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Proposal for the Rehabilitation of Household in Seismic Vulnerability Zones

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ABSTRACT

Worldwide earthquakes have caused a total of 719,501 human victim and 1,344.8 billion dollars in economic losses between 2000-2021. The Santa Elena province (Ecuador) is classified as an area of high seismic danger, according to the Ecuadorian Construction Standard (NEC). This coastal province has 70% of informal housing construction, structural problems and poor construction processes can be seen with the occurrence of these natural phenomena. This study aims to propose technical-economic rehabilitation solutions in informal housing constructions, through modelling and structural analysis, that guarantee occupational safety and the recovery of the structural capacity of the housing, case study (pilot). The applied methodology consisted of four phases: i) information on the pilot case study and its environment; review of the building regulations, ii) laboratory tests on soil characteristics, iii) structural modelling and analysis using SAP2000 software, and iv) structural support and rehabilitation solutions. The results indicate that the columns of the first floor require reinforcement because the average cross-section of the columns is less than the local construction regulations and defined by the criteria of experts in the construction sector. The structural elements of the second floor also require repair to reduce bending moments and distribute loads to the ground. The idea of innovation is the configuration of a protocol with construction methods for existing and new buildings, as tools for local authorities to promote reinforcement in areas of high seismic vulnerability, and thus a territorial order in the construction sector. This research recommends structural rehabilitation with reinforcements and structural repairs to guarantee its ability to withstand an earthquake and ensure the occupational well-being of inhabitants. This methodology can be replicated in houses with similar structural characteristics in Ecuadorian coast, considering SDGs 3, 9, and 11, which address health and well-being, industry, innovation and infrastructure, and sustainability.

1. INTRODUCTION

Earth dynamics can be explained by the theory of plate [1]. The theory postulates that the lithosphere, the most rigid and external layer of the Earth, is divided into seven main tectonic plates: Antarctic, African, Eurasian, Indoustralian, North American, Pacific, and South American [2] and secondary lithospheric plates for example Cocos, Caribbean, Scotia, Juan de Fuca, Philippine, Nazca, and Arabian are secondary. According to Hess H., the plates move owing to the expansion of the ocean floor over the asthenosphere, a more ductile or less viscous underlying layer driven by the convective forces of the mantle [3]. The contours of tectonic plate areas are regions of high geological activity, including volcanic activity, earthquakes, and plate movements [4].

The fire ring includes other areas where the tectonic plates interact. These can be areas of transform slip (where plates slide laterally against each other) [5] or areas of divergence (where plates move away) [6]. These areas can also experience seismic and volcanic activity, although generally less intense than those in subduction zones [7]. Interactions between plates can result in mountain ranges, oceanic trenches, and volcanic arc formations. Subduction zones are areas with the highest seismic activity in the world [8, 9]. They represent convergent boundaries in which an oceanic plate is introduced beneath another lithospheric plate, generating an accumulation of elastic potential energy released by seismic waves [10, 11]. The magnitude of these seismic waves is commonly measured using the Richter scale [12], which provides a quantitative representation of the energy released, thus allowing the classification of the magnitude of earthquakes and their impact on Earth's surface.

According to the Earthquake Country Alliance and the National Seismological Center of the University of Chile (CSN), earthquakes occur when a telluric movement causes severe damage to buildings and causes human casualties [13-15]. An example is the earthquake of 9.5 in Chile on May 22, 1960; this telluric event generated at least 2,000 deaths and affected approximately two million people [16]. On the other hand, a seism is a telluric event that does not cause perceptible economic damage [17, 18].

According to a study published by the Statista Research Department [19], the countries most prone to earthquakes in South America are those in the Andes Mountain range [20, 21]. This results from the risk index calculation (see Figure 1), considering parameters such as the number of people exposed and the lack of prevention and preparation to withstand these natural events. According to the United Nations Organization (ONU), between 2000 and 2019, these events caused 226,000 human losses and 339,000 injuries in Chile and Peru regions of the fire ring [22].

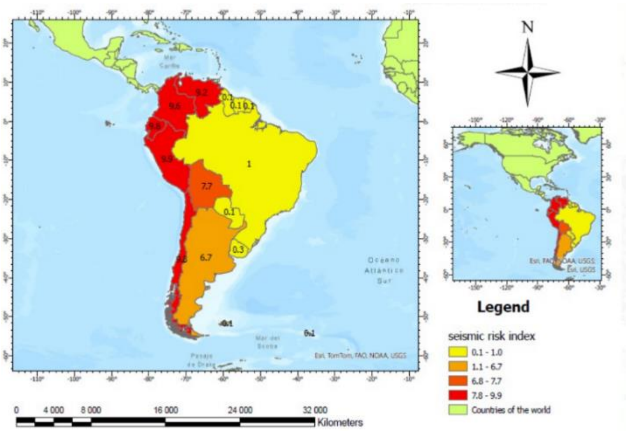


Figure 1. Seismic risk index of south American countries

The Pacific Fire Ring, or Circum-Pacific Belt represents an area of intense seismic activity [23]. The countries in the world that are part of the Ring of Fire belong to the continents of America, Asia, and Oceania [24]. This area extends more than 40,000 km and has a horseshoe appearance [25]. The Pacific Fire Ring comprises a series of tectonic plate boundaries under constant friction (when two plates move laterally relative to each other), resulting in a build-up of stresses [10]. A prominent example is the San Andreas Fault, where Pacific and North American tectonic plates slide laterally at approximately 13 mm per year. The persistent interaction between plates generates a significant accumulation of energy, finally released as earthquakes [26]. This area has more than 75% active and inactive volcanoes worldwide, totalling 452 [27]. Notably, 90% of the earthquakes worldwide and 80% of the strongest occurrences occur in this fire ring [22]. These natural events underline the importance of disaster preparedness and risk reduction in affected areas.

Seismic engineering studies carried out within the construction sector involve considering and analysing factors such as structural configuration, use, proportion, energy dissipation, resistance of materials, soil study, and appropriate construction processes [28, 29]. A crucial component in earthquake resistance is the use of anti-seismic dampers [30]. These devices dissipate seismic energy and reduce the forces transmitted to a structure during an earthquake. Shock absorbers can be of various types, such as viscous, metallic, and elastomeric, depending on their characteristics and applications [31, 32].

As part of the technologies and innovations in the structural rehabilitation of housing, the use of advanced construction materials, such as high-performance concrete and fibre components (such as steel and polypropylene) [33, 34] that reinforce structures without increasing their weight, improving the fragile behaviour of structural members, the energy absorption capacity and solving disadvantages such as low durability [35-37], stand out. The implementation of ‘technologies of things’ such as real-time monitoring using intelligent sensors allows the assessment of the structural state of infrastructures and their exposure conditions and early detection of damage [38, 39]. Shear walls, built with reinforced concrete to improve the support function and lateral resistance, allowing the dissipation of lateral forces, improving the seismic resilience of structures and being replaceable components [40, 41]. Epoxy resin injection to repair cracks in structural elements, restoring the continuity of the elements, improving the strength of the damaged material [42]. Structural steel sections, as rehabilitation elements such as beams and columns, allow for increased structural capacity, improved strength and durability, quick installation as they can be prefabricated and then assembled on site, negligible weight on structures, and are crucial in the rehabilitation of old buildings.

Structural rehabilitation promotes improving the safety and strength of buildings and extends the service life of structures [43]. The following are some case studies where structural rehabilitation methods mentioned in the previous paragraph are applied. A study conducted by the Department of civil engineering in Bhubaneswar, India, indicates that the addition of glass and steel composite fibres used in 1.5% of the total volume of the mix improves the flexural strength of concrete by 49%, while if 1% is used, the tensile strength increases up to 42.5% of its strength [44]. A study conducted by the Institute of Technology, Control Engineering and Automation of São Caetano do Sul, Brazil, indicates that the system based on real-time monitoring of a structure allows early detection of anomalies, prediction of possible failures and informed decision-making regarding maintenance and repairs, improving on traditional methods such as damage and failure detection based on periodic visual inspections and visual analysis [33]. A study conducted in Los Cerezos in the city of Arequipa (Peru) for a building of 75000 m^2 and 21 floors shows that installation costs 5,193.55 dollars. Sensors such as accelerometer, temperature, humidity, wind, tilt and deformation, data acquisition equipment, communications, visualisation and qualified personnel are used [45]. The Centre for Engineering Infrastructure and Safety at the University of New South Wales, Sydney, NSW, Australia, indicates that the use of structural rehabilitation using structural steel is sustainable because of its ease of connection and dismantling, as well as addressing aspects of connections and reducing shear forces, bending moments and axial loads on structural elements [46].

These earthquake-resistant designs follow building regulations, which vary depending on the country and region;

for example, the earthquake-resistant construction standard in Spain is Royal Decree 997/2002 [47]. The ACI 318-14 standard (American Concrete Institute) and the American Society for Testing and Materials (ASTM) are American construction standards applied regionally. Some countries are rigorous in their regulations due to their tectonic location and history of high-magnitude earthquakes, such as Chile, which focuses its construction regulations on seismic resistance, structural resistance and building safety; for example, NCh 433 establishes the use of criteria for earthquake-resistant building designs [48], according to their geographic location. According to the Construction Standardisation Council of the Chilean Construction Institute, the documents most used by professionals in the construction sector are Chilean standards (36%), construction manuals (26%) and Chilean regulations (21%) [49].

In Ecuador, the Ecuadorian Construction Standard [50] established the requirements for earthquake-resistant design and stability of structures [51]. These regulations also address structural redundancy and ductility, ensuring buildings can withstand seismic events without collapsing.

Ecuador, located in South America, has a territorial area of 257,217.07 km^2 [52] and is geographically situated on the eastern side of the Pacific. For this reason, NEC-15 qualifies as having a high seismic hazard. In 2015, Ecuador updated its construction regulations, which differed from the predecessor regulations owing to increased seismic threat levels. Furthermore, it should have considered the external loads (rain, earthquake, wind), the evaluation of the foundations, the geotechnical studies, and the lack of knowledge and tools for calculating earthquake-resistant structures [53].

Ecuador classifies 70% of its constructions as informal [54]. These informal constructions compromise their structural performance owing to the low quality of their materials [55], non-specialised personnel in charge of the work, and poor administrative management by owners within the construction [28, 56, 57]. Implies that informal construction brings methods based on personal experience, which is not optimal [58]. An example was evident in the Magnitude 7.8 earthquake that occurred in Pedernales, Ecuador, in 2016, which left 663 dead, 3.3 billion in economic losses, and thousands of people affected by structural problems in buildings [59, 60], where most buildings did not comply with the standards established in NEC-15 [50], which shows that structures must meet minimum requirements, such as the ability to resist the specified forces, dissipation of the energy generated during inelastic deformation, and floor displacements lower than the admissible values.

Considering that a large percentage of construction in Ecuador is classified as informal, the analysis focuses on the José Luis Tamayo sector in the province of Santa Elena (Figure 2). The study area comprises a sample of 18 infrastructures registered in the last INEC census as an area of poverty because of an income of less than $88.72 [61]. The inhabitants of this sector build their houses with low-quality materials, such as sea sand (causing corrosion of the reinforcement, reduction of concrete resistance, compromised durability and adhesion problems) [62], steel oil pipes as structural elements in the columns, and with high susceptibility to severe structural damage due to earthquakes. The technical diagnosis of these dwellings requires an analysis of the soil and structures.

This research focuses on: What immediate measures should be considered for the safety of the inhabitants in this sector? How could the safety and sustainability of informally constructed housing within a seismic coastal zone be preserved? The study aims to design engineering solutions for rehabilitation and improvements to an informally built house based on modelling and structural analysis, considering construction regulations to mitigate structural damage. These rehabilitation measures guarantee the house structure's safety, durability, and functionality.

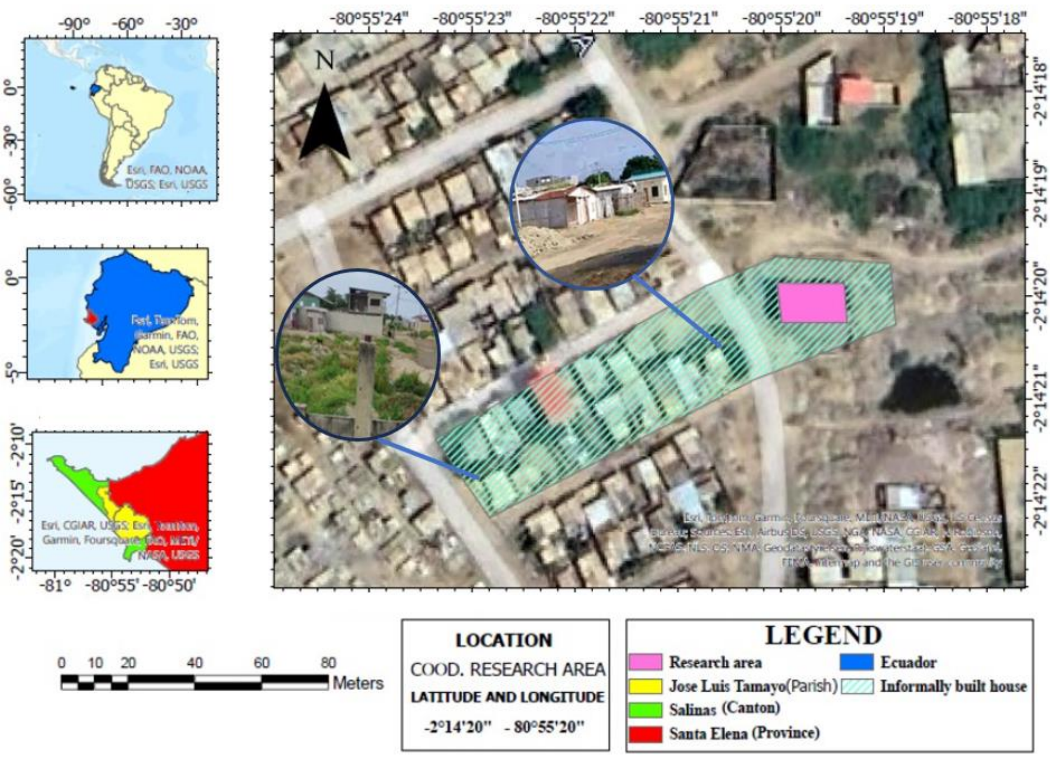


Figure 2. Location map of the study area

2. MATERIAL AND METHODS

Santa Elena is one of the seven coastal provinces of Ecuador, with a territorial area of 536.3 km^2 and 401,178 inhabitants, according to the last census in 2023 [63]. It comprises three cantons: Santa Elena, Salinas, and La Libertad (see Figure 2). The lack of structural stability of houses in depressed social sectors of Salinas and the lack of management by a specialist (civil engineer or architect), caused an earthquake of magnitude 6.1 in 2019 to cause structural damage to 34 houses [46]. This study focuses on a sector of 18 dwellings, built without technical assistance. Without a detailed diagnosis, a typical house, with the highest number of anomalies, was considered a pilot for the analysis. This house is located in Salinas, has a total area of 215.83 m^2, has three floors and is of mixed Construction (reinforced concrete and metal profiles).

This work involved designing rehabilitation and structural recommendations in houses, referenced from a case study, through technical visits to collect in situ information on land and infrastructure. With the data obtained from the static and dynamic parameters of the terrain, all infrastructure data were collected, especially in terms of its structural resistance characteristics. The previous information allowed for the development of architectural and structural plans and modelling and analysis of the house in current and improved conditions using SAP2000 software to obtain occupational safety conclusions and develop a rehabilitation protocol for the research area. Figure 3 shows the four phases considered for this work, which were as follows: I) Collection of base information and review of construction standards, II) Laboratory and in situ tests, III) Structural modelling and analysis, and IV) design and propose structural support and rehabilitation solutions.

2.1 Phase I

Reviewing national and international construction regulations was a basis for structural modelling, analysis and rehabilitation solutions designs. The national standard followed was the NEC-15, and internationally, the ACI 318-14 [64] and ASTM.

The survey and compilation of information in the case study house was carried out through measurements of the structural members and distributions of the spaces of the house using a tape measure to prepare the plans. Figure 4(a) represents the facade of the house under study, while Figure 4(b) illustrates the non-alignment of the columns in the house. In addition, it was necessary to carry out soil surveys and manual drilling at a depth of 2 meters using a drilling post (see Figure 4(c)), which allowed obtaining a soil sample for characterization. These soil samples were extracted at one-meter intervals using a Shelby tube, which guaranteed to preserve the sample's integrity for laboratory analysis. This process is essential to understanding the geotechnical properties of the soil and its load-bearing capacity, which are critical factors in structural design.

2.2 Phase II

The laboratory tests followed the procedures of the ASTM standards: Moisture Content [65], granulometric analysis by Sieving [66], and Atterberg limits [67]. Additionally, with these results, the calculation of the ultimate load capacity of the land was carried out using the Meyerhof equation (see Eq. (1)) [68].

$$q_{ult} = c'NcScdcic + \sigma'_{ZD}NqSqiq + \frac{1}{2}\gamma'B\text{n}\gamma S\gamma d\gamma i\gamma \quad (1)$$

where,

C' = Cohesion
σ'_{ZD} = Effective stress at the bottom of the foundation
γ = Soil Specific Weight
B = Foundation Width
$Nc, Nq, N\gamma$ = Load capacity factors
$Sc, Sq, S\gamma$ = Form factors
$dc, dq, d\gamma$ = Depth factors
$ic, iq, i\gamma$ = Load inclination factors

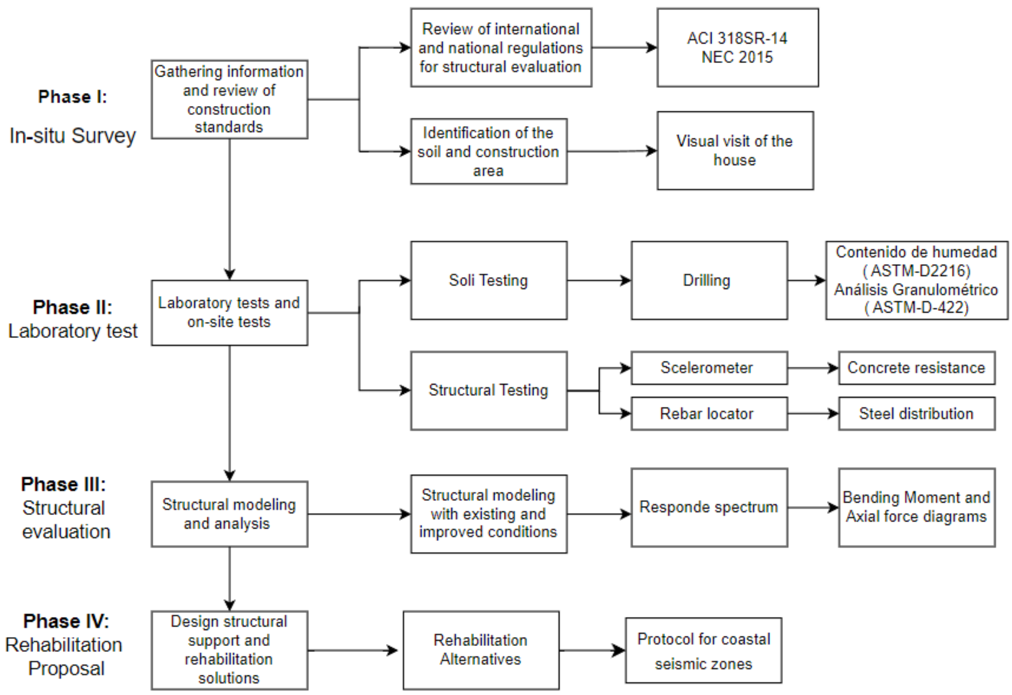


Figure 3. Outline of the methodology to be followed for the housing rehabilitation proposal

Figure 4. Representative images of the house. A: house in case of study, B: perimeter wall and alignment of the columns, C: manual drilling with hand augers

The sclerometric tests [69] with PROCEQ equipment with the ASTM C805 method consisted of recording ten (10) impact values that discarded deferred values in six (6) units of the average, which served to determine the strength of the concrete (in five columns: two on the first floor and three on the second floor). In addition, a bar location test was necessary to determine the distribution of the structural elements by disturbing the magnetic field at various points on the concrete surface through an electromagnetic probe, using PROFOSCOPE brand equipment in six (6) columns of the house, three on the first floor and three on the second floor.

2.3 Phase III

Table 1 lists the characteristics of the structural elements. An analysis of the seismic response spectrum obtained the force and displacement demands of the horizontal components of the earthquake. In this case, the parameters of the NEC-15 earthquake-resistant design regulations were used to establish criteria for the design of the response spectrum, depending on the area. The case study has type D soil, which is a rigid soil profile with a seismic acceleration value (z) greater than 0.50 g and an earthquake propagation characteristic of "Very high" [50].

Table 1. Characteristics of the structural elements

Structural Elements	Classification	Thickness
First-floor column	Oil pipeline	Diameter =101.6 mm and with thickness = 3 mm with low-density concrete cover
First-floor slab1	Reinforced concrete in two directions	200 mm
Second-floor columns	Low-resistance reinforced concrete	Variable in most locations according to plans
Second-floor steel deck slab	Slab with galvanized electro-welded meshes in two directions	Slab thickness=120 mm Galvanized electro-welded rod spacing = 200 mm

The structure will be modelled and analysed according to the architectural and structural plans obtained in phase I and II by SAP 2000 software [70], which describe a grid system for the axes (x, y) with a height for each floor of 3 m. The steel creep properties of fy= 4200 kg/cm^2 and the variable concrete resistance depend on the sclerometer tests in Phase 2. Subsequently, dead loads (Table 2), live loads (Table 3), seismic loads, and load combinations (Table 4) are according to national regulations [50]. The diagrams of axial forces and bending moments were obtained and analysed by SAP2000 software.

Table 2. Characteristics of the structural elements

Load of Structural Elements	Total Load [kg/m^2]
First-floor columns	1482.33
Second-floor columns	1528.12
Third-floor columns	17.74
First-floor ribbed slab	177.60
Second-floor steel deck slab	368.00
First-floor block	295.63
Second-floor block	257.92
Third-floor block	83.87

Table 3. Live load of the house

Live Load	Total Load [kg/m^2]
First-floor	100
Second-floor	100
Third-floor	100

Table 4. Load combination

No.	Load Combinations
1	U= 1.4 D
2	U= 1.2 D + 1.6 L + 0.5 (Lr o S o R)
3	U=1.2 D + 1.6 L + 0.5 (Lr o S o R) + (1.0 L O 0.5W)
4	U=1.2 D + 1.0W + 1.0 L+0.5 (Lr o S o R)
5	U=1.2 D + 1.0 E + 1.0 L + 0.2 S
6	U= 0.9 D + 1.0 W
7	U = 0.9 D + 1.0 E

Note: D= Dead load, E=Earthquake load, L=Overload (Lived load), Lr= Deck Overload (Lived load), S= Snow load, W= wind load

2.4 Phase IV

Based on the results of phases II and III, rehabilitation alternatives for the house's different structural members were developed [71]. These rehabilitations use expert criteria to meet both national and international standards.

Rehabilitation alternatives are necessary to reinforce and repair the structural elements in houses. On the first floor, the columns were reinforced with square metal profiles to reduce the axial loads on the ground, preventing the house from settling and forming cracks and fissures in its walls. The structural rehabilitation on the second floor consisted of repairing the columns with higher resistance structural concrete to repair the columns that the collaborative slab could support. These structural configurations contribute to the stability of the building in the event of an earthquake. (earthquake-resistant) [72].

Additionally, the authors have developed a technical construction protocol for regions with high seismic danger, and anyone without experience or with basic knowledge in construction can evaluate the structural capacity of their houses through simple physical inspections of the structural elements. These are compilations of the construction regulations provided in ACI [64] and NEC-15.

3. RESULTS

3.1 Diagnosis and analysis of agreement with regulations

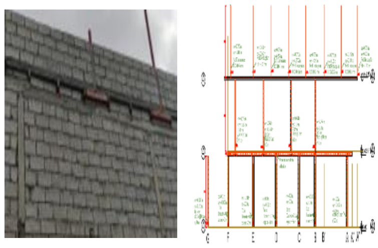
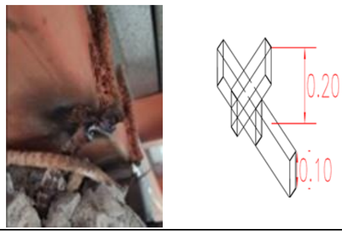
The construction regulations used for this diagnosis were the Ecuadorian standard for earthquake-resistant design and the international rules for structural modelling and analysis. Table 5 presents the description of problems seen in the initial inspection, where there was a poor construction process (informally), without compliance with national (NEC-15) and international technical regulations for construction (ACI) and materials (ASTM), poor quality of construction materials and lack of supervision by a construction specialist [50].

The initial results were obtained through measurements of the structural members and distribution of the spaces that form the integral basis for the preparation of architectural and structural plans, incorporating tangible data, such as the locations of the reinforcements and the resistance of the concrete of the three floors of the house, below are the results of the dimensions and locations of the structural elements, in addition to the architectural plans (see Figure 5) and references of the structural elements (See Figure 6).

3.2 Laboratory tests and on-site tests

Table 6 presents the soil study results obtained at 1 and 2 m depths. The results obtained at a one-meter depth indicate that the soil type is clay with low plasticity (according to the Unified Soil Classification System (USCS)). In contrast, at a depth of two meters, there were clays with low plasticity. Based on the results, the ultimate load capacity of the soil is 1.8 T/m^2, calculated using the Meyerhof equation (see equation 1) up to a depth of 2 m.

Table 5. Main structural problems in the house

Illustrations	Problems Description	R C
	Reuse of petroleum pipes as structural steel in columns	No
	Unaligned columns and cracked walls	No
	Columns structural damage	No

Note: Red colour indicates high risk and non-compliance with the NEC-15; R C=Regulatory compliance

Figure 5. Architectural plan of the house

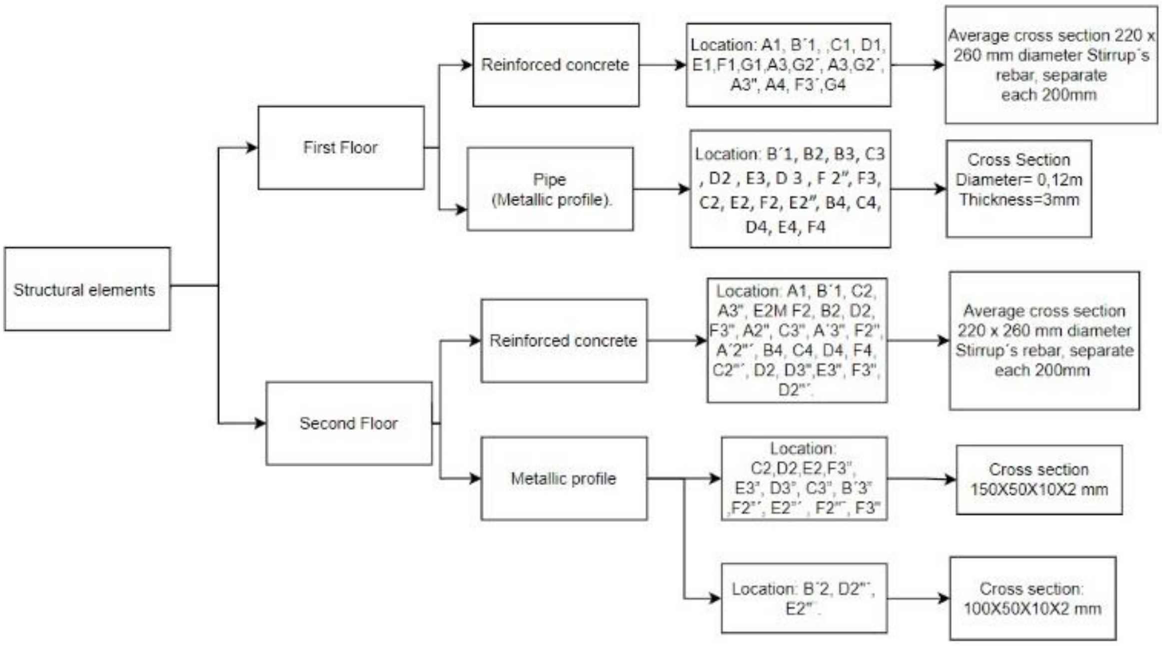


Figure 6. Structural elements according to location in the house

Table 6. Laboratory test

Test	Applied Standard	Results 1 m	Results 2 m
Moisture content	ASTM-D2216	5.79%	9.95%
ASTM D2974	ASTM-D-422	22.14%	12.59%
Granulometric analysis	ASTM-D-4318	Liquid limit=14.80% Plastic limit = 11.08% Plasticity index = 3.72% According to soil classification USCS = CL (Low plasticity clays)	Limit limit =15.10% Plastic limit = 9.48% Plasticity index = 5.66% According to soil classification USCS = CL (Low plasticity clays)

Table 7. Sclerometer result of the case study house

	Columns	Resistance Concrete (kg/cm^2)	Resistance Average (kg/cm^2)	Regulatory Compliance
First floor	Main or central	57-96	76.5	No
	Perimeters	70	70	No
Slab 1		127	127	No
Second floor	Main or central	140-153	146.5	No
	Perimeters	153-268	210.5	No
Slab 2		127	127	No

Note: Red colour indicates high risk and non-compliance with the NEC-15. The minimum concrete strength recommended by the regulations is 21 MPa (214 kg/cm^2)

Table 8. Rebar locator test results of the house

Level	Column Location	Materials	Longitudinal Roding (L.R) Pipe (L.P) Diameter(mm)	Regulatory Compliance
First floor	Secondary Column-B3	Concrete and used oil pipe.	L.P.	No
	Main column-B4	Concrete and used oil pipe.	L.P.	No
	Main Column -F4	Concrete and used oil pipe.	L.P. 101.6	No
Second floor	Main Column-E2	Reinforced concrete	4 L.R 12 mm	Yes
	Main Column-D2	Reinforced concrete	4 L.R. 12 mm	Yes
	Secondary Column-B´3”	Reinforced concrete	4 L.R. 12 mm	Yes

Notes: Red colour indicates high risk and non-compliance with the NEC-15, and green colour indicates compliance with the NEC-15.

Table 7 shows the results obtained from the evaluation of the resistance of the structural elements using the sclerometer. The compressive strength of concrete varies from 70-210.5 kg/cm^2, which is lower than the minimum resistance of concrete (21 MPa or 214 kg/cm^2); therefore, the results of the concrete resistance do not comply with the regulations.

Table 8 details the pachometry results for the house under investigation. These measurements with the pachometer allowed us to determine the distribution and position of the structural steel within the columns, divided between primary and secondary.

3.3 Structural modelling

3.3.1 Structural modelling with the current structural conditions

During the execution of the SAP2000 software, a notification appeared containing three warnings preventing suitable structural analysis. These caveats highlight several critical issues in modelling current conditions, such as geometric non-linearity and the absence of stiffness in specific columns (see Table 9).

3.3.2 Modelling with the proposed conditions for structural improvements

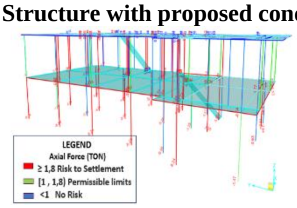
After confirming that the house's structure had flaws in the SAP 2000 structural analysis software, a new structural modelling design began. This rehabilitation approach included planned changes for the structural strengthening of the house. This rehabilitation approach included intended changes for the structural strengthening of the house. The first step in this process was to increase seismic resistance and load capacity. As part of the alternatives for housing rehabilitation and structural recovery, specific solutions to address the three warnings identified during Phase III were implemented (Table 10).

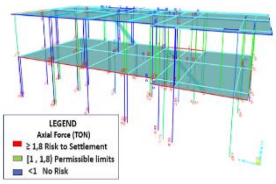
Table 9. Result of structural modelling of the house under current conditions

Modelling and Structural Analysis under Current Conditions	
Response spectrum	Seismic acceleration response: 0.126 g
Structural problem notifications	Warning 1: Geometric non-linearity of the elements Warning 2: Non-linearity of column elements Warning 3: Absence of rigidity of the column elements of the second floor

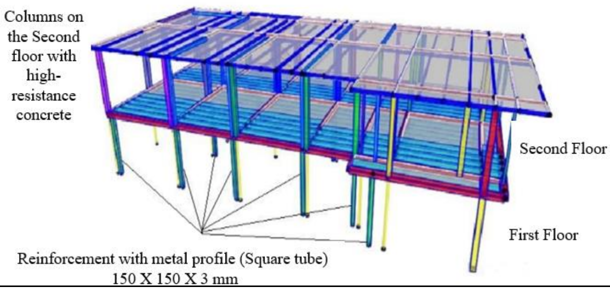
Table 10. Structural rehabilitation proposals in the house

Structural Modelling with Improved Structural Conditions	
Solution 1: resolves warning 1	Reinforcing the second-floor columns with square structural steel tubes of 150 mm × 150 mm × 3 mm reduces bending moments and improves load transfer to the ground. Steel plates of 0.25 m × 0.25 m are anchored to the columns to ensure a secure attachment, which will be welded to the foundation and slab of the second floor, and the connection of the plates to the foundation and slab will be made using expansion bolts. This new structural configuration allowed 14 columns of the second floor to be free of settlement risks, increasing the structural safety of the second floor by 120%.
Structure with current conditions	**Structure with proposed conditions.**

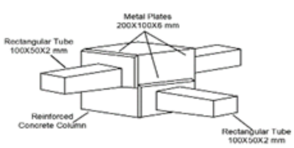


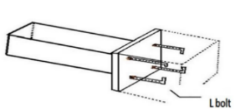


Solution 2: resolves warning 2	Vertical alignment of the second floor's columns with the second floor's corresponding columns by means of metal structures of square tube dimensions 150×150×3 mm.



Solution 3: resolves warning 3	To complete the columns of the second floor, use a high-strength concrete of 400 kg/cm^2. Next, two steel plates must be installed on the columns still under construction. These plates must be anchored and positioned with their horizontal rods. By completing the columns with high-performance concrete, the columns acquire an average resistance of 273.25 kg/cm^2, which is higher than the minimum resistance of the concrete suggested by NEC-15.





4. CONSTRUCTIVE TECHNICAL PROTOCOL

The studies on the structural elements of a house built informally in a coastal region of Ecuador, in the case of the study in this work on the circum-Pacific, recommend following the rehabilitation protocol proposed in Tables 11 (for structural elements) and 12 (for steel structural) to provide security to the home, be a prevention measure for a catastrophic seismic event. They show the technical construction protocol with minimum requirements for reinforced concrete houses in areas with high seismic risk to prevent structural damage and take care of people's lives.

Suppose a house does not meet minimum construction requirements. In such cases, it is essential to consult with a specialist in charge of construction (Civil Engineer or Architect) so that they can carry out the respective structural improvements and rehabilitation.

These structural rehabilitation recommendations are the most common problems in the houses presented previously. However, these solutions may change depending on the criteria of the responsible construction specialist.

In addition, Table 13 presents the analysis of the total costs of the rehabilitation project, which total USD $31,121.34, considering a two-story house with two slabs, with an area of 215.83 m^2, so the rehabilitation value is USD $144.19/ m^2.

Furthermore, according to the prices of construction materials in Ecuador, the price per square metre of construction can range from USD $590.00-1500.00 with first quality finishes, while for a normal low-income housing unit, the square metre of construction could reach USD $365 [73]. So, the price for a normal 2-story house with 2 slabs, considering that it is of popular class, would be USD $78,777.95.

Table 11. Constructive technical protocol for structural elements

Nª	Requirement	Description	Structural Recommendation
		Geotechnical studies	
1	Soil investigation	Field reconnaissance, subsurface investigation, and analysis	A soil study is recommended to determine the bearing capacity of the soil for the design or redesign of the structures.
		Columns	
2	Minimum column cross-section	For two-story houses, columns should have a minimum cross-section of 300 mm ×300 mm.	Increasing the section with a structural steel jacket, metal profiles or CFR
3	Column alignment	Columns must be aligned from floor to floor	Search for alignment with metal profiles to transmit loads.
4	Integrity of structural elements	Beams, columns, and slabs must be completely concreted throughout their entire section, which guarantees their rigidity.	complete the section with higher-strength concrete fixed with epoxy resin.
		Overhangs and separation between buildings	
5	Maximum length of overhangs (balconies)	Overhangs must be less than 1.50 m.	If they are larger, place structural frames on the lower floors.
6	Space between buildings	Leave spaces between the buildings for the striking effect.	30-50 mm spacing between buildings.
		Minimum concrete strength	
7	Concrete Resistance	The minimum resistance is f'c= 21 MPa (214 kg/cm^2). (Verify with sclerometry tests).	Reinforce structural elements that do not meet the required strength by means of metal profiles or CFR.

Notes: CFR= Carbon Fiber Reinforcement

Table 12. Constructive technical protocol for structural steel

Nª	Requirement	Description	Structural Recommendation
		Longitudinal steel	
1	Structural steel distribution	Use rebar and verify steel distribution using pachymetry tests.	Meet minimum structural steel requirements and correct layout if insufficient.
2	Stirrup reinforcement bar at ends	Place 50 mm stirrup reinforcing bars at the ends of the columns or beams and the last one at twice the cant.	Reinforce stirrups if they do not meet requirements, especially at the ends, using CFR or other methods.
3	Splices in longitudinal bars	Overlaps must not be less than twice the transverse camber of the structural element, or the overlap distance must be > 30 times the rod diameter.	Install the appropriate cover plates if they do not meet the standards.
		Overhangs and separation between buildings	
4	Stirrup reinforcing bar diameter.	Minimum diameter: 10 mm. Maximum diameter: 16 mm.	If the diameter of the stirrup reinforcing bars is less than 10 mm, increase it using CFR, metal sleeving, or other methods.
5	Distribution of stirrup reinforcing bars in the center of the structural element	The spacing of the stirrup reinforcing bars is the minimum of the following values: diameter/4, six times the diameter minus the reinforcement or 200 mm.	If the diameter of the stirrup reinforcement is less than 10 mm, CFR should be placed.

Notes: CFR= Carbon Fiber Reinforcement

Table 13. Structural rehabilitation cost analysis

Description	Unit	Quantity	Unit price	Total price
Problem 1				
Repair of second floor columns				
Cutting in slab for slab place	m^2	2.40	$386.93	$928.63
Excavation in foundation and dislodgement	m^3	9.00	$71.66	$644.94
Square plates 25×25 cm	u	30.00	$250.35	$7,510.50
Square tubular steel column 150×150×3.00 mm including welded	u	15.00	$477.74	$7,166.0
Compacted backfill with material replacement	m^2	9.00	$209.87	$1888.63
Problem 2				
Completion of second floor column				
Old concrete to mortar adhesive	m^2	0.80	$367.48	$293.98
Structural mortar f'c= 400 kg/cm^2 in column, including formwork.	m^3	0.40	$630.65	$252.26
Rectangular plates 20 10 cm	u	36.00	$233.73	$8,414.28
Problem 3				
Linearity of columns between floors				
Square plates 25×25 cm	u	8.00	$250.35	$2,002.80
Square tubular steel column 150×150×3.00 mm including welded	u	3.00	$477.74	$1,433.22
Debris removal and cleanup	m^2	10.00	$58.61	$586.10
Total budget				$31,121.34

5. DISCUSSION OF RESULTS

The calculated seismic acceleration response spectrum presented an acceleration of 0.126 g in type "D" soils in Salinas, Santa Elena. This acceleration, which can cause intense vibrations during an earthquake, poses a risk to structures, especially two-story houses built with low-quality materials [74, 75]. These houses are vulnerable because of their height and potential for more significant oscillations during an earthquake [76]. Inferior building materials may not withstand these forces, which can lead to structural collapse and endanger the lives and safety of the inhabitants [77].

The comparative analysis of the seismic responses and construction regulations in coastal regions of the fire ring, including Ecuador, Chile, Peru, and USA, for soil types "D" reveals significant differences [78, 79]. According to the results presented in Table 14, Chile, and California (USA) give high seismic accelerations (1.2343 g and 1 g, respectively), which indicates an increased vulnerability to damage to buildings during earthquakes [80, 81]. In comparison, the seismic acceleration on the Ecuadorian coast represents 10.24% and 12.60% of the acceleration in Chile and California, respectively. Peru's values were close to those of Ecuador. These data highlight the need for appropriate construction protocols and continuous structural integrity assessment in regions with high seismic activity.

Table 14. Comparison of parameters and seismic acceleration in coastal areas with soil type D

Countries	Standard/Response Spectrum	Seismic Acceleration
Ecuador-Santa Elena	NEC-15	0.126 g
Perú	E 030	0.233 g
USA-California	ASCE 7-10	1.00 g
Chile	NCH 433-2009	1.234 g

Tables 15 and 16 present a comparative analysis of the infrastructure in the case study, contrasting the current conditions with existing regulatory guidelines. The tables detailed the discrepancies between the current construction practices of craftsmen and established construction regulations.

Table 15. Comparison of the results obtained from the housing with the construction regulations for columns on the first floor and concrete resistance

Description	Regulations NEC-15 ASCE 7-16 ACI 318-19	Error (%)	Structural rehabilitation
Average sections of columns on the first-floor 220×260 mm.	Minimum sections for a two-story reinforced concrete house: 300×300 mm.	20	It is proposed to reinforce with square metal profiles measuring 150×150×3 mm.
There is no transverse reinforcement in the first-floor columns	Place stirrup´s rebar 50 mm at the ends of columns or beams and the last one at two times the superelevation (H)-max distribution w/20 cm, after the ends at 2H.	100	Symmetry in the cross-section of the reinforcements is proposed so that the distribution of the loads that make up the construction is uniform.
Concrete resistance of the column floors f´c=70 - 76.5kg/cm^2 of the first floor.	Minimum concrete resistance value f´c=21 MPa (214.14 kg/cm^2).	65.7	It is proposed that the reinforcements for structural rehabilitation comply with INEN 2415.

Notes: Ecuadorian Construction Standard (NEC-15); American Society of Civil Engineers (ASCE 7-16); American Concrete Institute (ACI 318-14)

Table 16. Comparison of the results obtained from the housing with the construction regulations for columns on the second floor and slab

Description	Regulations NEC-15 ASCE 7-16 ACI 318-19	Error (%)	Structural Rehabilitation
The compressive strength of the concrete of the columns on the second floor is 76.5 kg/cm^2.	Minimum compressive strength value of concrete f'c = 21 (214.14 kg/cm^2).	64.2	It is proposed that reinforcements be made with metal profiles on the second floor.
Lack of rigidity of the column elements of the second floor.	The NEC-15 (section 1.12.3 d) mentions that the connections of the structural elements must be ensured as a requirement for seismic resistance.	100	It is proposed to repair the columns of the second floor with higher resistance concrete, guaranteeing the connections of the structural elements.
Concrete resistance of the slab: 70 kg/cm^2.	Minimum concrete resistance value, f´c = 21 MPa (214.14 kg/cm^2).	67.2	Placing structural reinforcements on the first floor improves the structural capacity of the slab.
Nonlinearity of columns on each floor.	NEC-SE-DS 5.3.1.a, construction professionals ensure that the structural configuration is simple and regular.	100	Reinforcements with metal profiles aligned with the columns of the first floor are proposed.

Notes: Ecuadorian Construction Standard (NEC-15); American Society of Civil Engineers (ASCE 7-16); American Concrete Institute (ACI 318-14)

The results of the analysis of the house show that it does not comply with the construction standards of NEC-15, ASCE 7-16 and ACI 318-14 in aspects such as structural rehabilitation, average section of the columns on the first floor, distribution of the quantity in the columns, and resistance of the concrete. Therefore, the proposal of reinforcements with square metal profiles and the placement of plates at the ends of the columns will improve the symmetry in the cross-section of the reinforcements to guarantee a uniform distribution of the loads in the construction. Furthermore, the recommendation to propose structural reinforcements on the first floor will increase the structural capacity of the slab. In contrast, the reinforcement with metal profiles aligned with the columns of the first floor will improve the rigidity of the column elements of the second floor.

A technical construction and rehabilitation protocol will allow experts and non-experts to diagnose or evaluate housing structures according to the national and international regulations applied to coastal regions with similar seismic characteristics. In general, in this type of research, a trend has been observed towards using specific methods in structural rehabilitation.

A study conducted in New Zealand, a region with high seismic risk, reveals that this country is experiencing slow progress in seismic retrofitting, and this is due to the lack of government attention because homeowners who need attention in the rehabilitation of their homes do not have the necessary financial means, and do not receive support from government entities [82]. One risk of not preparing for an earthquake in a country with seismic vulnerability in a third world country is what happened in 2010 in Haiti, where a 7 Mw earthquake caused more than 200,000 lives lost and thousands injured [83], leaving a total of 8.1 billion dollars in economic losses [84].

A study carried out in Trujillo, Peru, on structural rehabilitation for two 6-storey buildings after the earthquake occurred in 2007 shows that it is necessary to analyze the elastic conditions of the structures in current conditions, and in case of not complying with the elastic demands, it is necessary to reinforce the structure, in this case the reinforcement was carried out by placing metal profiles for its easy acquisition and installation process. A study conducted at the school pavilion, I.E. San Fernando of 5 levels, Peru, shows two types of reinforcement; the first consists of a reinforced concrete jacket reinforcement to the beams and columns, and the second indicates the placement of shear walls in these proposals for structural rehabilitation, the most favourable seismic mitigation proposal is the inclusion of shear walls since its seismic response manages to reduce the periods of vibration, lateral displacement in the last floor of 1.32 cm, and maximum drifts up to 6.11% lower compared to the proposal for column and beam jacketing [85].

The most applied rehabilitation methods and technology in seismic zones are finite element strengthening [86], reinforced concrete repair and strengthening [87], the application of self-repairing nanoconcrete [88], performance-based rehabilitation for structural and non-structural members using moment-resisting steel frames, steel cladding [89] and the use of Fibre Reinforced Polymers (FRP) [90].

Regarding the methodology used, a similar procedure was that of Río Bueno [87], where a structural rehabilitation process includes I) the identification of causes and detailed inspection and II) repairing and reinforcing structures (focused on the prominent structural members).

This process addresses 55.83% of the rehabilitation procedures provided by the expert, implying a comprehensive approach to the reinforcement and repair of structural elements. Rehabilitation strategies contribute to achieving Sustainable Development Goal 11 by making cities more inclusive, safe, resilient, and sustainable [91]. Rehabilitation techniques can improve the quality of life by reducing the risks related to structural damage, improving architecture and benefiting areas such as tourism, as reported by several studies, such as; the stabilization in Zaruma [92], reconstruction of the Zaruma Hospital [93], the stability and conservation of Cerro Las Cabras [94, 95], the evaluation of slope stability in an urban area [96], mining houses in Lota, the Biobio region (Chile) [97], a and the restoration of the Ise Shrine in Japan [98], located in seismically vulnerable coastal areas.

The research (case study) focused on identifying three main structural problems. However, future research should consider challenges such as the problems of settlement and displacement and the importance of studying soil at greater depths using geophysical methods [99] and in-situ tests to understand the fundamental causes more deeply. Of these problems and thus be able to guide the appropriate solutions

[100]. Additionally, it is essential to study the connections between the columns and beams on the first floor to determine the nature of the transmission of load stresses in the connections of the structural elements [101] to ensure occupational safety and structural stability.

6. CONCLUSIONS

Analysis of a typical building in a coastal seismic zone, which has been built informally (without the direction of a professional), allowed us to recognize several structural problems, particularly in structural elements such as columns, beams, slabs, and materials such as concrete and structural steel. With measurements at the site, laboratory tests, and application of the SAP 2000 software. Reinforcement solutions that allow diagnosing, rehabilitating, and providing security to its occupants were determined. These implications are present in a technical protocol for rehabilitative diagnosis, which is valuable and easy to apply.

The biggest failures and risks in the infrastructure are found on the house's first floor under investigation because there are no abutments, and there is no linearity of the columns between floors with a 100% error in contrast to the regulations NEC-15. Three solutions are necessary to mitigate the structural instability messages generated by SAP 2000. These include the reinforcement with metal profiles on the first floor of the building, the alignment of the load distribution of the upper floors with metal reinforcements attached to base plates and fixed by mechanical anchors, including expansion bolts secured to the concrete, and the repair of the pillars with high strength concrete fixed through an epoxy resin providing the joint between the old concrete and the new concrete. These interventions will resolve the warning signs and correct the structural deficiencies caused by the structural problems of the house.

Many houses in Latin America and developing countries are built informally and need to be supervised by construction specialists. Several of these constructions are in tectonic plate boundary zones with a high seismic risk index, highlighting the need for audits and controls to correct the structure of the works and preserve the integrity of inhabitants. The protocol addresses common problems in houses and proposes intervention solutions, promoting a culture of rehabilitation and reducing the risk of losses due to earthquakes. It is essential to consider soil characteristics such as bearing capacity and susceptibility to liquefaction to conduct geotechnical studies that adopt rehabilitation techniques that guarantee safety and sustainability. This protocol proposes methods for existing and new constructions as tools for local authorities to issue ordinances to promote ordering and strengthening in areas of high seismic vulnerability in the construction sector.

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