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Assessing and Mitigating Seismic Risk for a Hospital Structure in Zaruma, Ecuador: A Structural and Regulatory Evaluation

Pedro P. Rojas[1,2,4], Cindy Moya[2], Martha Caballero[2], Wilmer Márquez[3], Josué Briones-Bitar[1,4], Fernando Morante-Carballo[4,5,6*]

[1] Facultad de Ingeniería en Ciencias de la Tierra (FICT), ESPOL Polytechnic University, Guayaquil P.O. Box 09-01-5863, Ecuador
[2] Engineering Department, Consultora-PRA Pedro Rojas & Asociados S.A., Guayaquil P.O. Box 090102, Ecuador
[3] Engineering Department, Consultora Jorge Tola y Asociados CONSULTOLA Cía. Ltda., Guayaquil, P.O. Box 090303, Ecuador
[4] Centro de Investigación y Proyectos Aplicados a las Ciencias de la Tierra (CIPAT), ESPOL Polytechnic University, Guayaquil P.O. Box 09-01-5863, Ecuador
[5] Facultad de Ciencias Naturales y Matemáticas (FCNM), ESPOL Polytechnic University, Guayaquil P.O. Box 09-01-5863, Ecuador
[6] Geo-Recursos y Aplicaciones (GIGA), ESPOL Polytechnic University, Guayaquil P.O. Box 09-01-5863, Ecuador

Corresponding Author Email: fmorante@espol.edu.ec

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ABSTRACT

This research, conducted in Zaruma, southern Ecuador, seeks to evaluate the seismic vulnerability and performance level of the Humberto Molina Hospital's reinforced concrete buildings. The study employs an examination of national and international seismic codes for rehabilitation, along with the implementation of recommended techniques. Structural characteristics of the buildings were identified through auscultation, surveys of reinforcing steel, and the extraction of concrete cores. The amassed data, coupled with a seismic hazard analysis of the site, facilitated a structural assessment of the blocks, conducted in accordance with national (MIDUVI) and international (ASCE/SEI) codes. The Federal Emergency Management Agency (FEMA) subsequently proposed rehabilitation alternatives for each block. Due to the importance of the hospital's functions, data collection was limited to blocks B3 and B4. The structural system, composed of moment-resisting concrete frames, exhibits potential vulnerabilities due to knocking (collision) and torsion, attributed to its irregular form. Structural evaluation revealed that block B4 adheres to the drift limits stipulated by the ASCE 41-13 standard (below 2%), while block B3 exceeds these limits (2.05-2.80%). Recommended rehabilitation strategies for B3 encompass mass reduction (removal of the second floor, representing a dead load of 700kg/m^2 and a live load of 200kg/m^2), and the introduction of additional rigidity and strength (extension of structural elements). For block B4, it is suggested that each sub-block be made independent. These interventions aim to facilitate the hospital's reopening, thereby benefiting the Zaruma Mining District community.

1. INTRODUCTION

Situated at an elevation of 1,200 meters, Zaruma, an Ecuadorian city with a rich mining history, is characterized by steep slopes and weathering natural conditions. The city's urban landscape has been significantly altered by the presence of mining galleries in the city center, a remnant of former and unauthorized mining activities. The ensuing impact on the mining-society relationship has manifested in the form of urban subsidence. The Humberto Molina Hospital, along with surrounding structures such as the San Juan Bosco School, have witnessed a series of geodynamic events, including seismic activities, landslides, and settlements, which have inflicted damage on their reinforced concrete buildings. This raises the critical question of how the reopening of the Humberto Molina Hospital can be achieved in a manner that ensures safety against seismic events, thereby providing the necessary assurance for local authorities to approve its rehabilitation.

Earthquakes are among the most devastating natural disasters, with their historic impact on various civilizations being well documented. They account for between 700 and 298,000 fatalities annually, globally [1]. The brunt of these fatalities and associated damages is borne by developing nations located within seismically active zones [2]. Structural failures, stemming from seismic activities, are the leading cause of such fatalities and economic losses [3, 4]. For instance, in the aftermath of the 2010 Chile earthquake, significant damage to the piping systems of Santiago International Airport led to its closure for several days [5]. Simultaneously, the functionality of four hospitals was completely lost, and over ten hospitals suffered nearly 75% loss in functionality due to damage to their sprinkler piping systems [6].

Critical infrastructures, particularly hospitals, necessitate comprehensive evaluation of their seismic behavior to ensure the safety of inhabitants and the seamless provision of medical assistance in the aftermath of seismic events or similar incidents [7, 8]. Seismic vulnerability assessments of buildings hinge upon an array of factors, including local seismicity data such as peak ground acceleration (PGA) and spectral displacement, as well as building characteristics such as construction material, age, and structural height [9-11]. These assessments are integral to devising realistic disaster preparedness, formulating effective response strategies, and managing seismic hazards efficiently [12, 13]. As stipulated by the Ecuadorian Construction Standard, hospitals fall under the category of essential occupancy [14]. Their strategic role in normal circumstances becomes even more crucial during disasters [15]. The uninterrupted functioning of such facilities is paramount for the operational continuity of a community or city. However, recent studies have underscored the high seismic risk associated with such constructions [16, 17]. Consequently, the call for improving seismic capacity through appropriate modernization interventions has been emphasized. These interventions, which extend beyond mere engineering parameters such as the seismic capacity of the building or seismic intensity demand, should encompass engineering, socioeconomic, and sustainability considerations [18, 19].

Hospitals, functioning round-the-clock and encompassing a diverse range of operations such as emergency rooms and laboratories, stand at the core of the health system, effectively serving as the final point in the rescue chain during disaster response [6, 20]. Ensuring the harmonization of seismic behavior across structural and non-structural elements, particularly during serviceability limit states, is critical to guarantee immediate functionality post-disaster [21, 22]. Damage assessment and validation under extreme load conditions, such as earthquakes, provide valuable insights into the behavior of structures, thereby highlighting the importance of post-earthquake damage assessment and interpretations or models for comprehending the seismic behavior of buildings [23, 24].

Zaruma, situated in the southwest of Ecuador in the province of El Oro, spans an area of 659.40 km^2 and houses a population of 24,097 [25, 26]. With a rich mining history, Zaruma was designated a cultural heritage site in 1990 [27, 28]. Since 1998, it has been on UNESCO's tentative list of candidates for World Heritage Site status, primarily due to its geological and mining sites [29]. It is also considered within the "Ruta del Oro" Geopark Project [30]. Currently, the area faces a high geological risk due to subsidence since 2016, resulting from illegal underground mining activities, as exemplified by the La Inmaculada School, and earthquakes that lead to structural damage in residential and commercial buildings, including hospitals such as the "Humberto Molina" Hospital [31].

Over the years, the Humberto Molina Hospital facilities have exhibited substantial damage, attributable to factors such as the aging of the approximately 50-year-old structure, the inferior quality of construction materials, and the recurrent seismic activities in Zaruma. The most frequently observed damages include cracks in the masonry, floors, and the retaining walls of the hospital's access stairs. Following the earthquake on 17th November 2017, with a magnitude of Mw 5.5 and an epicentre in Balao, located 153 km north of Zaruma (Figure 1), authorities mandated a preventive closure of the hospital, evacuating patients, officials, and employees [citation needed]. Subsequently, the hospital remained largely closed, with exceptions made for smaller buildings catering to specific needs such as emergencies, administration, pharmacy, and warehouses.

Two additional healthcare facilities serve Zaruma: The Maternal and Child Emergency Centre and the Piñas Basic Hospital Luis Moscoso. The former, inaugurated in 2017 and situated within Zaruma (600m from the Humberto Molina Hospital), offers specialties such as general medicine, gynaecology-obstetrics, cardiology, traumatology, paediatrics, short-stay maternity, and round-the-clock emergency services. However, it lacks surgical and post-surgical recovery services. The latter, inaugurated in 2020 and located 18 km from Zaruma (30-minute car ride), provides services including paediatrics, internal medicine, gynaecology, surgery, hospitalisation, respiratory therapy, emergency, physical rehabilitation, operating rooms, and an obstetric centre. The community has voiced concerns over the distance to this hospital, especially given the constant seismic issues.

The potential permanent closure of Humberto Molina Hospital by the authorities has elicited concerns from the community, accentuating the need to assess the hospital's seismic vulnerability and performance for its potential rehabilitation and reopening. This situation has fostered an environment of health and social anxiety within Zaruma. As a result, decision-makers have commissioned studies to ascertain the current state of the hospital and explore the possibility of reopening it post-rehabilitation.

Acknowledging the critical role of Humberto Molina Hospital for Zaruma, several initiatives have been undertaken. These include 1) field visits to the study area to gather base data and conduct preliminary evaluations of the hospital structures; 2) performance of the structural assessment in line with national and international codes under usage conditions; and 3) proposition of rehabilitation techniques and work to decision-makers.

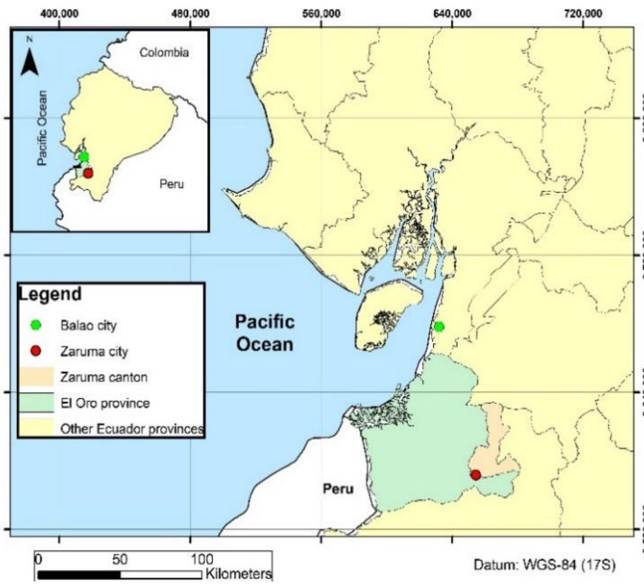


Figure 1. Geographic map with the location of the study area (Zaruma) and Balao (the epicentre of the earthquake that caused the temporary closure of Humberto Molina Hospital)

2. GENERAL DESCRIPTION OF THE INFRASTRUCTURE

The Humberto Molina Hospital, in the city of Zaruma, is catalogued by the Ministry of Public Health of Ecuador (MSP) as a "Basic Hospital" corresponding to the second level of health care that belongs to District 07D03 (includes the cities of Atahualpa-Portovelo-Zaruma). A "Basic Hospital" is considered a Health Unit that provides ambulatory, emergency, and short-stay hospitalisation care (such as general medicine, gynaecology-obstetrics, paediatrics and emergency surgery) [32].

Based on interviews conducted with officials, employees, and builders, the Hospital was inaugurated in 1975. The Humberto Molina Hospital has several facilities between one and three levels. Table 1 presents a list of the characteristics of the buildings that comprise the Hospital, while Figure 2 illustrates the general layout of the Hospital. Figure 3(a)-Figure 3(c) show images of some buildings in the Humberto Molina Hospital.

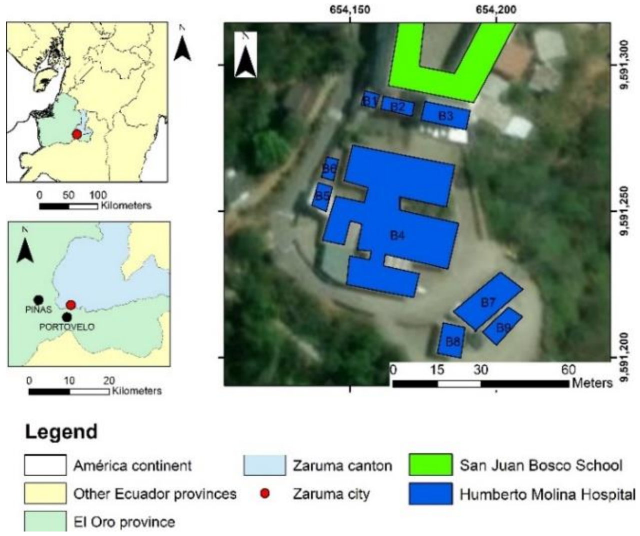


Figure 2. Location of the buildings of the Humberto Molina Hospital

Table 1. Identification and characteristics of the buildings that integrate the Humberto Molina Hospital

Block	Purpose	Starting Year	Building Features
B4*	Emergencies, Hospitalization, Traumatology Surgery	1975	• It consists of one story. • Construction area: 1300m^2. • It has a total height of 4.30m. • Moment-resisting concrete frames. • It was formally built. There are no structural plans.
B3*	Administration	2000	• It has three stories. • It was built in phases (according to interviews). • Construction area: 64m^2. • The total height of the building is 8.40m. • Use of reinforced concrete in the first two mezzanines. The last mezzanine has a metallic structure. • The ground floor was formally built, while the other floors were informal.
B1	Archive	2000	• The building has two stories (a first floor and a basement). • Construction area: 24m^2. • It has a height of 2.70m in the basement and 3.00m on the first floor. • It was formally built. There are no structural plans.
B2	Vaccine storage	-	• It is located between B1 and B3. • It has a ground story. • The material used for its construction was concrete. • It is adjacent to the stairs leading to block B3. • It was formally built. There are no structural plans.
B6	Pharmacy	2004	• It has only one mezzanine. • Construction area: 155m^2. • It was formally built. There are no structural plans.
B7	Pharmacy warehouse	2004	• It has only one mezzanine. • Construction area: 54m^2. • It has a total height of 4.70m. • It was formally built. Structural plans are available.
B8	Vaccination	2009	• Initially, the first floor was built, and a mezzanine was added. • Construction area: 40m^2. • The total height is 6.40m. • It was informally built. • The building consists of reinforced concrete porticoes.
B9	Chlorination	2005	• It has three stories. • Used to store oxygen tanks on the first floor and water tanks on the top floor. • Construction area: 18m^2. • It has a total height of 6.62m. • Reinforced concrete frames.
B10	Hospital Warehouse	2017	• It has only one story. • Construction area: 18m^2. • It has a height of 2.20m. • It was informally built.

* Essential buildings, according to authorities of the Public Health Ministry of Zaruma

(a) B4 front view

(b) B3 front facade

(c) B8 west-south facade

Figure 3. Building facade of the Humberto Molina Hospital of Zaruma

3. MATERIALS AND METHODS

The methodological procedure proposed in this research consists of reviewing the base information of public institutions in charge of infrastructure welfare (e.g., MSP, Zaruma city hall, Risk Management Secretariat (SGR for its acronym in Spanish) and field data collection (e.g., surveys and in-situ measurements in buildings) for structural evaluation under current conditions and geodynamic conditions. These data and assessments, solutions, and proposals for rehabilitation work at the Humberto Molina Hospital for its rehabilitation and reopening within the Zaruma-Portovelo mining district were analysed.

The procedure followed in this study is divided into three different phases (Figure 4): 1) processing and systematisation of the basic information provided by government entities, 2) information gathering and fieldwork, and 3) carrying out structural evaluation and proposal of rehabilitation alternatives to decision-makers.

3.1 Processing and systematizing existing information

The inspection was conducted during several visits. Owing to the need for more information on the architectural and structural plans of the hospital blocks, a survey of the buildings was carried out during the inspection visits. This survey determines the exterior and interior dimensions of structures and the dimensions of the structural elements of each block. The survey was carried out for this investigation only in blocks B3 and B4, owing to their importance in hospital facilities.

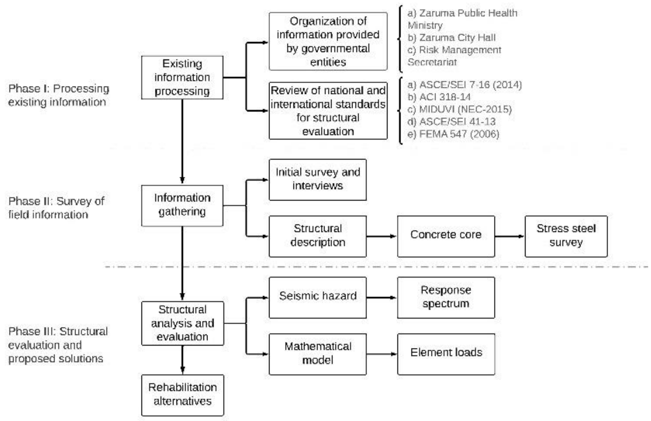


Figure 4. Methodological scheme followed in this research

3.2 Information gathering and fieldwork

A field exploration program was carried out to determine the different types of damage and investigate their causes. This included the following activities:

3.2.1 Initial survey

The inspection was conducted during several visits. Owing to the need for more information on the architectural and structural plans of the hospital blocks, a survey of the buildings was conducted during the inspection visits. This survey determined the exterior and interior dimensions of the structures and the dimensions of the structural elements of each block. The survey was carried out for this investigation only in blocks B3 and B4, owing to their importance in hospital facilities.

This initial inspection was based on the international standard ASCE/SEI 41-13 [33], which provides a preliminary structural evaluation of a building. Flexometer and tape were used to determine the exterior and interior dimensions of the buildings.

3.2.2 Structural characterization

Concrete cores were used for structural characterisation, and a stress-steel survey was conducted. Seven concrete cores were obtained from the columns, beams, and masonry in blocks B3 and B4 of the Hospital. These cores were collected at the midpoint of the structural elements. The standard followed was ASTM-C39. Table 2 presents the locations and dimensions of the extracted cores.

The survey of reinforcing steel was conducted by auscultation of the structural elements (beam, column, and foundation). This auscultation enabled us to determine the type and amount of reinforcing steel in the structural elements of the blocks. This was performed in the same elements where the concrete cores and foundations of both blocks were removed. For this purpose, a flexometer and a digital Vernier calliper were used. Figure 5(a)-Figure 5(b) show images taken during the surveys and sampling of the concrete cores.

Table 2. Location and dimensions of the extracted cores

No.	Block	Element	Dimension (mm)	
			Height	Diameter
1	B4	Column	88.20	43.20
2	B4	Beam	79.00	43.10
3	B4	Column	102.40	43.20
4	B4	Beam	86.30	43.20
5	B4	Masonry	97.00	42.00
6	B3	Column	83.90	43.30
7	B3	Beam	82.30	43.00

(a) Reinforcing steel

(b) Extraction of concrete cores

Figure 5. Auscultation work in the column of B4

3.3 Structural evaluation and proposal of rehabilitation alternatives

3.3.1 Seismic hazard and response spectrum

Before conducting the structural evaluation, a characterization of the seismic hazard was carried out based on the Ecuadorian Construction Standard (NEC): Seismic Hazard, Earthquake Resistant Design NEC-SE-DS, promulgated by the Ministry of Urban Development and Housing of Ecuador. (MIDUVI) [14]. The MIDUVI standards [14] and Chapter 2/Appendix C of the American Society of Civil Engineers and Structural Engineering Institute (ASCE/SEI) [33] determine the elastic response spectrum. According to this manual, the procedure is applied to existing buildings to provide a certain level of performance for a selected seismic group.

The "10%/50 years" earthquake corresponds to the earthquake known as Design Basis Earthquake (DBE) and is the one commonly used to design new buildings [33]. This earthquake had a probability of exceeding 10% in 50 years, and its mean return period was estimated to be 475 years. From Table 3, it can be deduced that for existing buildings, the earthquake to be used must be the Basic Safety Earthquake-1 Existing (BSE-1E) which has a probability of exceeding 20% in 50 years, and its mean return period is estimated at 225 years [33]. Because the most important and relevant hospital buildings (B4 and B3) are between 20 and 44 years old, the spectrum corresponding to BSE-1E was selected as the earthquake for structural evaluation.

Table 3. Measurements and compressive strength of the concrete of structural elements

Block	Element	Typical Dimensions [mm × mm]	f'_c [kgf/cm^2]
B4	Columns	300×300	150
	Beams	250×300 250×400	150
B3	Columns	180×180	150
	Beams	190×190	150
	Slab	160	150

3.3.2 Structural evaluation

Standards such as ASCE/SEI [34], American Concrete Institute (ACI) [35], and MIDUVI [14] have been used for the structural evaluation of buildings. It is important to highlight that according to current regulations, buildings for hospital use must be designed as essential structures. They must be prepared to respond to elastic behaviour during a severe earthquake.

MIDUVI [14] presents the categories of structures according to their use, destination, and importance. In this investigation, block B4 was categorised as an Essential Building, whereas block B3 was categorised as other structure. In summary, the parameters used in this study for structural evaluation were based on the provisions of ASCE/SEI [34]. The most important parameters are summarised below.

(1) The Essential Structure for B4 and Other Structures for B3.

(2) The structural system of moment-resisting concrete frames with unreinforced masonry walls confined by beams and columns.

(3) Immediate occupation performance level before a seismic excitation level is equivalent to the Basic Security Earthquake (BSE-1E), whose return period is 225 years.

(4) Soil Type C (Profiles of very dense soils or soft rock).

3.3.3 Mathematical model and loads on the elements

This section describes the mathematical model of the most important structures of Humberto Molina Hospital. The columns and beams of the buildings were modelled using FRAME-type elements, whereas the floor slabs were modelled using SHELL (membrane) elements. The materials used for the various structural elements were determined based on the results of the tests (see section 3.2.2) and are as follows:

(1) Compressive strength f'c=150kg/cm^2 for the beams, columns, and slabs.

(2) Modulus of elasticity of concrete: Ec=185,000kg/cm^2

SAP2000 was used to perform elastic analyses of the structures [36].

Structural elements typically exhibit a certain level of cracking during a severe earthquake. However, some of the structures have been in service for several decades, and during this period, earthquakes have occurred. Therefore, it is convenient to use the effective inertia of the elements; that is, it is considered that the members present a certain level of cracking. According to MIDUVI [14], the stiffness of the elements must be as follows:

(1) Beams: Flexural stiffness=$0.50E_cI_g$
(2) Columns: Flexural stiffness=$0.80E_cI_g$ (compression)
(3) Walls: Flexural stiffness=$0.60E_cI_g$

where,

Ig: inertia moment

The models include rigid zones. The columns were embedded at the base of the building. The gravity loads used for the structural analysis are detailed below.

Slabs

(1) Total dead load≈700kg/m^2

Slab (ribbed, two directions)=330kg/m^2

Tiles=130kg/m^2

Facilities and ceiling =40kg/m^2

Walls =200kg/m^2

(2) Live load (staff in offices)=200kg/m^2

Metallic covers

(1) Total dead load≈20kg/m^2

(2) Live load=70kg/m^2

3.3.4 Structural analysis and rehabilitation alternatives

As described in the previous section, three-dimensional mathematical models developed in SAP2000 were used for the structural analysis. The analysis was performed according to the provisions contained in ASCE/SEI [33].

Similarly, a table was created where the general deficiencies of the blocks of the Humberto Molina Hospital are presented as the recommended structural rehabilitation alternatives. These recommendations are based on what is stipulated in MIDUVI [14] and the Federal Emergency Management Agency (FEMA) [37].

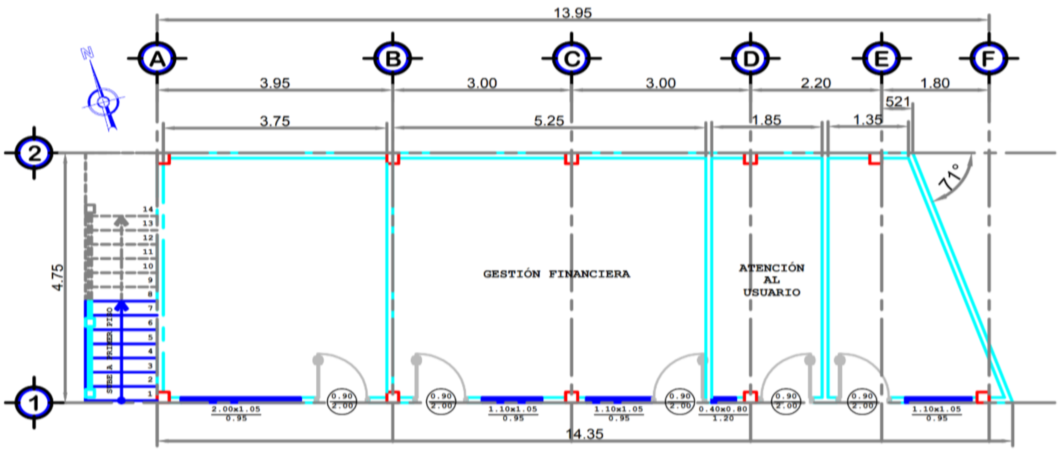
4. RESULTS

4.1 Initial survey

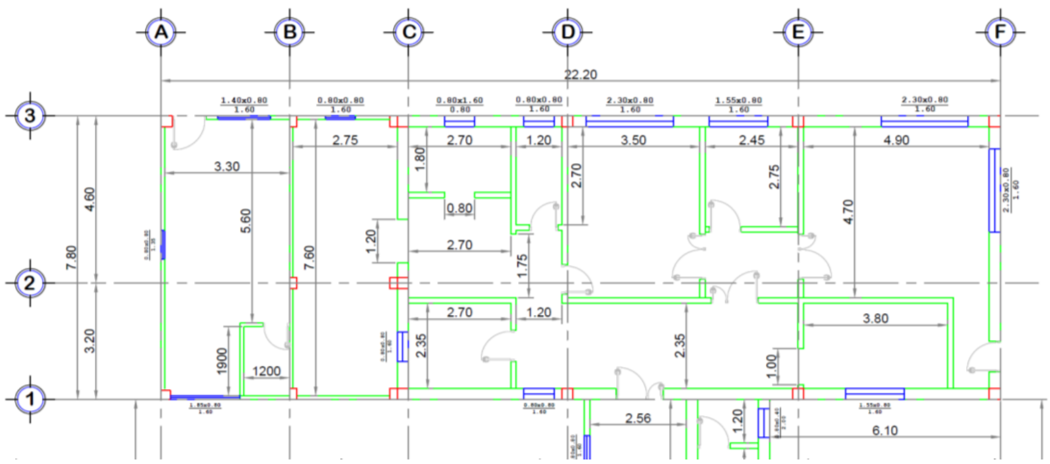
In the first part (data collection), initial inspections were conducted on B3 and B4 to obtain the dimensions of each block. Figure 6 shows the architectural plans of B3. It can be seen that both plants are irregular.

B3 is made of reinforced concrete in the first two mezzanines, whereas the last mezzanine is made of a metallic structure. According to auscultations, the structural system consists of moment-resisting concrete frames, with a ribbed slab-type horizontal system in one direction with band beams. Among the damage found were cut and vertical cracks in the masonry. Knocking between the administrative building (B3) and the San Juan Bosco school is possible.

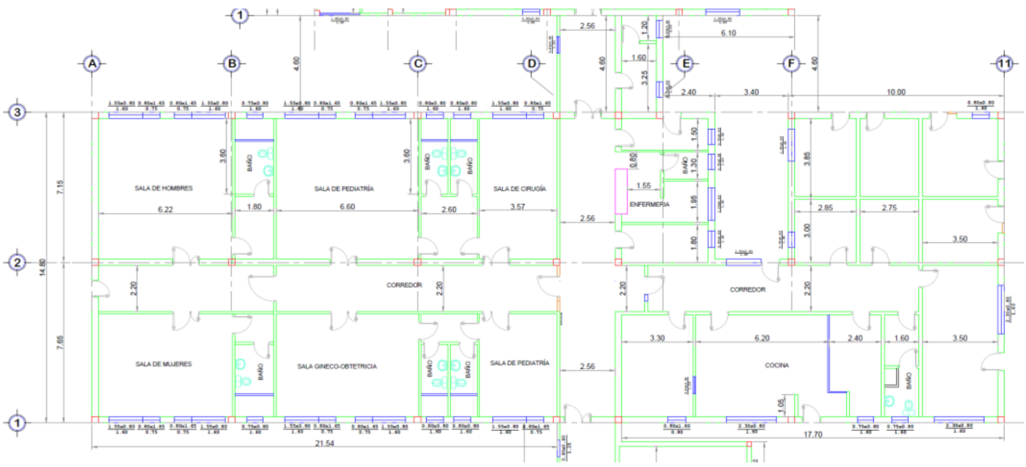
Block B4 is comprised of moment-resistant concrete frames. The building has an irregular shape without joints between the sub-blocks. B4 had no horizontal structural system because it was directly over the portico. Among the damages found inside B4, the following can be observed: a) Cutting cracks along the masonry surface; b) Joint formation at the floor level, damaging non-structural elements such as tiles; and c) Vertical cracks in the masonry and beams.



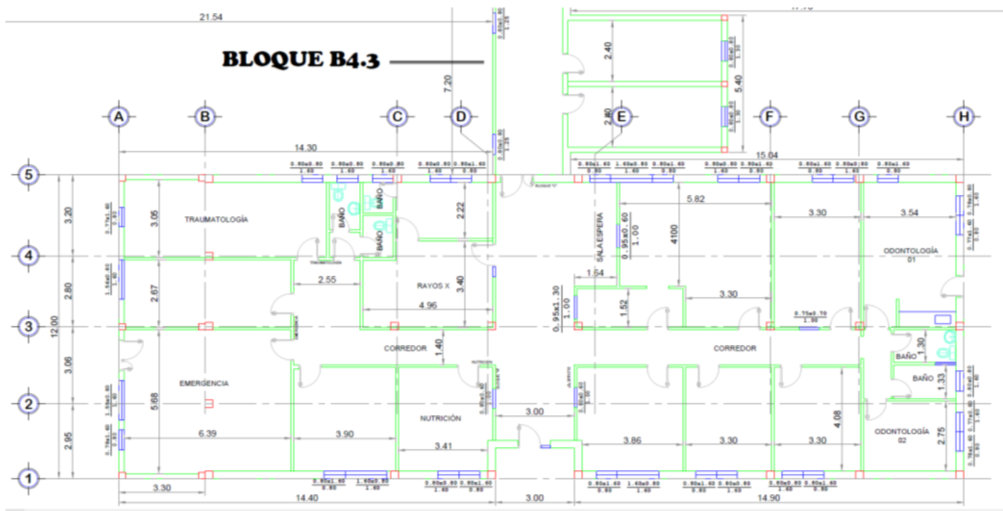
(a) B3 architectural plan



(b) B4.1 architectural plan (upper part of B4)

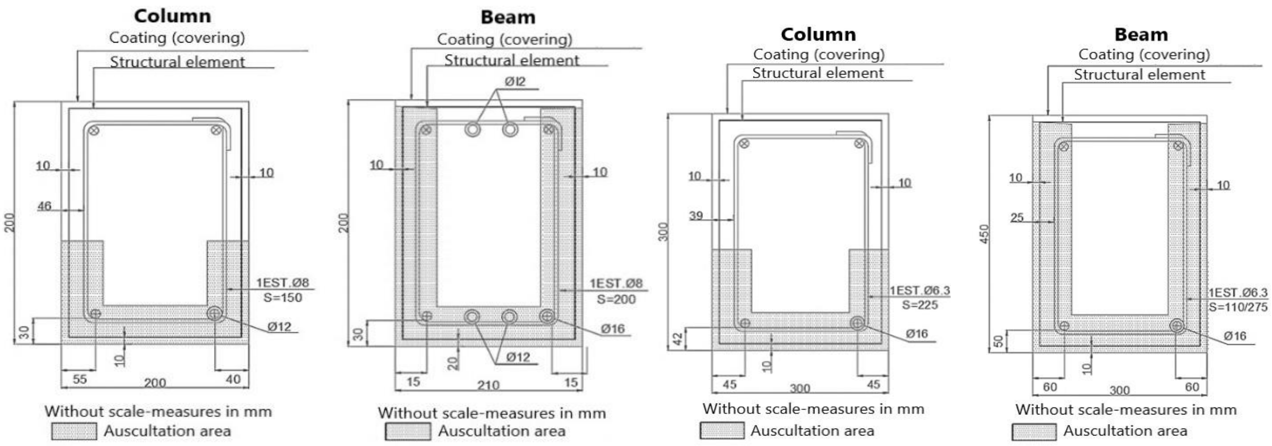


(c) B4.2 architectural plan (central part of B4)



(d) B4.3 architectural plan (lower part of B4)

Figure 6. Humberto Molina Hospital architectural plan and measurements



(a) Typical column and beam of B3

(b) Typical column and beam of B4

Figure 7. Typical section of B3 and B4

4.2 Material testing

Table 4 presents the results of the compression tests of seven concrete cores extracted from structural elements B3 and B4 (beams, columns, and masonry). The ASTM-C39 standard was used as the reference for these tests.

The cylinders had an average diameter of 43mm and a height of 90mm. The cylinders in beams had an average effort of 10.22Mpa; the columns had an effort of 13.30Mpa, and a masonry of 3.90Mpa.

However, owing to the auscultation of the structural elements, we were able to survey reinforcing steel. Representative diagrams of auscultation performed on the typical columns and beams of B3 Figure 7(a) and B4 Figure 7(b).

Table 3 shows the dimensions and compressive strength of the concrete adopted from the core tests and auscultations carried out on B3 and B4.

Table 4. Results of compression test on cores extracted from the hospital

No.	Block	Element	f´c (Mpa)
1	B4	Column	15.40
2	B4	Beam	12.50
3	B4	Column	8.40
4	B4	Beam	9.50
5	B4	Masonry	3.90
6	B3	Column	15.10
7	B3	Beam	8.40

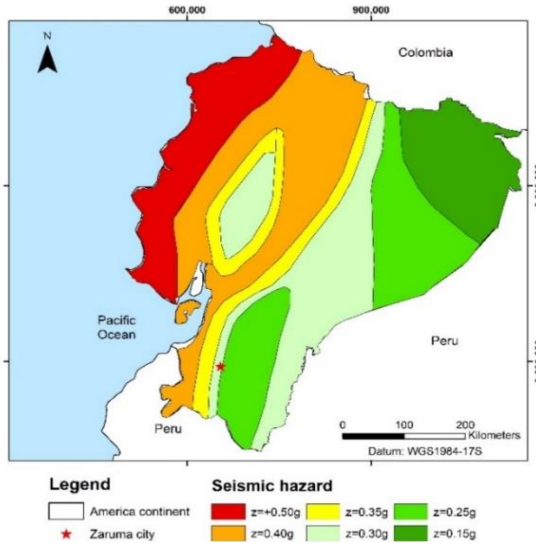


Figure 8. Ecuador seismic hazard map [14]

4.3 Seismic hazard

According to MIDUVI [14], Zaruma is located in seismic Zone III (Figure 8), corresponding to a Z factor of 0.30g. This factor indicates that the seismic hazard for Zaruma and its surroundings was high. The Z value of each zone represents the maximum rock acceleration expected for the design earthquake and is expressed as a fraction of the acceleration due to gravity [14].

Data of the most relevant earthquakes (magnitudes greater than Mw 5.5) were collected within an approximate radius of 250km from the study area, with a period from 1959-2019, to complement the information provided by the NEC Standard. Table 5 presents the most relevant earthquakes that occurred during this period.

According to Amagua [38], the earthquake on November 17th 2017 caused the evacuation and subsequent temporary hospital closure.

According to the MIDUVI standard [14], it is considered a type C soil (very dense soil or soft rock). Thus, the elastic response spectrum corresponding to the BSE-1E earthquake was obtained (Figure 9). For the construction of the inelastic range, a response modification coefficient of R=3.0 was considered because, from the structural survey, the components of the structural system have limited ductility.

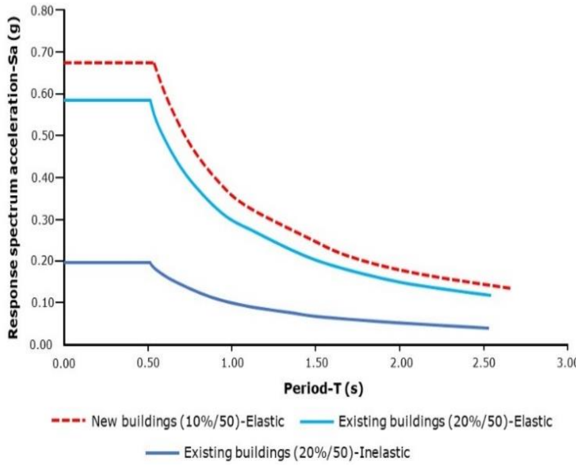


Figure 9. The elastic and inelastic response spectrum of the soil type of the Humberto Molina Hospital

4.4 Structural analysis

Due to the series of seismic deficiencies found in the building, it was decided to conduct a spectral modal analysis. The spectrum was applied in two mutually perpendicular directions (100% in one direction and 30% in the other). Accidental eccentricity was also considered. The load combinations used for the structural analysis, based on the provisions of ASCE/SEI 41-13 [34], are as follows:

$$1.1(D + 0.25L) + E \quad (1)$$

$$0.9D + E \quad (2)$$

where,

D: dead load

L: live load

E: seismic load

The seismic load was obtained from the response spectrum described in Section 4.2. (seismic hazards and response spectrum). With this, we conducted a structural analysis of B3 (Figure 10, Table 6 and Table 7) and B4 (Figure 11, Table 8 and Table 9).

Table 5. Earthquakes around Zaruma in a radius of approximately 250km from 1959-2019

Magnitude (Mw)	Description	Seismic Focus (km)	Distance to Zaruma (km)	Date
7	Ecuador-Peru border	24.4	217	10-02-1995
6.8		122.9	249	11-15-2007
6.		105.7	250	11-22-1986
6.5		16.7	217	10-03-1995
6.3		39.5	159	05-21-2005
5.8		12.3	230	10-07-1995
5.8		33.0	155	06-30-1997
5.6		33.0	230	10-02-1995
5.6		37.7	150	03-29-1991
5.6		56.9	150	02-10-1990
5.5	13km ESE of Balao	35.0	80	11-17-2017

Source: USGS [1]

Table 6. B3 periods

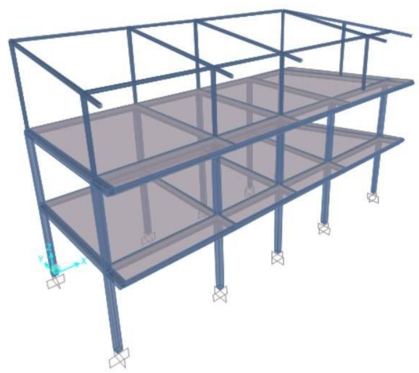
Vibration Modes	Direction	Period (s)
T1	X	0.98
T2	Y	1.01
T3	Z	0.89

Table 7. Results of the modal analysis of B3 of the Humberto Molina Hospital (X direction and Y direction)

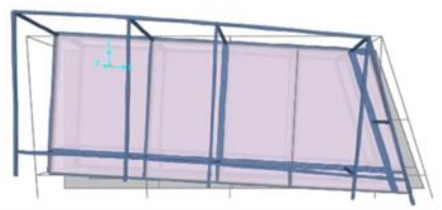
	X-axis					
	hx (m)	h (m)	Δ_I (m)	Δ_E (m)	θx	Δ_I (cm)
3	8.40	2.90	0.0623	0.1402	2.219	14.0175
2	5.50	2.70	0.0337	0.0758	0.000	7.5825
1	2.80	2.80	0.0337	0.0758	2.708	7.5825
0	0	0	0	0	0.000	0
	Y-axis					
3	8.40	2.9	0.0469	0.1055	0.628	10.5525
2	5.50	2.7	0.0388	0.0873	0.000	8.73
1	2.80	2.8	0.0388	0.0873	3.118	8.73
0	0	0	0	0	0.000	0

Table 8. B4 periods

Vibration modes	Direction	Period (s)
T1	X	0.35
T2	Y	0.36
T3	Z	0.33

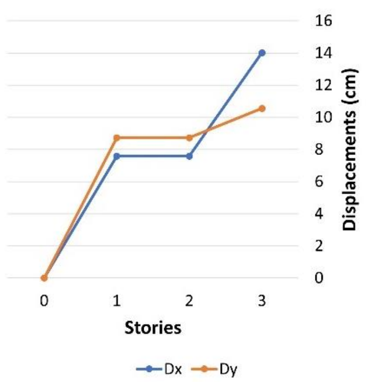


(a) 3D view of block B3

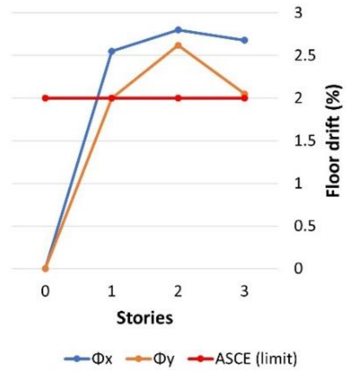


T1 = 0.98 s. (x)

(b) X-axis period

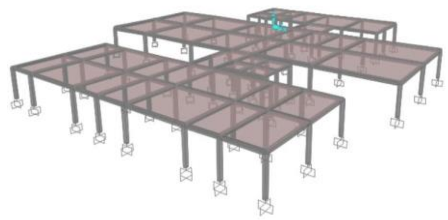


(c) Displacements in B3

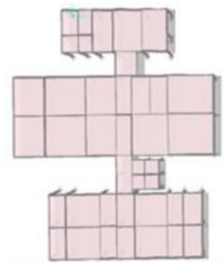


(d) Floor drift (%) in B3

Figure 10. Spectral modal analysis of B3

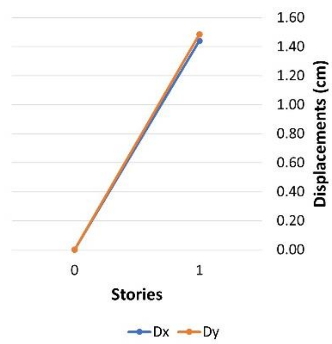


(a) 3D view of block B4

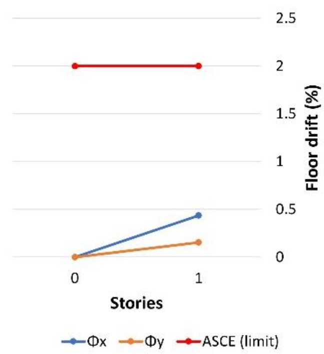


T1 = 0.35 s. (x)

(b) X-axis period



(c) Displacements in B3



(d) Floor drift (%) in B3

Figure 11. Spectral modal analysis of B4

Table 9. Results of the modal analysis of block B4 of the Humberto Molina Hospital (X direction and Y direction)

	hx (m)	h (m)	Δ_I (m)	Δ_E (m)	θx	Δ_I (cm)
X-axis						
1	3.30	3.30	0.0064	0.0144	0.436	1.44
0	0	0	0	0	0.000	0
Y-axis						
1	9.674	9.674	0.0066	0.0149	0.154	1.485
0	0	0	0	0	0.000	0.00

4.5 Rehabilitation alternatives

In general, most blocks exhibit similar seismic deficiencies. Next, Table 10 is presented, in which the structural weakness and the recommended structural rehabilitation alternative are listed.

Similarly, Table 11 shows the deficiencies presented by the masonry walls and the proposed rehabilitation techniques.

Table 10. Seismic deficiencies and rehabilitation alternatives for blocks B3 and B4

Deficiency	Rehabilitation Alternatives		
Deficiency	**Insertion of New Elements**	**Improve Existing Elements**	**Demand Reduction**
Low compressive strength of concrete and smooth rods	Adding walls	Increase element size[1]	Remove upper floors[1,2]
Torsion	Adding walls Adding braced frames Adding moment-resisting frames	Increase element size[1*]	
Inadequate shear and confinement strength		Increased column cross-section[1,2] Metallic shell[1,2]	

Source: modified from FEMA [37]
[1] Apply in B4 blocks.
[2] Apply only in B3.
[*] Alternative considered most suitable for the existing seismic deficiency.

Table 11. Non-structural deficiencies and rehabilitation techniques for B3 and B4

Deficiency		Rehabilitation technique
Non-structural elements	Minor cracks	Sealing cracks
	Cracks	Apply repair mortar
	Slender walls	Placing pillars or joists
	Unconfined cracked walls	Remove the wall and build a new one

Source: modified from FEMA [37]

5. RESULTS ANALYSIS

From the results obtained from the field inspections, the survey of structural elements, and their structural analysis, Tables 12-14 are presented the evaluations of the configuration of B3 and B4, as stipulated in international code ASCE/SEI 41-13. The methodology proposed in ASCE/SEI 41-13 is based on questions designed to detect possible structural deficiencies in buildings. The questions were formulated as affirmative evaluation statements describing the essential characteristics of the building necessary to mitigate the possibility of collapses observed in past earthquakes.

There are configurations within each block that do not comply with the national and international standards used (such as adjacent buildings (seismic joints), the existence of cracks in the masonry walls, masonry wall connection, the presence of a short column, and a high ratio of appearance of walls). Table 10 and Table 11 present solutions for each problem, as suggested by FEMA [37]. Figure 12 shows images of damage found in B3 and B4, respectively.

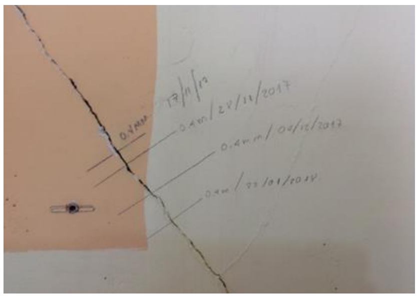
Below is a summary of the earthquake-resistant structural evaluation of B3 and B4.

(1) Building B3 is attached to the San Juan Bosco School block. Therefore, in the event of a moderate or severe earthquake, blocks may collide (knocking).

(2) Building B4 has an irregular plan; it does not have a regular configuration; therefore, it is susceptible to torsion in a moderate or severe earthquake.

(3) In B3, the dimensions of the structural elements (beams and columns) did not meet the minimum dimensions stipulated in the codes.

(4) The compressive strength of concrete is low (both in B3 and B4) and does not satisfy the minimum requirements stipulated in the current codes (210kg/cm^2).



(a) Measurements in crack in masonry of mezzanine 1 of B3

(b) Crack in subfloor in correspondence with joint in B4

Figure 12. Damage found in B3 and B4

(5) In B4, the auscultated rods are smooth. It was concluded that the yield stress of the reinforcing steel was 2800kg/cm^2. Consequently, the yield stress did not meet the minimum requirements stipulated in the current codes (4200kg/cm^2).

(6) In both blocks, the stirrups of the elements had 90-degree hooks. Consequently, the hooks used did not meet the seismic requirements stipulated in the current codes (at 135°).

(7) In B3, the walls have a thickness of 100mm. The slenderness ratio for this building is of the order of 27, which is considered unacceptable for areas of high seismicity and an immediate occupancy performance level.

According to Carrión-Mero et al. [39], areas surrounding the hospital present a potential instability condition because of the application of extreme conditions (e.g., seismic acceleration and soil saturation). They also recommended drainage control actions within the hospital area to reduce the surrounding saturation.

Likewise, Carrión-Mero et al. [40] complemented the research with the perception of the Zaruma population, where it was observed that 96.97% completely disagreed with the closure of the hospital. In addition, 95.45% of the respondents recommended immediate hospital reopening because they experienced difficulties going to other, more distant hospitals.

Table 12. B3 and B4 architectural configuration

Architectural Configuration	**Y**	**N**	**N/A**	**U**
Load path (The structure must contain a complete and well-defined load path)	X			
Adjacent buildings (Distance between buildings greater than 4% of the height of the smaller building)		X		
Mezzanine (braced independently of the main structure)			X	
Vertical irregularity (vertical elements are continuous with the foundation)	X			
Geometry (changes less than 30% between the dimensions of adjacent floors)	X			
Mass (less than 50% changes between the masses of adjacent floors)	X			
Overturning (base/building height ratio is greater than 0.6 Sa)	X			
B4				
Load path	X			
Adjacent buildings (seismic joint)		X		
Mezzanine			X	
Vertical irregularity	X			
Geometry	X			
Mass	X			
Overturning	X			

Y: Yes, it does comply; NC: No, it does not comply; N/A: Not applicable; U: Unknown

Table 13. B3 and B4 material condition

B3				
Material Condition	**Y**	**N**	**N/A**	**U**
Deterioration of steel reinforcement	X			
Concrete deterioration	X			
Masonry joints	X			
Masonry elements	X			
Cracks in masonry walls		X		
Cracks on edge columns	X			
B4				
Deterioration of steel reinforcement	X			
Concrete deterioration	X			
Masonry joints	X			
Masonry elements	X			
Cracks in masonry walls		X		
Cracks on edge columns	X			

Table 14. B3 and B4 structural system

B3				
Structural System	**Y**	**N**	**N/A**	**U**
Redundancy (The number of moment-resisting frame lines in each main direction is greater than or equal to 2)	X			
Masonry wall connection (Masonry is in full contact with the frame)		X		
Column-foundation connection	X			
Flat slab (Slabs have continuous bottom steel through column joints)	X			
Wall aspect ratio hw/t (The height-thickness ratio of unreinforced infill walls on each story is less than 13)		X		
Masonry Wall Continuity (Short Column)		X		
B4				
Redundancy	X			
Masonry wall connection	X			
Column-foundation connection	X			
Flat slab			X	
Wall aspect ratio hw/t	X			
Masonry Wall Continuity (Short Column)	X			

6. CONCLUSIONS

This study structurally evaluated the B3 and B4 reinforced concrete blocks of Humberto Molina Hospital through field visits, analysis of the materials, and comparison with national (NEC-15) and international (ASCE/SEI) standards. This made it possible to determine the vulnerability and level of seismic performance of the structural system of hospital buildings for the proposal of structural rehabilitation strategies according to the techniques recommended by FEMA.

Ecuador has a high seismic activity that affects the stability and functionality of its buildings, as in the case of the Humberto Molina Hospital in Zaruma. This infrastructure has been in operation for almost 50 years. The Hospital does not have necessary adjustments or maintenance during its years of operation. Regarding the structural design of the hospital elements, it can be indicated that:

(1) The compressive strength of the concrete in the columns, beams, and slabs analysed was low (approximately 150kg/cm^2) and did not meet the minimum requirements stipulated in NEC-15 and ACI code (210kg/cm^2).

(2) The auscultated rods are smooth; therefore, it is concluded that the yield stress of the reinforcing steel used is 2800kg/cm^2. Consequently, the yield stress did not meet the minimum requirements stipulated in NEC-15 and ASCE/SEI codes (4200kg/cm^2).

(3) The stirrups of the elements had hooks at 90°. Consequently, the hooks did not meet the seismic requirements stipulated in NEC-15 and ASCE/SEI codes (135°).

(4) According to the interviews, expansions in B3 and B4 were informally conducted. For this reason, in the event of a moderate-to-severe earthquake, B3 can be struck (because of its proximity to a block from the San Juan Bosco School), while B4 has the possibility of twisting (due to its irregular shape).

The fundamental aim of seismic rehabilitation for each block is to improve the performance of the structures in the face of moderate or severe seismic events. For blocks B3 and B4, an increase in the section of the structural elements is proposed to improve the existing conditions of compression and torsion. Additionally, the removal of the upper floors of block B3 is proposed to reduce the demand for structural elements.

The structural characterisation, evaluation, analysis, and proposal of rehabilitation alternatives in B3 and B4 will facilitate decision-making by the authorities of the Risk Management Secretariat (SGR), Ministry of Health Public (MSP) and Zaruma Mayor's office. The Humberto Molina Hospital is considered vital for the health and well-being of approximately 45,000 people.

The rehabilitation strategies selected for block B3 consisted of reducing the mass/load in the structure, such as eliminating the top floor (representing 700kg/m^2 of dead load and 200kg/m^2 of live load). In addition, it is recommended that the section of the beam and column elements be expanded to improve their seismic performance. In block B4, it is proposed to make the sub-blocks independent and to avoid torsion in the event of an earthquake.

The methodology presented in this study will serve as a model to be replicated in other hospitals or other health buildings in Ecuador with the same or worse conditions than Zaruma Hospital. Because Ecuador is a country with constant geodynamic risk and has hospital structures with many years of service, its application in these cases is necessary. Reproducing it in essential facilities in other countries is also possible, but it is necessary to review national standards and seismic spectra.

The current study presents a limited number of concrete cores, which is dependent on the budget of the current research project. Expanding the study by investigating the other six blocks of Humberto Molina Hospital is possible. Thus, there is security in all facilities within the hospital. The realisation and interpretation of the shear/moment diagrams must be completed to observe the behaviour of the elements under seismic conditions.

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