Disaster Medicine and Public Health Preparedness

www.cambridge.org/dmp

Original Research

Cite this article: Estrella-Villarreal C, Ospina-Ostios L and Díaz-Tamayo A (2024). Exposure to Seismic Hazard in a High-Complexity Hospital in Cali, Colombia. *Disaster Medicine and Public Health Preparedness*, **18**, e301, 1–8
https://doi.org/10.1017/dmp.2024.313

Received: 05 August 2024
Revised: 12 October 2024
Accepted: 23 October 2024

Keywords:
seismic hazard; risk management; hospitals; emergency medical services; geographic information systems

Corresponding author:
Camilo Estrella Villarreal;
Email: camilo.estrella.v@gmail.com

Exposure to Seismic Hazard in a High-Complexity Hospital in Cali, Colombia

Camilo Estrella-Villarreal[1], Lina Ospina-Ostios[2] and Alejandra Díaz-Tamayo[3]

[1]University of Salamanca, Salamanca, Spain; [2]Department of Geography, School of Humanities, Universidad del Valle, Cali, Colombia and [3]Technology Program in Prehospital Care, School of Medicine, Universidad del Valle, Cali, Colombia

Abstract

Objectives: The project aimed to characterize the exposure to seismic hazard in the emergency area of a high-complexity hospital in Cali, Colombia.
Methods: The occupancy of the emergency area was analyzed over 6 months, determining the value of material elements exposed to the seismic hazard. Four phases were executed: search for pre-existing information, occupancy analysis, evaluation of exposed assets, and results analysis. The information was analyzed using a Geographic Information System (GIS), which allowed the visualization of demographic behavior in different locations and times.
Results: The results confirmed that the seismic hazard is high, exacerbated by local geomechanical characteristics. It was observed that the average occupancy of most studied areas exceeded capacity. The value of the exposed assets was estimated at COP 3 221 008 640 (USD 959 844.76), the demolition value at COP 10 582 770 000 (USD 3 153 613.49), and the reconstruction value at COP 30 293 640 275 (USD 9 027 356.03). In the worst-case scenario, the losses were equivalent to 12.4% of the hospital's annual budget.
Conclusions: The data allow the hospital to take preventive measures and educate the staff to identify and mitigate critical areas. It also contributes to the knowledge of the approximate value of economic losses and the impact of potential human losses.

Risk is the combination of hazard, vulnerability, and exposure. Thus, it is a function of the decisions made and how they are implemented, shaping the world around us.[1] In general, it is directly proportional to hazard, exposure, and vulnerability and inversely proportional to the capacity for mitigation,[2] where exposure refers to the presence of people, environmental services, livelihoods, economic and social resources, cultural goods, and infrastructure, which, by their location, may be affected if a hazard manifests.[3]

Discussing exposure to seismic hazard involves geographically situating the study area to understand the variables to be developed more clearly. Colombia is in a region where 3 major tectonic plates interact: the Nazca plate, the Caribbean plate, and the South American plate, which configure the highest seismic activity in the country (Figure 1). This configuration places a large part of the country, particularly the city of Cali, in a zone classified as having high seismic hazard.[5] This is supported by the occurrence of several significant magnitude and intensity earthquakes that have historically affected the city, such as those in 1776, with an epicenter in the city of Buga;[6] Valle del Cauca in 1925, with an epicenter in the city of Cali;[7] Pizarro in 2004, with an epicenter in Chocó;[8] among the most notable; and this seismic behavior is expected to remain a common denominator in the future.

The hospital where the study was conducted is in the third-most populated city in the country and is also the largest hospital in southwestern Colombia. As a university hospital, it not only provides health care services but also engages in research and medical teaching, hosting students from various health fields who carry out their clinical practices there.

The construction of the hospital began in 1936 under the direction of the firm Guillermo Garrido Tovar. It was completed in 1940 by the architect Hernando Vargas Rubiano, but it was not until 1956 that it began operations, being the only center that provided emergency services in the region. In 1973, the expansion of various services allowed for greater care capacity. In the 1990s, adjustments were made to its physical plant,[9] and in 2019, an architectural renovation was completed within one of the emergency areas,[10] which was considered for the present occupancy analysis.

Emergency services are vital for hospitals as they are responsible for receiving, stabilizing, and treating patients who require immediate medical attention due to their critical conditions. These areas have a high flow of workers, patients, families, and students.

Given the limited number of studies that emphasize the analysis of seismic hazard exposure in essential buildings, conducting research in this area is crucial. These studies are important for mitigating risk through various methodologies, as identifying the exposed elements allows for

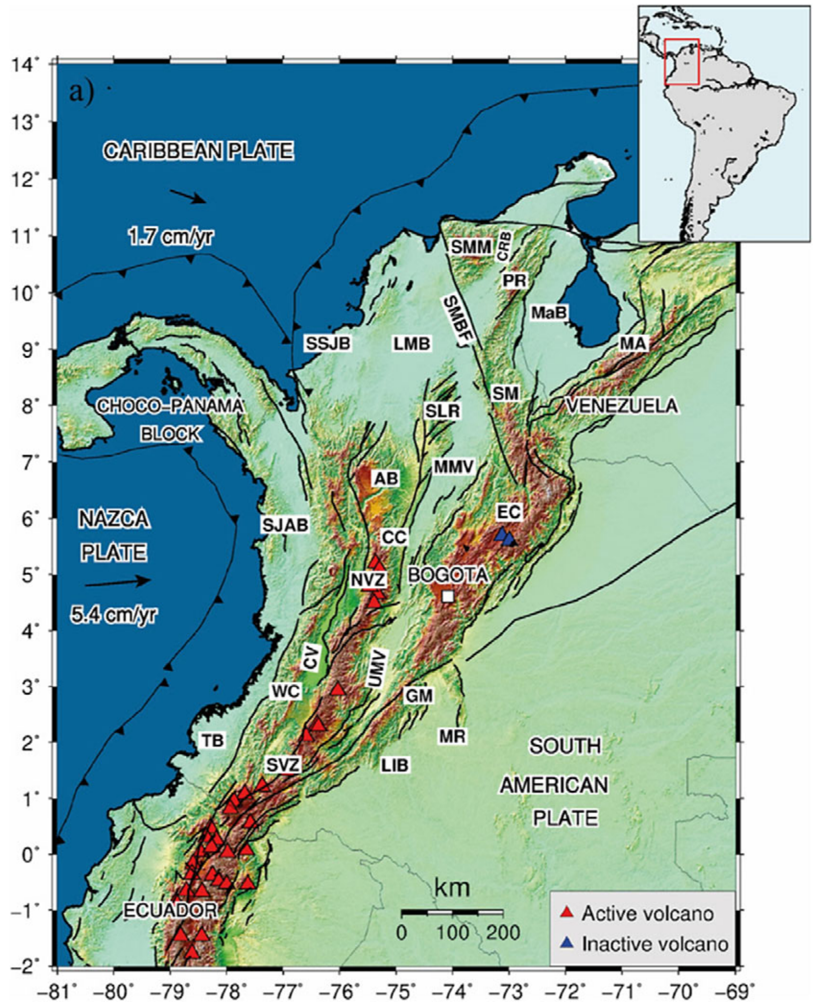

Figure 1. Tectonic map of northwestern South America. Black arrows indicate the relative movement of the tectonic plates.[4]

proper planning in the development of evacuation plans. They also identify areas with a higher concentration of people and where the most valuable assets are located.

The research aimed to characterize the exposure to seismic hazard of the elements in the hospital's emergency area: health care personnel, patients, visitors, students, physical infrastructure, and other material elements.

Methods

The research corresponds to a retrospective descriptive study, which was conducted by collecting information mainly stored in databases and archives of various hospital departments.

The research area belongs to the hospital's north wing (emergency area), composed of the following subareas: triage, resuscitation room, emergency intensive care unit (ICU), pediatric emergencies, trauma rooms I and II, internal medicine, and other multipurpose spaces.

The phases developed during the research are presented below:

Search for Pre-existing Information

Collection of hospital-specific information, including recent architectural plans of the areas of interest, vulnerability studies, and hospital physical registry.

Additionally, macroseismic information related to Cali, including historical seismicity and the results of the Seismic Microzonation Study of Cali[11], was compiled and included.

A regional and local macroseismic profile was constructed with the macroseismic and microseismic information, and the microseismicity associated with the study area was analyzed.

Occupancy Analysis

The information was collected over 6 months. The analyzed variables correspond to the number of patients by clinical areas, general practitioners, specialists, nurses, nursing assistants, visitors, and administrative staff; additionally, security personnel, cleaning staff, and stretcher-bearers were considered.

The occupancy information was obtained through the hospital's Central of Reference and Counter-Reference (CRYC) databases, which generate patient reports every 12 hours.

The number of healthcare professionals and nursing assistants was obtained through the shift schedules provided by the administrative section of the hospital's emergency area. The number of students in practice was obtained with the collaboration of the Hospital Teaching and Extension Office.

The administrative and non-medical staff data were collected through visits on different days and times to construct a better population behavior model.

The number of visitors was assumed to be the maximum expected to model the most critical situation, where each patient is allowed 1 visitor at a time within the institution.

Evaluation of Exposed Assets

The list of exposed assets was obtained through the hospital's inventory office, and their value was provided with the depreciation of December 2019.

The value per square meter of the building was determined as the average by a source consulted regarding the construction cost of a clinical building for the National University of Colombia. This value was updated to the present using annual inflation. Additionally, a professional opinion from a professor at the School of Civil and Geomatics Engineering of the Universidad del Valle was considered, who also provided an approximate demolition cost per square meter for the current structure based on her experience.[12]

The variables considered were the location of the asset, according to the cost center associated with each clinical area, the type of asset, the number of assets per type, and the value of the assets per type.

The variables were analyzed by finding the total number and value of assets and their relationship with each clinical and administrative area, both in percentage and value. Likewise, the total value per square meter of the hospital's emergency area was determined.

Results Analysis

The collected information was input into a Geographic Information System (GIS) to facilitate its presentation and analysis, placing the population in the emergency area at different times. The software used was ArcGIS®.

Results

Seismic Characteristics of the Study Area

Because of the country's seismotectonic characteristics, 3 types of seismogenic sources are recognized in the study area: cortical (shallow), Pacific subduction zone (interplate), and Benioff zone.[13] To understand the characteristics of the seismic hazard affecting the study area, it is crucial to consider its location in the city of Cali and the department of Valle del Cauca.

According to the 2010 Colombian Seismic Resistant Code (NSR-10), there are 3 types of seismic hazard applicable to buildings: high, intermediate, and low. The city of Cali, the capital of the department of Valle del Cauca, is classified within the code as a high seismic hazard zone.[14] This is reflected in the high seismic activity observed in the region. Earthquakes of different impacts have occurred in Cali throughout history, with the oldest recorded earthquake being in 1566.[15]

Locally, Cali's seismic microzonation allows for understanding the specific characteristics of the soil and subsoil of each zone in the city. This confirms the hospital's particular situation due to its location within Zone 3 (Foothills), further complicating its seismic outlook. Other structures, such as parking lots and green areas on colluvial soil and Zone 1 (Hills), also have this situation.[16]

In the design spectrum resulting from the calculations of the characteristics of each type of soil, it can be observed that Zone 3 presents spectral acceleration values among the highest in the city, after the Cañaveralejo Fan (alluvial fan) (Table 1). This places the hospital's emergency area in one of Cali's highest seismic hazard zones. Combined with other historical, regional, and local seismicity factors, these characteristics are essential when designing and constructing such a vital special-use structure for the city, the department, and the region.

Table 1. Control parameters for the design spectrum construction

Seismic response zone		SA
Zone 1: Hills		0,45
Zone 2: Flux and residual soil		0,75
Zone 3: Foothills		**0,85**
Zone 4A: Influence zone of middle Cali		0,75
Zone 4B: Influence zone of distal Cali and Menga	Ss	0,65
	S1	0,50
Zone 4C: Influence zone of Cañaveralejo	Ss	1,00
	S1	0,65
Zone 4D: Influence zone of Meléndez and Lili		0,62
Zone 4E: Influence zone of Pance		0,57
Zone 5: Transition to influence zone - grassland	Ss	0,70
	S1	0,52
Zone 6: Alluvial grassland		0,68

SA: Maximum Spectral Acceleration, Ss: Short Period Spectrum, S1: Long Period Spectrum. Adapted.[16]

Occupancy Characteristics

The hospital's emergency area comprises 2 floors where different clinical specialties, administrative spaces, and complementary areas are distributed. The following is located on the first floor (Figure 2a): waiting room, doctors' offices, pharmacy, plaster room, emergency intensive care unit (ICU), pediatric emergency room, trauma center, resuscitation area, emergency procedures room, billing department, emergency department administration and management, and the CRYC. The following are situated on the second floor (Figure 2b): clinical decision unit (CDU), emergency room observation unit, and surgical observation unit (SOU).

For each area where patients are located, data on the number of patients and occupancy for day and night shifts are available, each completing a 12-hour block and data for 24 hours or the entire day. The results are presented as a daily average.

The occupancy analysis of the different clinical areas on both floors showed that most of these emergency areas are over-occupied, with a peak in July. This occupancy is related to the number of patients, not the medical and non-medical staff.

Additionally, with the help of ArcGIS, the occupancy results are presented spatially within the structure's layout (Figure 3), using color scales to identify the areas with higher or lower occupancy percentages.

Figure 4(b) presents the monthly average number of people in each clinical area. This value is directly related to occupancy, as patients represent a very high percentage of the total number of people in the different zones of the emergency area.

The total number of people in the different areas includes patients, medical staff, administrative staff, support staff, visitors, and others. Figure 4 (c) notes that up to twice as many people can be on floor 1 compared to floor 2 and the peak demographic values in different months.

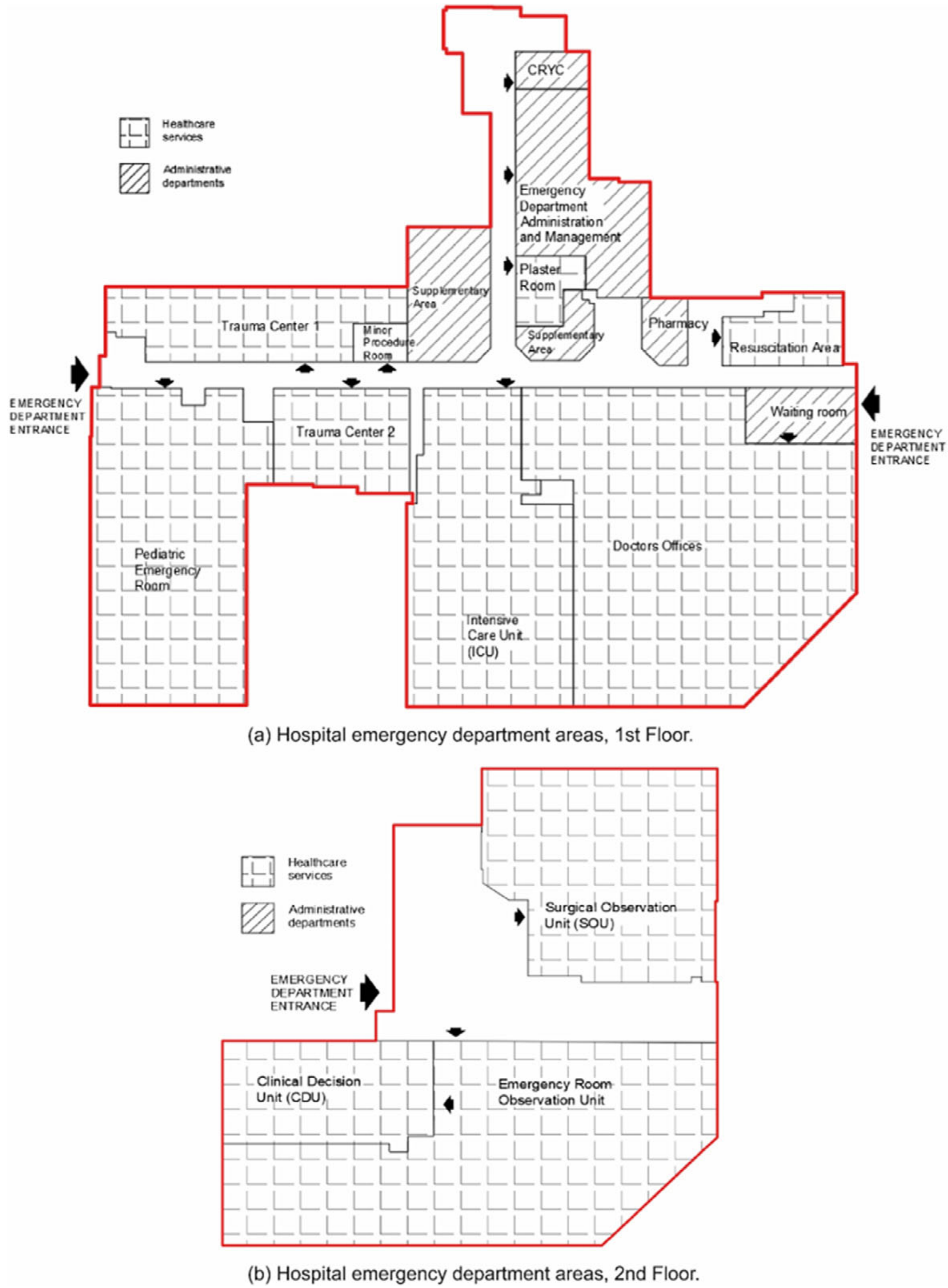

Figure 2. Floors 1 (a) and 2 (b), hospital emergency area. Adapted from.[10]

The total number of people on the different floors of the hospital is distributed in defined areas. The average of these data is presented in Figure 4 (a). Doctors' offices and the emergency room observation unit have the highest average number of people.

In addition to this monthly analysis, a weekly analysis was conducted, obtaining the days and shifts with the highest number of people. Figure 4 (c, d, and f) shows the behavior for each floor and the total emergency area.

For the entire emergency area, Figure 4 (f) shows that the highest peak of people occurs on Fridays, and in all cases, the concentration of people is higher during the day than at night. The lowest value was recorded on Saturday during the day and Monday night.

Figure 3. Average monthly occupancy rate. (a) 1st floor. (b) 2nd floor.

Characteristics of Exposed Assets

The list of exposed assets was filtered for the emergency area and each associated cost center. The total number of assets is 1478, and their value in Colombian pesos amounted to $3 221 008 640 (approximately USD 959 844.76).

Table 2 presents the relationship of assets to the total for each of the cost centers and their value. Over 35% of the assets are distributed among pediatric emergency room, trauma, and resuscitation, while more than 50% of the asset value is found in the emergency room observation unit and ICU.

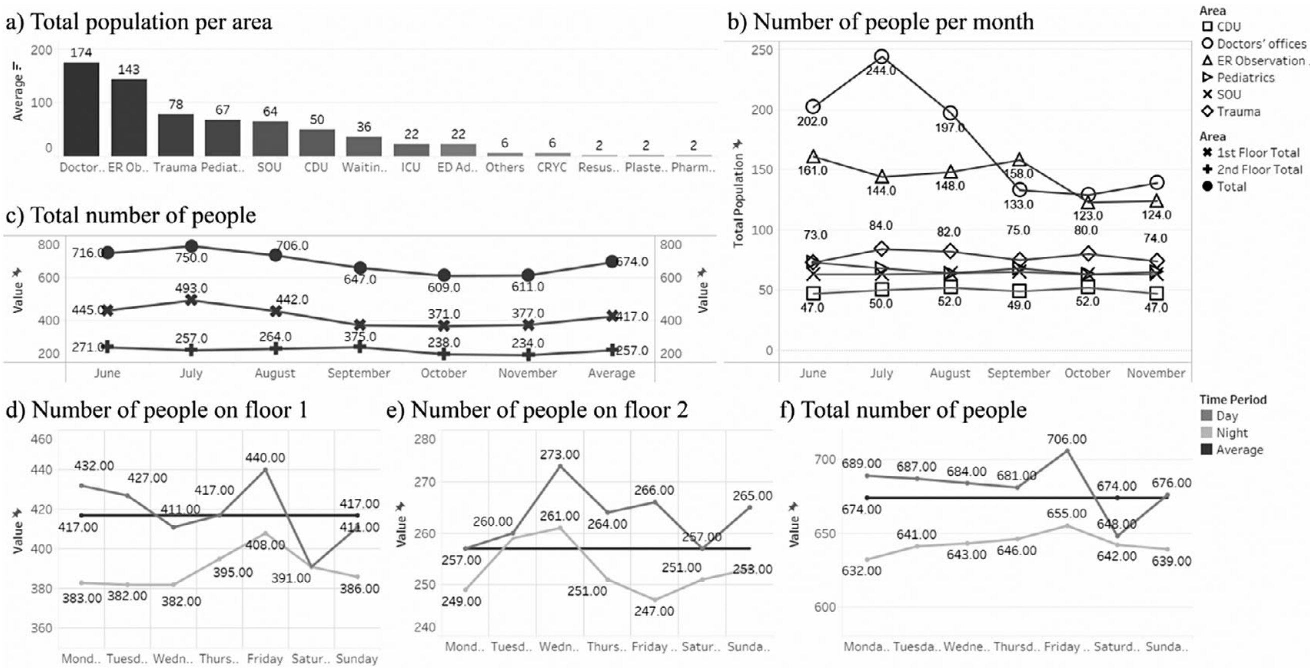

Figure 4. (a) Total population by area. (b) Number of people per month. (c) Total number of people. (d) Number of people on floor 1. (e) Number of people on floor 2. (f) Total number of people.

Table 2. Assets per cost center as a percentage of total assets and their value

Cost center	% assets total	% assets total value
Coordination between emergency and urgent care departments	10,89	2,68
Trauma Center and Resuscitation Area	15,22	10,93
CRYC (hospital database)	5,14	3,90
Surgical Observation Unit (SOU)	9,40	7,51
Doctors' offices	5,01	4,87
Emergency Room Observation Unit	9,40	27,47
Pediatric Emergency Room	20,77	11,72
Intensive Care Unit (ICU)	8,86	30,91

In addition to the exposed assets, the cost of the structure, including demolition and reconstruction costs, must be considered if it is affected by an earthquake. According to Cano,[12] the demolition cost of the resulting structure can vary between COP 2 000 000 and COP 3 000 000 (approximately between USD 596 and USD 894 using an average exchange rate of COP 3355.76) per square meter.

Two sources were used to calculate the construction cost of the new building. Cano[12] estimated the construction cost to be COP 6 000 000 (USD 1788) per square meter. The second source corresponds to the data obtained from the construction project of a university hospital for the National University of Colombia, Bogotá campus, which included the construction of an ambulatory care facility with an area of 3038 square meters and a cost of COP 21 200 000 000 (USD 6 317 496).[17] The construction cost per square meter was estimated at COP 6 978 275 (USD 2079).

Based on the cost per square meter and applying inflation for each year,[18] the current cost for this project's ambulatory care facility structure for 2020 was obtained. The results are shown in the following table (Table 3).

Table 3. Annual construction cost of an ambulatory care facility for the National University of Colombia

Source	Year	Inflation	**Value per m^2**
University hospital National University of Colombia	2008	7,67	$ 6.978.275
	2009	2,00	$ 7.513.509
	2010	3,17	$ 7.663.779
	2011	3,73	$ 7.906.721
	2012	2,44	$ 8.201.642
	2013	1,94	$ 8.401.762
	2014	3,66	$ 8.564.756
	2015	6,77	$ 8.878.226
	2016	5,75	$ 9.479.282
	2017	4,09	$ 10.024.340
	2018	3,18	$ 10.434.336
	2019	3,80	$ 10.766.148
	2020		**$ 11.175.261**

With the obtained data, an average of both sources was used to approximate the construction cost per square meter for the study area, resulting in a value of COP 8 587 631 (USD 2559).

The areas of each section of the hospital's emergency area were calculated, and the values per square meter for each section, including assets and construction per square meter, were determined. Additionally, the total construction value for the entire study area amounted to COP 30 293 640 275 (USD 9 027 356).

https://doi.org/10.1017/dmp.2024.313 Published online by Cambridge University Press

Limitations

During the development of this project, administrative, accounting, and statistical limitations were encountered. Administratively, many barriers related to accessing information had to be overcome. The hospital's cost and inventory office has reports on the hospital's assets divided by administrative areas, but these reports only include certain information. It was impossible to access a consolidated database of all assets in the emergency area. The value of the missing assets is also significant within the potential material losses, which were not considered in this study.

Knowing the exact number of people present in the emergency area at all times is statistically complex, and because it involves a floating population, statistical biases or errors may arise, preventing an accurate understanding of population behavior.

Despite the limitations related to obtaining information, this project generates results with a focus that has not been previously presented for essential structures such as hospitals, making it useful as an approach to a more comprehensive study applied to them.

Discussion

Latin America and the Caribbean are prone to experiencing the impact of earthquakes due to their location on the "Ring of Fire," where several tectonic plates converge along the Pacific Ocean. As part of this region, Colombia presents a high hazard for such events. Therefore, institutions providing health services must be aware of their seismic hazard, specifically the areas responsible for immediate response to such events. This research aimed to characterize the exposure to seismic hazard in the emergency area of a high-complexity hospital in southwestern Colombia, one of the most important university hospitals in the region and the country.

The macroseismic information of the city reports that this structure is in a high seismic hazard zone, which, combined with the hospital's microseismic location characteristics, causes the emergency area of the building to experience higher acceleration values than most buildings in the city. Other Latin American studies[19,20] have reported similar characteristics regarding the location of health institutions in high seismic risk areas, highlighting the importance of understanding the ground on which the structure is located to undertake preventive actions that minimize the loss of human lives and goods and services.

In addition to the aforementioned hazard, human lives, and material goods are also at risk. Patients, family members, and visitors are part of the exposed population. Patients represent most people within the building and, thus, have the most significant statistical impact because they do not represent a volatile or mobile population, placing them in a position of permanent exposure to seismic hazard due to strict schedules and precise spatial location within the building. Administrative and health care workers typically circulate through different spaces, working shifts that permanently locate them within the emergency area. These 2 populations are essential for this study, representing a specific, constant exposure in different spaces. Therefore, they should be the first group to consider developing capacities to respond to the occurrence of the seismic phenomenon adequately. Similar studies[21] have determined that health care institution staff must be continuously trained to respond quickly to an emergency that affects their integrity and that of patients requiring rapid evacuation due to their condition.

Material losses are an essential factor in the occurrence of this phenomenon due to the social and economic impact that must be considered when managing risk correctly. This research found that the planning area of this institution did not have a database that included all the assets present in the emergency area. This limits the knowledge of the economic losses of these assets, making it impossible to accurately estimate the impact of potential material losses and adequately analyze whether the institution has the resilience capacity to face future risk scenarios. Other developing countries[22] have also described that knowing the exposed assets also ensures that hospitals remain operational during disasters, meaning creating and updating inventories of these elements and equipment is crucial. As mentioned by the UNDRR,[23] people in poorer countries are comparatively more likely to need medical care or shelter and to suffer the consequences of damage to critical infrastructure (including loss of essential services and damage to schools, health centers, and workplaces).

Conclusions

The previously described hazard exposes both assets and human lives. Among the latter, patients represent most people in the building and consequently have a more significant statistical impact.

The 2 populations with the highest exposure are administrative workers and health care workers. Because they do not represent a volatile or mobile population like the patients, the former is permanently exposed to seismic hazard due to strict schedules and specific spatial locations within the building. The latter, while they typically circulate through different spaces, work shifts that also permanently locate them within the emergency area. These 2 populations are essential for this study, representing specific, constant exposure in different spaces. Therefore, they should be the first group considered for developing capacities to face the seismic phenomenon.

On the other hand, material losses are also significant, as they bring a social and economic impact that must be considered when properly managing risk, especially because this type of structure is essential and represents the first line of hospital medical care in the event of such an occurrence. As evidenced in the Armenia (Colombia) earthquake of 1999 or the Turkey earthquake of 2023, the impact on this type of infrastructure significantly increases the event's severity.

This study provides essential values that the hospital can use to effectively take preventive or educational measures, to identify critical areas with the highest number of people, and to facilitate the implementation of evacuation routes according to that number. It also contributes to understanding the approximate value of economic losses, which will help make decisions about relocating assets to safer areas, understanding the impact of material loss, and analyzing if there is adequate resilience capacity in future risk analyses.

References

1. **United Nations Office for Disaster Risk Reduction (UNDRR)**. Understanding Risk. Published 2024. Accessed April 14, 2023 https://www.undrr.org/building-risk-knowledge/understanding-risk
2. **Aristizábal GL, Pérez J.** Metodologías para Evaluar la Amenaza, Vulnerabilidad, Exposición y Riesgo por Ciclones Tropicales. Published 2018. https://repositorio.gestiondelriesgo.gov.co/bitstream/handle/20.500.11762/27226/Metodologias_evaluar_amenaza_ciclones%20tropicales.pdf?sequence=4&isAllowed=y
3. **Congreso de Colombia**. Ley 1523 de 2012. Published 2012. http://portal.gestiondelriesgo.gov.co/Documents/Normatividad/LEY%201523%20DEL%2024%20DE%20ABRIL%20DE%202012.pdf
4. **Mojica Boada MJ, Poveda E, Tary JB**. Lithospheric and slab configurations from receiver function imaging in northwestern South America, Colombia. *J Geophys Res Solid Earth.* 2022;**127**(12):e2022JB024475.

5. **Servicio Geológico Colombiano (SGC)**. Resultados de Amenaza en Roca. Published 2018. https://amenazasismica.sgc.gov.co/map/co18_results_rock_grid/#5/4.600/-74.265
6. **Espinosa A.** El terremoto de Buga del 9 de Julio de 1766. Análisis histórico y geotécnico. *Rev Acad Colomb Cienc Exactas Fis Nat.* 1996;**20**(77): 247–258.
7. **Salcedo-Hurtado E de J**, **Blandón J Ríos L.** Reevaluación de intensidades macrosísmicas del terremoto del 07 de junio de 1925 en Colombia. *Boletín de Geología.* 2021;**43**(3):35–61. doi:10.18273/revbol.v43n3-2021002
8. **El Tiempo**. Sismo a las 4:06 de la madrugada. Published 2004. https://www.eltiempo.com/archivo/documento/MAM-1591237
9. **Hospital Universitario del Valle (HUV)**. Quienes Somos. Historia. Published 2020. https://huv.gov.co/index.php/quienes-somos/
10. **Quintero LA**. Información Necesaria para Caracterización de Amenaza Sísmica del Área de Urgencias. Published 2019.
11. **Ingeominas**. Estudio de Microzonificación Sísmica de Santiago de Cali. Informe No. 5-2. Published 2005. http://recordcenter.sgc.gov.co/B7/21003002515005/documento/pdf/2105150051120000.pdf
12. **Cano SL**. Private Communication. Published 2020.
13. **Servicio Geológico Colombiano (SGC).** Modelo Nacional de Amenaza Sísmica para Colombia. Published 2018. http://recordcenter.sgc.gov.co/B23/656_19ModeloNalAmenSismparaColombia/Documento/Pdf/ModeloNacionaldeAmenazaSismicaparaColombia.pdf
14. **Asociación Colombiana de Ingeniería Sísmica**. Reglamento Colombiano de Construcción Sismo Resistente. Published 2010. https://www.andi.com.co/uploads/reglamento_colombiano_construccion_sismo_resistente_636536179523160220.pdf
15. **Rosales C.** Sobre el Comportamiento Sísmico de los Depósitos de Suelos del Área de Cañaveralejo, Cali, Colombia. Published 2001.
16. **Ingeominas**. Mapa de Microzonificación Sísmica. Published 2005. https://aivalle.com/pdf/MZSC-RS2-MapaMicrozonificaci%C3%B3nS%C3%ADsmica.pdf
17. **Arteaga J**, **Betancourt V.** Propuesta de creación -Hospital Universitario-Universidad Nacional de Colombia. *Revista Morfolia.* 2014;**6**(1).
18. **Banco de la República**. Boletín de indicadores económicos. Published 2020. https://www.banrep.gov.co/economia/pli/bie.pdf
19. **Gamas AB**, **Magaña Adorno AM**, **González Gutiérrez KP**, et al. Plan de contingencia por sismo en el área de urgencias del Hospital Regional de Alta Especialidad Dr. *Gustavo A. Rovirosa Pérez.* Ciencia Latina Revista Científica Multidisciplinar. 2023;**7**(5):1717–1741. doi:10.37811/cl_rcm.v7i5.7837
20. **Gaytán R**, **Hernández Barrios H**, **Olmos Navarrete BA**, et al. Morfología urbana, daños en estructuras, sismicidad y red acelerométrica de la ciudad de Morelia. *Revista de Ingeniería Sísmica.* 2022;**108**:1–22.
21. **Osorio CC**. Revisión documental de los planes de emergencia en las unidades hospitalarias y la respuesta funcional por parte del personal de la salud. *Revista Sinergia.* Published 2022:20–33. doi:10.54997/rsinergia.n12a2
22. **Lestari F**, **Paramitasari D**, **Fatmah**, et al. Analysis of Hospital's Emergency and Disaster Preparedness Using Hospital Safety Index in Indonesia. *Sustainability (Switzerland).* 2022;**14**(10). doi:10.3390/su14105879
23. **UNDRR, CRED**. *Pérdidas Económicas, Pobreza y DESASTRES.*; 2017.