the city, this caused the fall of the wall of an old mixed house, and the breakage of glass in the hotel, in addition to other incidents such as the fall of furniture and decoration in other places. ▪ No one was killed or injured in this city.	7.1
16/04/2016	▪ The epicentre was in the Pedernales canton. ▪ A bridge built as a traffic interchange on "Avenida de las Americas" collapsed on top of a car, killing two people. ▪ In several shopping centres such as the San Marino shopping centre, the roof collapsed due to power supply problems and a fire broke out, ▪ Buildings and houses had damage to their structures. ▪ On the other hand, in Durán the structure of an elevated road traffic bridge was affected, and the local municipality and the Ministry of Transport and Public Works demolished the bridge.	7.8

Complementary to Table 1, Figure 1 illustrates the location and moment magnitude of some most strong seismic events along the Coast of Ecuador, where the red asterisk represents the location of the latest most devastating earthquake (April 16th, 2016).

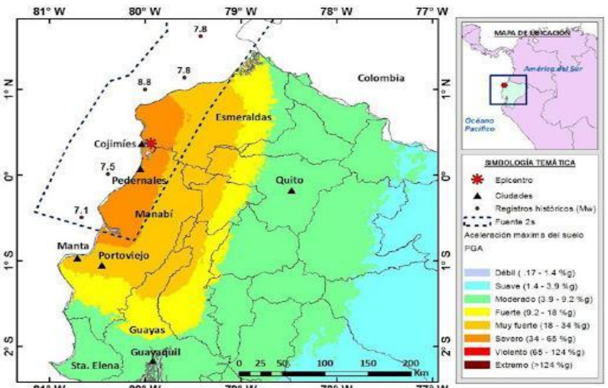

Figure 1. Ecuador Seismic Hazard Map

2.2 Soil characteristics in the city of Guayaquil

The city of Guayaquil is characterized by the following distribution of soils: soft, rocky, transitional and areas to landslides; that in the event of a severe earthquake, they affect the behaviour of the structure in one way or another [16-19. The city's soil type (mostly soft soil) makes the buildings built on it vulnerable. Guayaquil faces the Nazca tectonic plate colliding with the South American plate, which makes it extremely vulnerable to this possible disaster. The city is extremely vulnerable to earthquakes, not only because of its location, but also because of its type of soil and existing buildings [5].

It presents mixed and very old buildings, mostly in the centre, where there are more than 250,000 old buildings and temples, such as the cathedral and the church of La Merced, these buildings are not made with seismic technology. The type of soil in this area is soft white clay, which is recommended for small buildings. For its part in the north, suitable for high-rise buildings. Most of the northern part of Pascuales is based on rocks, for example, from Mapasingue to the southern part of the Popular Basin. In the northern part of the city, on the hills of Santa Ana and El Carmen, the city is located on sedimentary rocks. The mechanical properties of these soils are better than other existing structures in cities. The distribution of the different types of soils in Guayaquil, elaborated in the RADIUS Project, is shown in Figure 2 [5].

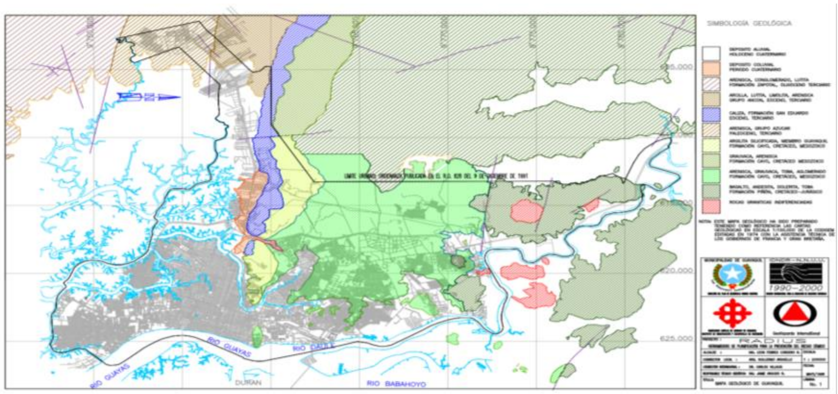

Figure 2, Guayaquil geology map

3. Case Study Building

The present work will be designed under the methodology of quantitative approach since this is the one that best adapts to the characteristics and needs, being objective, sequential and evidential for the investigation.

The quantitative approach helps researchers to pose a specific research question with limits. Once the research question is posed, the researcher will consider previous research (document review) and establish a theoretical framework (guide the research), from which one or more hypotheses will be derived. Providing evidence to know if the result confirms or is consistent with the hypothesis.

For this research, two techniques will be implemented, on the one hand, the observation that allows collecting quantifiable information about the structure in its current state by means of, in turn, the technique of using document review, allowing to implement the review of existing documents on the subject, documents on the geology of the site, plans of the structure and other situations with respect to the object of study [20-21.

3.1. Description of the case study building

The building to be studied is located within the city of Guayaquil specifically in the centre of the city between Cuenca and Los Ríos streets behind the Yeyo Uraga baseball stadium. The structure was selected since it is in an area where there are many structures that have been built empirically without prior design or analysis. The selected structure has unforeseen amplifications because floors were added, and the structure was enlarged from a two-story house to a 5-story building. As observed in Figure 3, the building presents several irregularities in terms of its design based on the geometry of its columns and beams. Too slender columns supporting a 1.50-meter overhang, as well as being in the middle of homes of much lower height, being a dangerous building, leaving in doubt its earthquake resistant capacity. The building in its first design previously occupied an area of 60 m², but today it is 210 m².

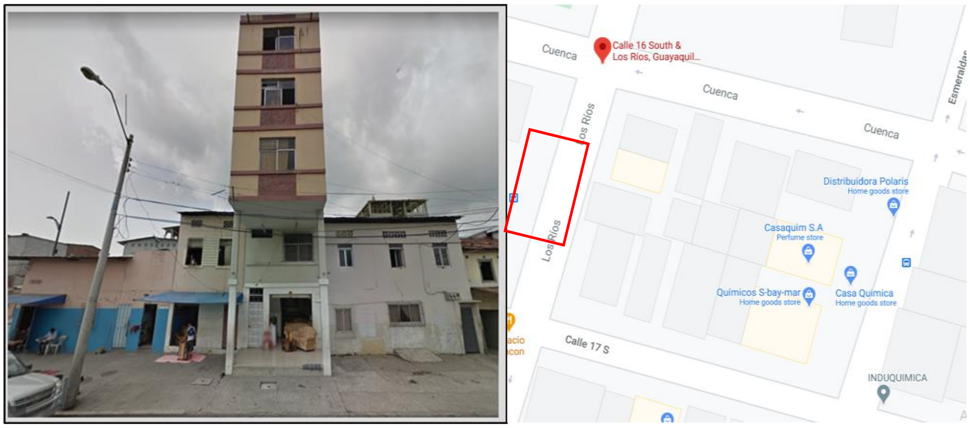

Figure 3. Front and plan view of the building

To carry out the study, the use of various tools will be implemented, that is, on the one hand, a rapid visual screening evaluation is developed to determine the potential seismic vulnerability of the building based on visual observation of the building's main deficiencies. Additionally, more rigorous, and detailed evaluation is conducted based on the NEC-15 [3] construction regulations regarding seismic solicitations.

3.2. Rapid visual screening evaluation

The Rapid visual screening (RVS) is a qualitative evaluation procedure that allows to estimate the seismic vulnerability of existing buildings. The procedure can be implemented relatively quickly, and it is quite convenient for large building stock to identify potentially hazardous structures without the high costs of the detailed seismic analyses of individual buildings. The Federal Emergency Management Agency (FEMA) developed several guidelines for the seismic risk assessment and rehabilitation of buildings. The FEMA P-154 Report [1] present a complete and detailed methodology for RVS of buildings for potential seismic hazards. The methodology consists of a survey with a set of questions that assess the current condition of the building and structural configuration (i.e. irregularity in plan and elevation, resisting structural system, concentration of masses, strong beam-weak column, etc.). Each question is scored based on a scale for different building typologies, the vulnerability is estimated through a vulnerability index which is the summation of all the aspects evaluated in the survey. The NEC-15 also includes a section for RVS, which is based on the previous version of FEMA P-154 and adapted to the country characteristics. Furthermore, many studies have been developed on determining the seismic vulnerability of building through RVS. For example, Perrone et al. [4], evaluated the seismic vulnerability of an existing hospital building in Italy through a vulnerability index. Similarly, Lang and Singh [2] proposed a set of questionnaires to examine the seismic risk of school and hospital building for typologies of reinforced concrete and masonry. Despite these studies not addressing residential building, the methodology can be adopted to estimate the seismic vulnerability of residential buildings since the questionnaires can evaluate the structural condition of general structures. Therefore, four RVS methodologies were evaluated, and their vulnerability index is reported in Table 2.

Table 2. Vulnerability index for the case study building using four RVS frameworks.

Methodology	NEC-15	FEMA P-154	Lang and Singh, 2009 [2]	Perrone et al., 2015 [4]
Vulnerability Index	0	0.1	7.89	0.74
Seismic Vulnerability	<2	<0.3	Max 8.61	>0.67

Location: Cuenca and Los Ríos streets, Guayaquil.

All the vulnerability indexes are compared with respect to the limit that defines their seismic vulnerability (except for the methodology of Lang and Singh in which the maximum index is presented), all the methodologies indicate that the case study building presents a high seismic vulnerability due to its structural configuration and visible lack of seismic solicitations.

Furthermore, during the 2016 Ecuador Earthquake, a very irregular building, located in the corner of García Moreno and Ayacucho streets in Guayaquil (Figure 4, collapsed. Fortunately, neither casualties nor harm to people were reported. The four RVS methodologies were applied to this building and reported in Table 3. It is not surprising that the building presented a very high seismic vulnerability, similar to the case study building.

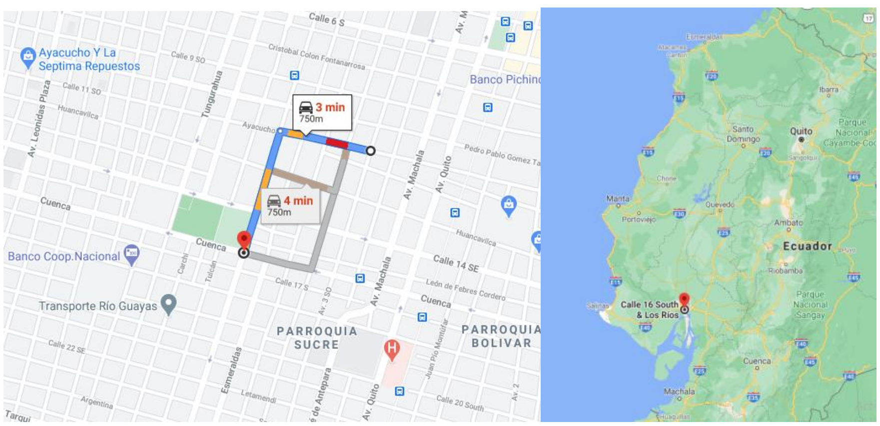

Figure 4 Collapse building in Guayaquil, during 2016 Ecuador earthquake

Table 3. Vulnerability index for collapse building in Guayaquil during the 2016 Ecuador

Methodology	NEC-15	FEMA P-154	Lang and Singh, 2009 [2]	Perrone et al., 2015[4]
Vulnerability Index	0	0.1	7.89	0.79
Seismic Vulnerability	<2	<0.3	Max 8.61	>0.67

Location: García Moreno and Ayacucho streets Guayaquil

What is more interesting about this case is that the case study building is located just a few blocks from the collapse building, as illustrated in Figure 4. The collapse building presented more irregularities than that of the case study building. However, some of the structural deficiencies as well as the soil conditions are shared. Therefore, conducting a more detailed analysis through a numerical model can helps us to understand what conditions can trigger the collapse of the case study building or to determine that earthquake loading will be detrimental for this residential building.

3.3. Numerical modelling

The structural analysis of the building allows to know the external and internal loads considered in the design of the building, structural damages such as settlement, deformation, and displacement of the elements of the structure before the forces to which they were subjected, allowing to evaluate the dynamic behaviour of the building. The design of concrete structures will allow to observe through a structural review, the geometric designs of footings, beams, columns, and slabs implemented in the construction.

ETABS is a revolutionary software for structural analysis and building sizing. It is a tool with linear and non-linear analysis capabilities. You can perform experiments on a variety of materials, generate very clear and descriptive graphics, schematic design, and reporting tools. It could cover all the following steps: structural details, modelling, creation, and generation. It includes the determination of the size of metal and reinforced concrete structures through automatic optimization, as well as the size of beams and mixed columns of concrete and masonry walls, as well as safety inspections of connections and metal sheets. For reinforced concrete structures and metal structures, you can get the schematic design of the model, a summary table of steel bars, a table of information about the size of the profile and connection, the details of the structural elements and the corresponding cuts (CSI SPAIN, 2021).

4. Dynamic spectral analysis (time-history)

The tables presented in this subsection show the results of structure drifts with respect to the spectral dynamic analysis (time-history), it is highlighted that under NEC regulations -15 is designated as maximum permissible values for drifts not greater than 2%, that is, 0.02. NEC-SE-DS 4.2.22.

Table 4. Mezzanine drifts by dynamic spectral analysis (time-history) in X direction

Time-History Analysis X							
R factor	Floors	Mezzanine height	Displacement X (m)	X displacement (cm)	Drift Mezzanine	Max Allowable Drift	complies
6	1	3	0.000	0.019	0.00028	0.02	Complies
6	2	3	0.000	0.046	0.00042	0.02	Complies
6	3	2.7	0.001	0.070	0.00039	0.02	Complies
6	4	2.7	0.001	0.086	0.00028	0.02	Complies
6	5	2.7	0.001	0.099	0.00021	0.02	Complies

Table 5. Mezzanine drifts by dynamic spectral analysis (time-history) in Y direction

Time-History Analysis Y							
ETABS data entered							
R factor	Floors	Mezzanine height	Displacement Y (m)	Displacement Y (cm)	Drift Mezzanine	Max Allowable Drift	complies
6	1	3	0.000	0.013	0.00019	0.02	Complies
6	2	3	0.000	0.036	0.00035	0.02	Complies
6	3	2.7	0.001	0.059	0.00038	0.02	Complies
6	4	2.7	0.001	0.080	0.00036	0.02	Complies
6	5	2.7	0.001	0.098	0.00030	0.02	Complies

5. Analysis and Discussion

After carrying out the analysis of the current structure, it was observed that it presents slenderness in the elements, which causes a low structural rigidity, especially in the lower levels, which instigates very high periods of vibration to the structure, causing a structure susceptible to severe damage (Fissures, tearing, non-habitability or collapse) in the face of future seismic events.

The existing structure presents a relationship of structural elements without engineering criteria, this due to the informality in its construction, this point is demonstrated by observing columns of lower floors with smaller dimensions than the upper floors, causing the soft floor effect, since the resistance in the lower floors is less than 70% of the resistance of the immediately superior floor in the first two levels.

The effects of the constructive irregularity of the structure cause mezzanine drifts to be much greater than the maximum permissible by the Ecuadorian Construction Standard (2%) in the first two floors.

The new structure proposed when performing the static, pseudo-dynamic and dynamic time-history analyses, the structure, and its redesigned elements are suitable and meet the requirements of the Ecuadorian construction regulations in contrast to the current structure that has structural elements Without criteria, this being a structure that puts its occupants at risk.

When subjecting the redesigned structure to the earthquake of April 16, 2016, two situations can be observed: as a first observation, the accelerogram of Guayaquil records the accelerations of the earthquake; however, since it was not the epicentre of the earthquake, it did not have an effect that could be fatal to the occupants since its intensity was much lower in the areas surrounding the epicentre and as a second observation, the structure is subjected to accelerations from the Manta accelerogram where an effect very similar to the pseudo-analysis is observed. dynamic. Therefore, the structure, if it is to be found in the city of Manta, would be earthquake-resistant and would comply with the design philosophy.

An analysis of general costs is carried out for the possible cost of the infrastructure where a total cost of $ 131,026.28 is determined for the redesign and construction of the new proposed structure. Ground studies, materials and quality tests are considered for the budget. It should be noted that a seismic reduction factor was also designated in the pseudo-dynamic and dynamic time-history analysis section, where a construction process with not so qualified labour is considered.

6. Conclusions

• The Guayaquil accelerogram has a record in units of cm / s2 at the same time, it is emphasized the fact of an analysis of an earthquake that occurred hundreds of kilometres from the epicentre, its accelerations show low values due to this. That is why, when performing the analysis, the seismic shear of the proposed structure would have a very low response shear. On the other hand, if we consider the Manabí earthquake registered in the Manta accelerogram, the shear values would be very similar to those estimated by the pseudo-dynamic analyses.

• The proposed structure complies with the requirements dictated in the Ecuadorian regulations; in addition, the proposed elements meet the steel requirements designated by ACI 318S-14.

• As it is a regular structure, it will not be affected by torsion or the P-Δ effect, this is corroborated in the stability index section.

• In the event of an earthquake of similar magnitudes in Manta in the city of Guayaquil, it was confirmed that the structure is completely adequate as shown in the results through dynamic analysis using the information from the MANTA accelerogram.

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