Balao, Ecuador Mw 6.8 Earthquake of March 18, 2023

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PRELIMINARY VIRTUAL RECONNAISSANCE REPORT (PVRR)

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PREFACE

The National Science Foundation (NSF) awarded an EAGER grant (CMMI 1841667) to a consortium of universities to form the Structural Extreme Events Reconnaissance (StEER) Network (see https://www.steer.network for more details). StEER was renewed through a second award (CMMI 2103550) to further enhance its operational model and develop new capabilities for more efficient and impactful post-event reconnaissance. StEER builds societal resilience by generating new knowledge on the performance of the built environment through impactful post-disaster reconnaissance disseminated to affected communities. StEER achieves this vision by: (1) deepening structural engineers' capacity for post-event reconnaissance by promoting community-driven standards, best practices, and training, as well as their understanding of the effect of natural hazards on society; (2) coordination leveraging its distributed network of members and partners for early, efficient and impactful responses to disasters; and (3) collaboration that broadly engages communities of research, practice and policy to accelerate learning from disasters.

Under the banner of the Natural Hazards Engineering Research Infrastructure (NHERI) CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium to promote interdisciplinary disaster reconnaissance and research. The consortium includes the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Interdisciplinary Science and Engineering Extreme Events Research (ISEEER), Nearshore Extreme Event Reconnaissance (NEER), Operations and Systems Engineering Extreme Events Research (OSEEER), Social Science Extreme Events Research (SSEER), and Sustainable Material Management Extreme Events Reconnaissance (SUMMEER), as well as the NHERI RAPID equipment facility, the NHERI Network Coordination Office (NCO), and NHERI DesignSafe CI, curation site for all StEER products.

While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Southeast Regional Node), and University of California, Berkeley (Pacific Regional Node), StEER is currently expanding its network of regional nodes worldwide to enable swift and high-quality responses to major disasters globally.

StEER's founding organizational structure includes a governance layer comprised of core leadership with Associate Directors for each of the primary hazards as well as cross-cutting areas of Assessment Technologies and Data Standards, led by the following individuals:

- **Tracy Kijewski-Correa (PI),** University of Notre Dame, serves as StEER Director responsible for overseeing the design and operationalization of the network and representing StEER in the NHERI Converge Leadership Corps.
- **Khalid Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, serving as primary liaison to the Earthquake Engineering community.
- **David O. Prevatt (co-PI),** University of Florida, serves as StEER Associate Director for Wind Hazards, serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** University of Hawai'i at Manoa, serves as StEER Associate Director for Coastal Hazards, serving as a primary liaison to the coastal engineering community and ensuring a robust capacity for multi-hazard assessments.
- **David Roueche (co-PI),** Auburn University, serves as StEER Associate Director for Data Standards, ensuring StEER processes deliver reliable and standardized reconnaissance data suitable for re-use by the community.

This core leadership team works closely with StEER Research Associates, Data Librarians and its Student Administrator in event responses, in consultation with its Advisory Boards for Coastal, Seismic and Wind Hazards.

ATTRIBUTION GUIDANCE

Reference to PVRR Analyses, Discussions or Recommendations

Reference to the analyses, discussions or recommendations within this report should be cited using the full citation information and DOI from DesignSafe (these are available at https://www.steer.network/products).

Citing Images from this PVRR

Images in this report are taken from public sources. Each figure caption specifies the source; re-use of the image should cite that source directly. Note that public sources might still have copyright issues and depending on the use case, the user may need to secure additional permissions/rights from the original copyright owner.

ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI 2103550. Any opinions, findings, and conclusions or recommendations expressed in this material are those of StEER and do not necessarily reflect the views of the National Science Foundation. All authors and editors listed on the cover page participate as volunteer professionals. Thus, any opinions, findings, and conclusions or recommendations expressed herein are those of the individual contributors and do not necessarily reflect the views of their employer or other institutions and organizations with which they affiliate.

Special thanks also go to Laura Hernandez-Bassal, Laura Vargas, and Yvonne Merino-Peña who provided valuable information about the earthquake which helped in the preparation of this preliminary, Virtual Reconnaissance Report (PVRR). Deserved recognition to the Geophysics Institute, at the "Instituto Geofísico de la Escuela Politécnica Nacional" (IGEPN) in Ecuador for making resources available on their website.

The sharing of videos, damage reports and briefings via Slack by the entire NHERI community was tremendously helpful and much appreciated. StEER recognizes the efforts of the DesignSafe CI team who continuously supported and responded to StEER's emerging needs.

For a full listing of all StEER products (briefings, reports and datasets) please visit the StEER website: https://www.steer.network/products

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Common Terms & Acronyms

Acronym	General Terms	Brief Description
--	DesignSafe	Data Repository
--	DesignSafe-CI	Academic Organization within NHERI
ASCE	American Society of Civil Engineers	Professional Organization
ASTM	American Society for Testing and Materials (now ASTM International)	Standards Body
ATC	Applied Technology Council	Professional Organization
BOCA	Building Officials and Code Administrators	Code Body
CC-BY	Creative Commons Attribution License	Code/Standard
CESMD	Center for Engineering Strong Motion Data	Governmental Agency
CI	Cyberinfrastructure	Research Asset
CLPE	Critical Load Path Elements	StEER Term
CMU	Concrete Masonry Unit	Building Material
DBE	Design Basis Earthquake	Design Terminology
DEQC	Data Enrichment and Quality Control	StEER Term
DOI	Digital Object Identifier	Common Term
EARR	Early Access Reconnaissance Report	StEER Term
EERI	Earthquake Engineering Research Institute	Professional Organization
EEFIT	Earthquake Engineering Field Investigation Team	Professional Organization
EF	Enhanced Fujita Scale	Hazard Intensity Scale
EF	Equipment Facility	Academic Organization within NHERI
EIFS	Exterior Insulation Finish System	Building Component
FAA	Federal Aviation Administration	Governmental Agency
FAQ	Frequently Asked Questions	Common Term
FAST	Field Assessment Structural Team	StEER Term
FEMA	Federal Emergency Management Agency	Governmental Agency
GEER	Geotechnical Extreme Events Reconnaissance	Academic Organization within NHERI
GPS	Global Positioning System	Measurement Technology
GSA	Government Services Administration	Governmental Agency

HVAC	Heating, ventilation and air conditioning	Building System
HWM	High Water Mark	Intensity Measure
IBC	International Building Code	Code/Standard
ICC	International Code Council	Code Body
IRC	International Residential Code	Code/Standard
ISEEER	Interdisciplinary Science and Engineering Extreme Events Research	Academic Organization within NHERI
LiDAR	Light Detection and Ranging	Measurement Technology
MCE	Maximum Considered Earthquake	Design Terminology
ME&P	Mechanical, electrical and plumbing	Building System
MMI	Modified Mercalli Intensity	Hazard Intensity Scale
NBC	National Building Code	Code/Standard
NEER	Nearshore Extreme Event Reconnaissance	Academic Organization within NHERI
NFIP	National Flood Insurance Program	Government Program
NHERI	Natural Hazards Engineering Research Infrastructure	Academic Organization within NHERI
NIST	National Institute of Standards and Technology	Governmental Agency
NOAA	National Oceanic and Atmospheric Administration	Governmental Agency
NSF	National Science Foundation	Governmental Agency
NWS	National Weather Service	Governmental Agency
OSB	Oriented strand board	Construction Material
OSEEER	Operations and Systems Engineering Extreme Events Research	Academic Organization within NHERI
PEER	Pacific Earthquake Engineering Research center	Academic Organization (Earthquakes)
PGA	Peak Ground Acceleration	Intensity Measure
PHEER	Public Health Extreme Events Research	Academic Organization within NHERI
PVRR	Preliminary Virtual Reconnaissance Report	StEER Term
QC	Quality Control	Oversight process
RAPID	RAPID Grant	Funding Mechanism
RAPID-EF	RAPID Experimental Facility	Academic Organization within NHERI
RC	Reinforced Concrete	Building Material

SAR	Search and Rescue	Standard Hazards Terminology
SGI	Special Government Interest	FAA Process
SLP	Surface-Level Panoramas	Measurement Technology
SMS	Short Message Service	Communication Modality
SPC	Storm Prediction Center	Governmental Agency
SSEER	Social Science Extreme Events Research	Academic Organization within NHERI
StEER	Structural Extreme Events Reconnaissance network	Academic Organization within NHERI
SUMMEER	SUstainable Material Management Extreme Events Reconnaissance	Academic Organization within NHERI
TAS	Testing Application Standard	Technical Standard
UAS/V	Unmanned Aerial Survey/System/Vehicle	Measurement Technology
USD	US Dollar	Standard Currency
USGS	United States Geological Survey	Governmental Agency
VAST	Virtual Assessment Structural Team	StEER Term
WS	Windshield Survey	Measurement Technology

Executive Summary

On March 18, 2023, a Magnitude 6.8 earthquake occurred in Ecuador, which caused substantial damage to the cantons and cities within the three provinces of El Oro, Guayas, and Azuay nearest to the epicenter. At least 45 aftershocks were reported one day after the event with the largest aftershock reaching a magnitude of 4.9. The largest peak ground acceleration was 0.32g for the north-south component recorded at Machala, approximately 53 km from the epicenter.

Fortunately, the number of lives lost and injuries from this earthquake were remarkably low, resulting in only 14 deaths and 494 injuries in comparison to the 2016 event. Still, the Balao earthquake caused damage to over 900 structures. In general, engineered structures (commercial, and government buildings and multi-family residential structures) performed well, exhibiting only non-structural damage. The earthquake drew attention to the vulnerability of historic buildings, and non-engineered (mainly residential) structures built using flexible reinforced concrete frames in combination with stiff infill masonry.

The earthquake highlights the need for more research into retrofit solutions that address the incompatibility of stiff brick/concrete infill masonry and reinforced concrete frames. This is particularly important for non-engineered buildings where inadvertent design choices yield extremely flexible reinforced concrete frames. New construction should encourage the use of alternative structural systems using lighter cladding materials that retain some aesthetic characteristics that make these stiff infills appealing (moderate cost, simple construction methods, and acoustic isolation), but are more compatible with the displacement tolerances of structural framing.

The event also underscored the vulnerability of the large historic building inventory in Ecuador. Ecuador is a very important architectural center for historic buildings in Latin America. Ecuador’s capital city, Quito, holds the single largest collection of historically significant architecture in Latin America and the city of Cuenca, a UNESCO World Heritage Site, traces its earliest urban planning guidelines and development back some 400 years. Given the concentration of historic, culturally significant buildings in Ecuador and frequency of earthquakes in the region, a need exists to develop and implement cost-effective and structurally efficient retrofits for these cultural heritage sites that address the systemic failures occurring in many of Ecuador’s historic churches.

In light of these impacts, StEER activated a Level 1 response to this earthquake on March 20, 2023, and formed a Virtual Assessment Structural Team (VAST) to assemble this **Preliminary Virtual Reconnaissance Report (PVRR).** The PVRR is intended to:

1. provide an overview of the Mw 6.8 Balao Earthquake, particularly relating to the earthquake impact on the built environment,
2. overview the regulatory environment and construction practices in the affected area,
3. synthesize preliminary reports of damage to buildings and other infrastructure, and
4. provide recommendations for continued study of this event by StEER and the wider engineering reconnaissance community.

RESUMEN EJECUTIVO

El 18 de marzo de 2023, un terremoto de magnitud 6,8 ocurrió en Ecuador, el cual causó un daño considerable a los cantones y ciudades de las tres provincias de El Oro, Guayas y Azuay más cercanas al epicentro. Al menos se reportaron 45 réplicas un día después del evento, siendo la mayor de ellas de magnitud 4,9. La mayor aceleración del suelo registrada fue de 0,32g para la componente norte-sur en Machala, aproximadamente a 53 km del epicentro.

Afortunadamente, el número de vidas perdidas y lesiones a causa de este terremoto fue notablemente bajo, resultando en solo 14 muertes y 494 heridos en comparación con el evento de 2016. Aún así, el terremoto de Balao causó daños a más de 900 estructuras. En general, las estructuras diseñadas (edificios comerciales, gubernamentales y residenciales multifamiliares) tuvieron un buen desempeño, exhibiendo solo daños no estructurales. El terremoto llamó la atención sobre la vulnerabilidad de los edificios históricos y las estructuras no diseñadas (principalmente residenciales) construidas con marcos de concreto reforzado flexibles en combinación con albañilería rígida.

El terremoto destaca la necesidad de más investigación en soluciones de refuerzo que aborden la incompatibilidad de la mampostería rígida de ladrillo/concreto y los marcos de concreto reforzado. Esto es particularmente importante para edificios no diseñados donde las opciones de diseño inadvertidas producen marcos de concreto reforzado extremadamente flexibles. La nueva construcción debería fomentar el uso de sistemas estructurales alternativos que utilicen materiales de revestimiento más livianos que conserven algunas características estéticas que hacen que estos rellenos rígidos sean atractivos (costo moderado, métodos de construcción simples y aislamiento acústico), pero que sean más compatibles con las tolerancias de desplazamiento del marco estructural.

El evento también subrayó la vulnerabilidad del gran inventario de edificios históricos en Ecuador. Ecuador es un centro arquitectónico muy importante para edificios históricos en América Latina. La ciudad capital de Ecuador, Quito, tiene la colección más grande de arquitectura históricamente significativa de América Latina y la ciudad de Cuenca, un sitio de Patrimonio Mundial de la UNESCO, remonta su desarrollo urbano más temprano hace unos 400 años. Dada la concentración de edificios históricos y culturalmente significativos en Ecuador y la frecuencia de terremotos en la región, existe la necesidad de desarrollar e implementar soluciones de refuerzo eficientes desde el punto de vista estructural y rentables para estos sitios de patrimonio cultural que aborden las fallas sistémicas que ocurren en muchas de las iglesias históricas de Ecuador.

Teniendo en cuenta estos impactos, StEER activó una respuesta de Nivel 1 a este terremoto el 20 de marzo de 2023 y formó un Equipo Virtual de Evaluación Estructural (VAST) para reunir este **Informe Preliminar de Reconocimiento Virtual (PVRR)**. El PVRR tiene como objetivo:

1. proporcionar una visión general del terremoto de Balao de magnitud 6,8, en particular en relación con el impacto del terremoto en el entorno construido,
2. resumir el entorno regulatorio y las prácticas de construcción en el área afectada,
3. sintetizar los informes preliminares de daños a edificios y otras infraestructuras, y
4. proporcionar recomendaciones para el estudio continuo de este evento por parte de StEER y la comunidad más amplia de reconocimiento de ingeniería.

1. Introduction

On March 18th, 2023, a magnitude 6.8 earthquake occurred with the epicenter located 35 km west of the city of Balao, Ecuador (Fig. 1.1). At least 45 aftershocks were reported within the next day following the event according to local sources (IGEPN 2023a). The largest aftershock recorded was a magnitude 4.9 earthquake. Balao city is in Guayas Province of 20,523 inhabitants according to the latest Census from 2010 (INEC 2010). The city has around 7,600 residential buildings.

The Balao canton shares land borders with Naranjal (to the north), Azuay (to the east), Jambelí Channel which is part of the Gulf of Guayaquil (to the west), and Tenguel to the south. Predominant damage from the earthquake was reported throughout Guayas, El Oro, and Azuay provinces. There was structural damage observed in residential buildings, centers of education, churches and public health facilities. Soil liquefaction was reported at Isla Puná, Guayaquil, Guayas, which is located next to the epicenter as shown in Fig 1. Another salient report noted the partial collapse of a historic residential structure in Azuay (110 km southeast of the epicenter), with fatal consequences (Solano G. 2023). The earthquake also caused 13 landslides in different locations along the routes Cuenca-Molleturo and Girón-Pasaje, as well as more than 2000 reports of power outages and other water supply disruptions. However, CNEL (Corporación Nacional de Electricidad) informed that by March 19th, 2023, the electricity network was operating at 99% of its efficiency (El Comercio 2023a).

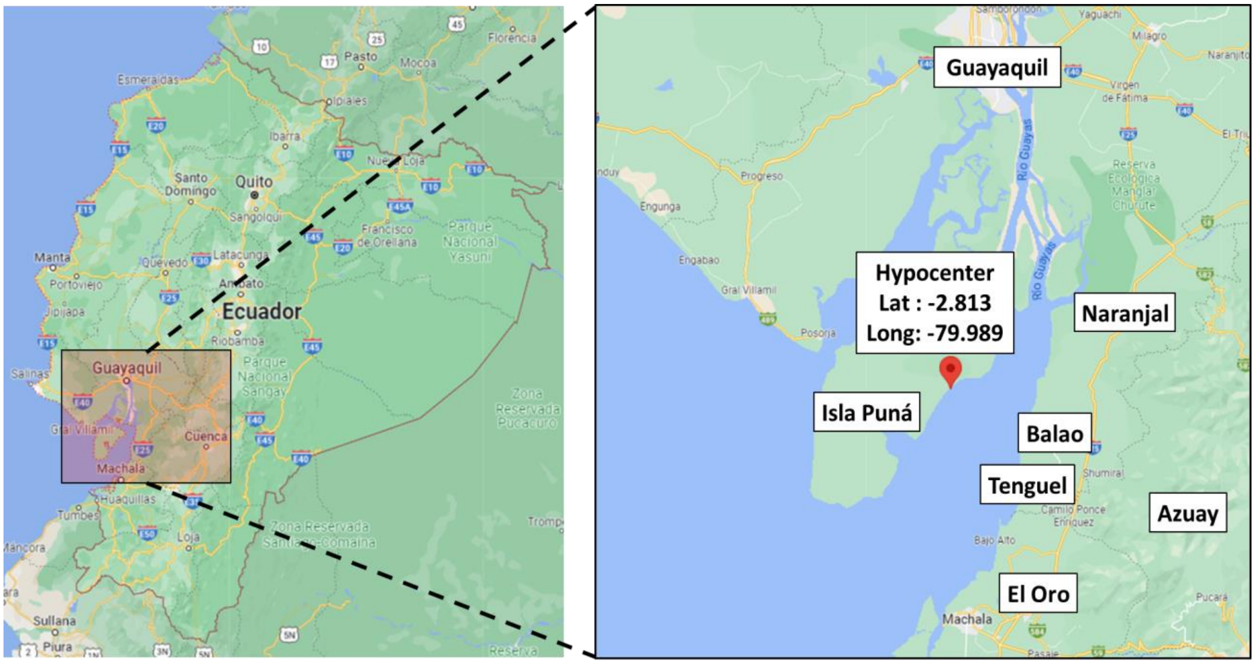


Figure 1.1. Geographic Location (Instituto Geofísico de la Escuela Politécnica Nacional).

1.1. Seismic Perception

Ecuador is subdivided into 24 provinces. Each province has smaller subdivisions known as cantons. The 6.8M Balao earthquake was felt in 17 of the 24 provinces with intensity reports coming from 160 of the 221 cantons affecting over 70% of Ecuador as shown in Fig 1.2.

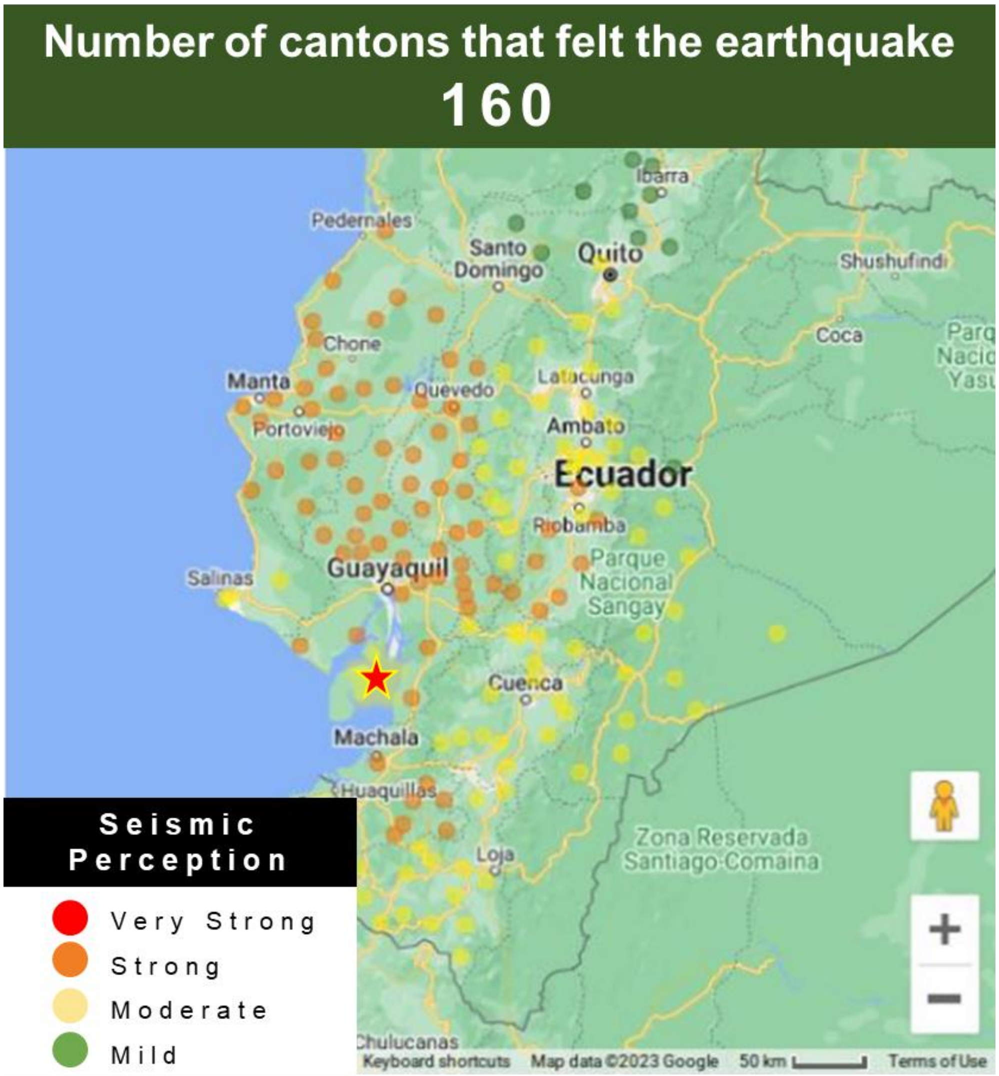


Figure 1.2. Seismic Perception of the 6.8M Balao Earthquake (star indicates the location of the Epicenter) (Dirección de Monitoreo de Eventos Adversos 2023).

USGS also has a system to collect information coming from people who felt the earthquake. Using the vast amount of internet users, it is possible to understand the seismic perception and describe the scope of the earthquake as seen in Figure 1.3.

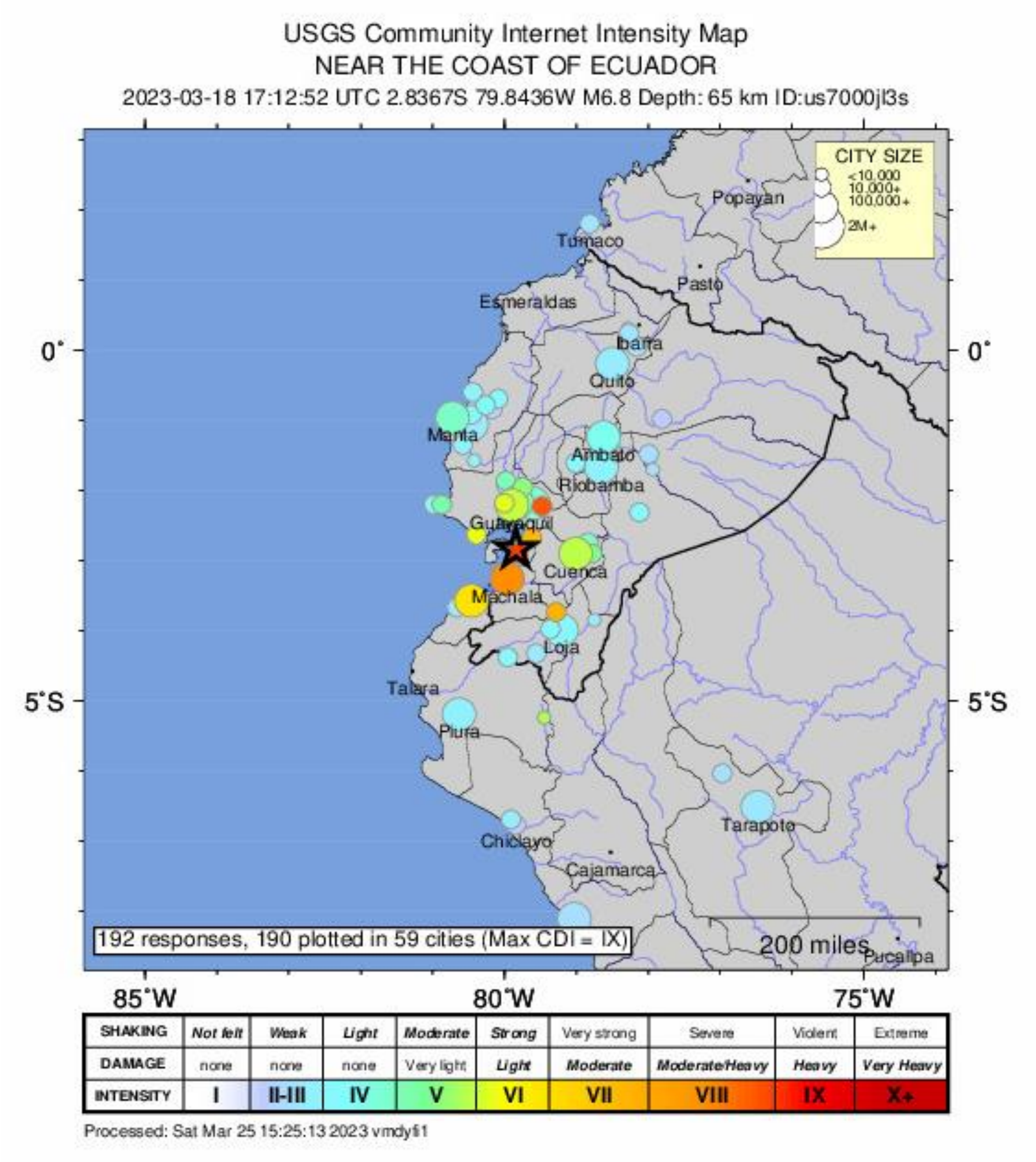


Figure 1.3. Did you feel it? report (star represents the location of the epicenter of the 6.8Mw Balao earthquake) (USGS 2023).

1.2. Societal Impact

According to the Directorate of Adverse Event Monitoring in Ecuador, fourteen out of the twenty-four provinces in Ecuador reported some type of structural damage. Insurable losses from the Ecuador earthquake are estimated to be around $600 million (Corelogic 2023). The DAEM reported that around 1686 structures were damaged, including structural damage to 331 educational center buildings (school and universities) and 57 health care facilities, and 256 residential structures that collapsed. (Table 1.1). El Oro province had by far the most structures affected with a high percentage of them (nearly 14%) collapsed. Ninety-five percent of the residential structural damage was concentrated in the three provinces of El Oro, Guayas, and Azuay, as were the largest impacts on educational centers and healthcare facilities (Dirección de Monitoreo de Eventos Adversos 2023). A major transportation route connecting Cuenca, Molleturo, El Empalme, was interrupted by several landslides caused by the earthquake. There were also reports of fallen utility poles in the cities of Machala and Pasaje and water supply disruptions in El Oro.

Table 1.1. Distribution of Structural Damage to Buildings from the Balao Earthquake 04/06/2023.

Province	**Collapsed Structures**		**Affected Structures**				
	Residential	**Public**	**Residential**	**Public**	**Education**	**Health**	**Bridges**
El Oro	170	8	542	30	63	20	2
Guayas	50		320	18	56	18	3
Azuay	29		55	4	117	8	
Bolivar	1		15		1	1	
Cañar	5		11	1	21	3	
Cotopaxi			7		4		
Los Ríos			5	2	5	4	
Loja			9	2	23		
Santa Elena	1		2	2	5	2	
Tunfurahua			1				
Chimborazo			1	2		1	
Manabí					26		
Morona Santiago					5		
Zamora Chinchipe					5		
Subtotal	**256**	**8**	**968**	**61**	**331**	**57**	**5**

Source: Dirección de Monitoreo de Eventos Adversos (2023)

The state-run oil company Petroecuador reported damage to an offshore platform located near the epicenter that caused some machinery to fail, temporarily reducing oil production (BusinessDay, 2023). Authorities ordered the closure of three vehicular tunnels in Guayaquil, which anchors a metro area of over 3 million people (The Korea Times, 2023).

1.3. Loss of Life and Injuries

The reported number of deaths and injuries from the earthquake were thankfully small, 14 and 494, respectively anot most of these occurred in the El Oro province. Twelve deaths occurred in El Oro and two in Azuay Province. The main cause of deaths was building collapse. One particular case stands out in Azuay where pieces of the cornice of a historical building facade collapsed on top of a car, killing its driver who was just passing through the street. Another particular cause of death was the landslide in the route that connects Cuenca and Molleturo. Furthermore, injuries spread through four provinces namely El Oro, Guayas, Azuay, and Los Ríos (Table 1.2 and Figure 1.4).

Table 1.2. Number of Deaths and Injuries 04/06/2023.

Province	Deaths	Injuries
El Oro	12	433
Guayas		36
Azuay	2	21
Los Ríos		4
Subtotal	14	494

Source: Dirección de Monitoreo de Eventos Adversos (2023)

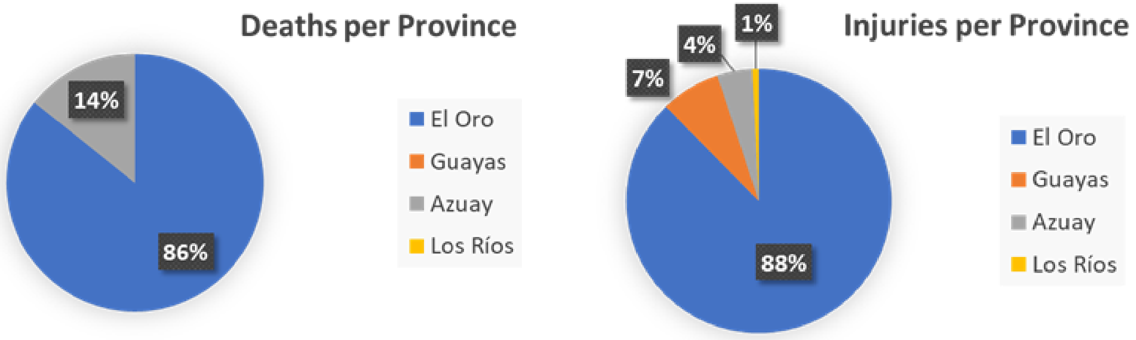


Figure 1.4. Deaths and Injuries per Province (Source: Dirección de Monitoreo de Eventos Adversos (2023)).

1.4. Official Response

Immediately after the 6.8Mw Balao earthquake, the Ecuadorian government started rescue efforts by mobilizing its fire departments, the Public Health Ministry, and the Army. In addition, the Red Cross also mobilized its personnel to assist in the recovery. Simultaneously, medical emergency squads with support from the Ministry of Public Health and the Red Cross were deployed to Isla Puná and surrounding areas in the Gulf of Guayaquil. Subsequently, the Government of Ecuador activated reconnaissance squads to evaluate structural damage and assist the immediate recovery of affected communities. The National Emergency Actions Committee (COE), which is organization with national and local jurisdictions that coordinates the emergency response, led efforts collaborating with the local governments from the affected provinces of Azuay, Cañar, El Oro, and Guayas as well as smaller jurisdictions such as El Guabo, Pasaje, Machala, Santa Rosa, Huaquillas, Cuenca and Santa Isabel. States of emergency were issued for Pasaje and El Guabo in El Oro province, and Naranjal in Guayas. Meanwhile, the Ministry of Public Works and Transportation (MTOP) performed a structural assessment of possibly affected bridges and highways. A total of 711 structures were inspected, with 242 rated as “limited access” (yellow label) and 300 rated as “unsafe” (red label) (Table 1.3).

A total of 39 shelters were opened for those displaced by damage to their residences. As of March 28th 2023, 137 people had been accommodated at these shelters (Table 1.4). Utilities had been reestablished at the national level by the afternoon of March 25th. The interruptions due to landslides in the routes Lican-Riobamba and Cuenca-Molleturo were also cleared.

Table 1.3. Structural Evaluation of Residential Structures Progress (as of 04/06/2023).

Province	**Canton**	**Evaluated Residential Structures**	**Green Label**	**Yellow Label**	**Red Label**
Azuay	Cuenca	44	11	11	22
	Pucará	37	28	6	3
	Nabón	100	48	39	13
	Santa Isabel	53	8	20	25
	Girón	20	0	7	13
	Camilo Ponce E.	21	5	10	6
Cañar	Cañar	5	0	5	0
	Deleg	2	0	0	2
Guayas	Balao	2	1	0	1
	Guayaquil	66	12	22	32
	Naranjal	36	3	22	11
El oro	Machala	243	46	91	106
	Pasaje	177	56	59	62
	El Guabo	52	0	2	50
	Santa Rosa	59	11	24	24
	Arenillas	6	1	3	2
Total		**923**	**230**	**321**	**372**

Green label: sound structure ready to use.
Yellow label: partial damage, restricted access
Red label: unsafe structure, access is denied until further evaluation.
Source: Dirección de Monitoreo de Eventos Adversos (2023)

Table 1.4. Working Shelters (as of 03/28/2023).

Location	**Type**	**Name**	**No. of Families**	**Number of People**
Pasaje	Shelter	Unidad Educativa John F Kennedy	17	60
El Guabo	Shelter	Casa Comunal Coop. 10 de Agosto	19	63
El Guabo	Shelter	CasaComunal 24 de Mayo	3	14
Total			39	137

Source: Dirección de Monitoreo de Eventos Adversos (2023)

1.5. Report Scope

Evaluation of this earthquake against StEER's activation criteria affirmed that more than half of the Level 1 criteria were met (see Table 1.4). As such StEER activated a Level 1 response on March 20, 2023, and formed a Virtual Assessment Structural Team (VAST) to assemble this **Preliminary Virtual Reconnaissance Report (PVRR).** The PVRR is intended to:

5. provide an overview of the Mw 6.8 Balao Earthquake, particularly relating to the earthquake impact on the built environment,
6. overview the regulatory environment and construction practices in the affected area,
7. synthesize preliminary reports of damage to buildings and other infrastructure, and
8. provide recommendations for continued study of this event by StEER and the wider engineering reconnaissance community.

Table 1.4. Summary of Level 1 Activation Criteria.

Hazard	Exposure	Feasibility
● Major intensity event ● Compounding hazards (earthquake, landslides, liquefaction)	● Sufficiently populated areas impacted ● History of recovery ● Noteworthy construction practices	● Sufficient media/social media coverage ● Interest of members

2. Hazard Characteristics

2.1. Historical Background to Earthquakes in Ecuador

Although there is evidence of prehistoric seismic activity in the Andes (Combey et al. 2020), the first available seismic record in the Ecuadorian repository dates from 1541 with the epicenter in Napo province. Since then, the list has been rapidly increasing including earthquakes of diverse magnitudes (Table 2.1), including records of thirty-seven major earthquakes (i.e., intensity equal to or larger than VIII MSK) in the period of 1541 to 2007. Further, there have been 88 earthquakes recorded that had intensities of VI and above. The most recent earthquake that affected Ecuador prior to the Balao earthquake, was the 7.8M Muisne earthquake in 2016 that caused widespread destruction and 668 fatalities (Wikipedia 2023). Ecuador has experienced a major earthquake once every 12.4 years on average since 1451 (Rivadeneira et al. 2007). The average of destructive earthquakes per year from 1451 to 1999 is 0.08 which translates to a return period of 12.5 years.

Table 2.1. Largest Historical Seismic Intensities in Ecuador (1645 through 2016).

Province	MSK Intensity	Magnitude	Year
Riobamba	IX	7.0	1645
Baños	IX	7.7	1698
Loja	VIII	6.3	1749
Baños / Chimborazo	XI	8.3	1797
Ibarra / Imbabura	IX	7.0	1868
Canoa	IX	7.0	1896
Manabí	IX	7.1	1896
Atacames / Esmeraldas	IX	8.8	1906
Loja / Azuay	VIII	6.3	1913
Quito	VIII	6.3	1923
Carchi	VIII	7.0	1923
Quito / Pichincha	VIII	6.3	1929
Guayas	VIII	7.9	1942
Pedernales	IX	7.8	1942
Baños / Cotopaxi, Tungurahua	X	6.7	1949
Taisha	VIII	6.6	1961
Calceta	VIII	6.2	1964
El Oro	VIII	7.2	1970
Esmeraldas	VIII	6.7	1976
Tena / Napo, Sucumbíos	IX	6.4	1987
Sucúa / Morona Santiago	VIII	6.5	1995
Bahia de Caraquez	VIII	7.2	1998
Muisne	IX	7.8	2016

Sources: Compiled based on Rivadeneira et al. (2007), Cajamarca-Zuniga et al. (2022), Aguiar et al. 2016, and Monsalve and Laverde 2016

Note: Abbreviated description of the levels of Medvedev Sponheuer Karnink (MSK)

The most seismically active period in Ecuador occurred between1953 and 1964, when eleven earthquakes of intensity VI and higher occurred. The earthquake epicenters from these historical records cover most of continental Ecuador, so there is no seismically risk-free location in the national territory (Fig. 2.1). That said, the coastal regions of Ecuador have experienced some of the largest earthquakes caused by fractures in the adjacent subduction zone. Some of the most important records in recent history of the coastal region happened near Manabí, reaching magnitudes of 7.8Mw, 7.7Mw, and 8.2Mw in May 1942, January 1958, and December 1979, respectively (Rivadeneira et al. 2007).

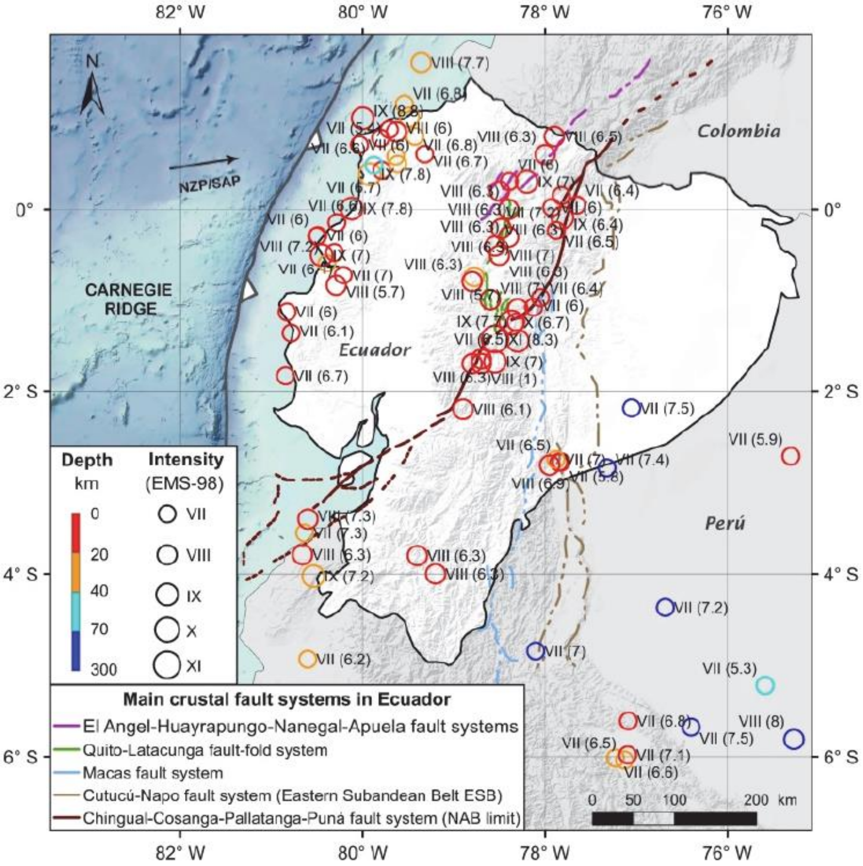


Figure 2.1. Locations and depth of earthquakes with intensities ≥ VII from 1900 to 2021. The shoreline of Ecuador experienced large and great megathrust earthquakes mainly along the northern flank of the Carnegie Ridge collision zone. The central and north Andean region of Ecuador shows high crustal activity and registers large historical earthquakes along the CCPP fault system. The sub-Andean zone at the Amazon basin shows an intermediate-depth seismicity in the Pastaza-Napo region and a high shallow-focus activity to the south, between the Macas and Quito-Napo fault systems" (Cajamarca-Zuniga et al., 2022).

2.2.Seismic Hazard

Figure 2.2 shows the Seismic Hazard Map for Ecuador. The western part of the country is characterized by inter-plate seismicity close to plate boundaries, with high magnitude and depth less than 40 km. However, in eastern regions of the country intra-plate seismicity can be observed as shown in the map of seismic zones of Ecuador (Fig. 2.2) (NEC 2015a). Seismic hazard decreases from very high on the coast to moderate in the eastern region, but intensity has been observed to be higher in the Sierra region (intensity greater than or equal to VIII). "Quito, capital of Ecuador (located in the northern Sierra), sustained major damage to its temples and houses from the April 1755 earthquake, whose intensity has been estimated between VIII and IX (MSK); Riobamba and Ibarra (cities of the northern Sierra) had to be rebuilt after the earthquakes of 1797 and 1868, respectively; Ambato (a city of the central Sierra) lost much of his historic center in the earthquake of August 5, 1949." (Lima et al., 2022).

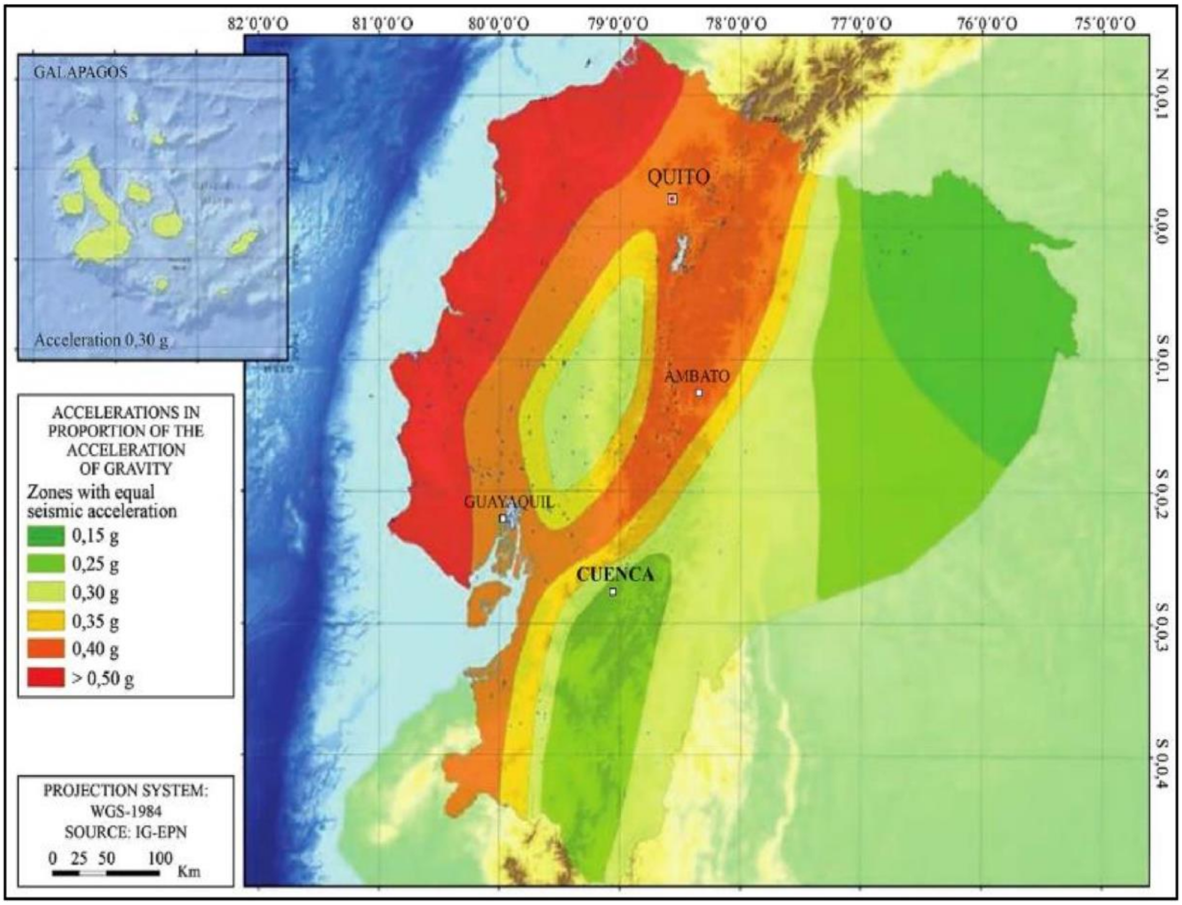


Figure 2.2. Seismic hazard map of Ecuador: zoning by maximum accelerations in bedrock NEC (2015).

Analysis by Cajamarca-Zuniga et al. (2022) demonstrates that 95% of Ecuador has a PGA>0.1g corresponding to intensities greater than VII, 86% has a PGA>0.2g corresponding to intensities greater than VII, while 3.8% of the country has very high seismicity (>IX), where the peak seismic acceleration exceeds 0.5g (Fig. 2.3). These might be even higher than those determined in Ecuadorian building standard (NEC-SE-DS 2015), which specifies a design PGA of 0.30 -- 0.40g for these zones (Cajamarca-Zuniga et al., 2022).

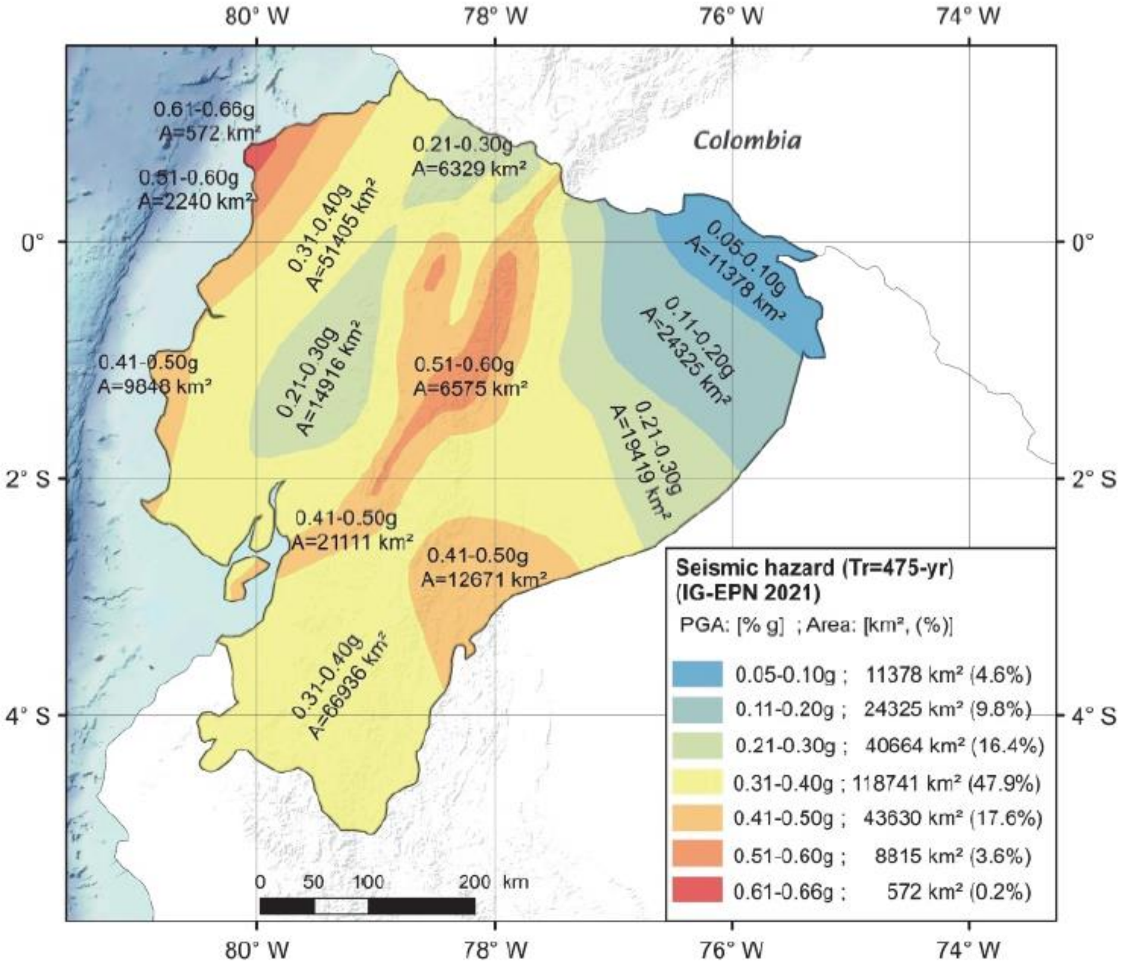


Figure 2.3. Areas of seismic regions, km^2, and their respective percentages in relation to the continental surface of Ecuador based on the non-normative seismic hazard map of the Institute of Geophysics of the National Polytechnic School of Ecuador (Cajamarca-Zuniga et al., 2022).

2.3. Earthquake Details

On March 18th, 2023, at approximately 12:12 pm local time, an earthquake occurred 29.14 km west of Balao, Ecuador (Fig. 2.4). The moment magnitude of the event was 6.8 according to USGS (2023). The USGS located the hypocenter at 2.837°S and 79.844°W with a depth of 65.8 km, whereas the IGEPN located it at 2.813 °S and 79.989°W with a depth of 34.5 km (IGEPN 2023a). The earthquake was followed by more than 45 aftershocks as indicated by the Directorate of Adverse Event Monitoring in Ecuador (Dirección de Monitoreo de Eventos Adversos 2023) (Fig. 2.4).

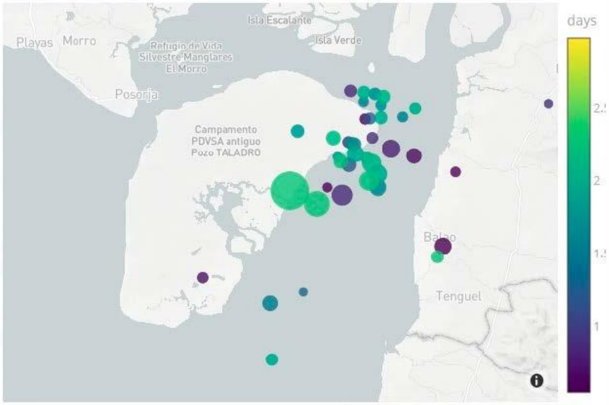


Figure 2.4. Aftershocks following Balao, Ecuador earthquake [(IGEPN 2023a)]().

The USGS estimated a significant area exposed to liquefaction triggered by the Balao earthquake, which is consistent with the reports from Isla Puná, Guayas where inhabitants reported gushing water. There is also significant risk along all locations near the gulf as seen in the map of liquefaction probability in Figure 2.5.

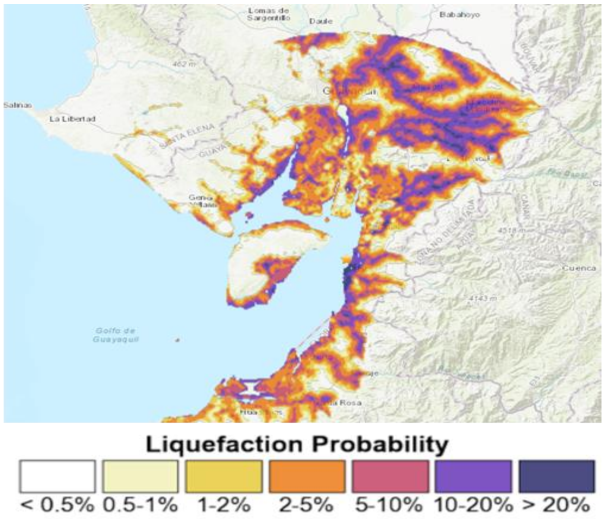
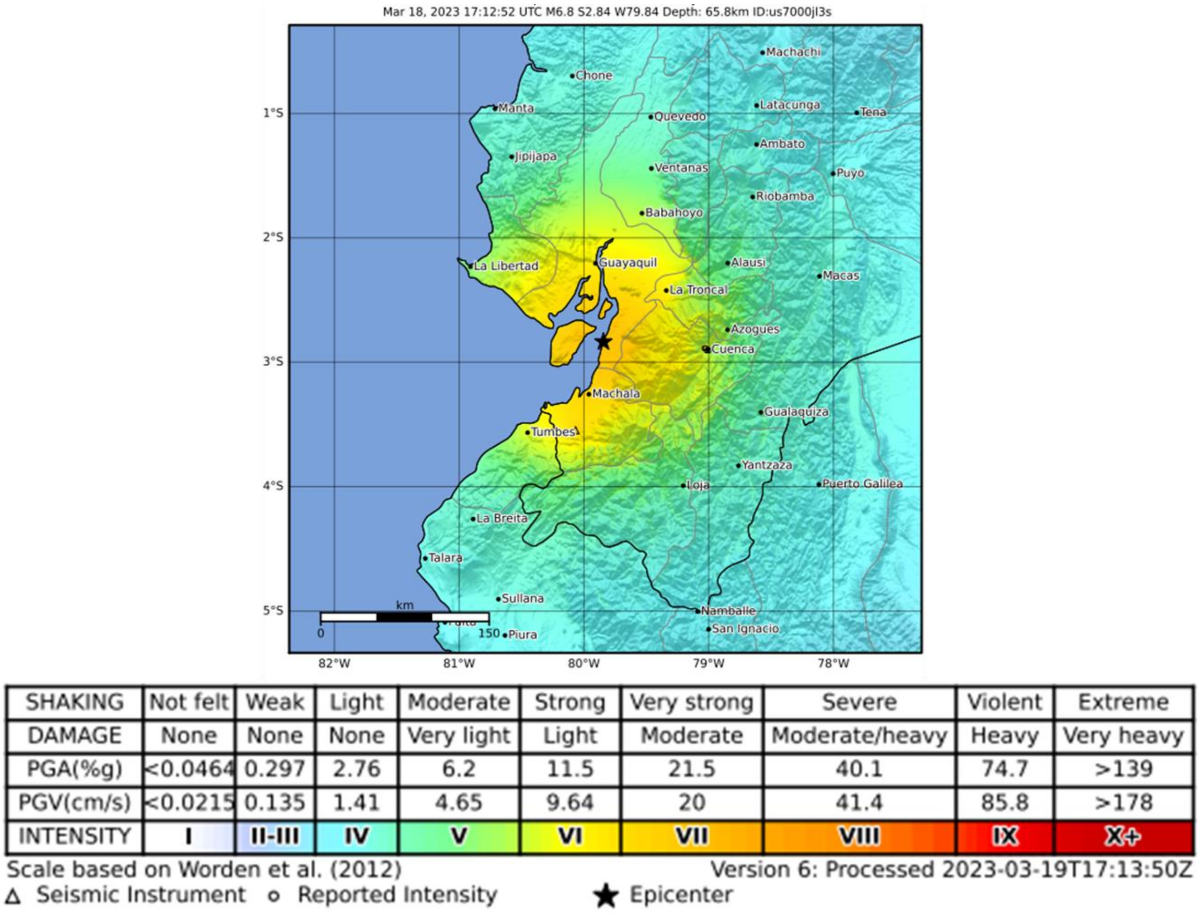


Figure 2.5. Risk of liquefaction from the Balao, Ecuador earthquake [(USGS 2023)]().

The USGS shakemap map of intensities estimated an intensity of VII and a Peak Ground Acceleration (PGA) of approximately 0.2g to 0.4g near the epicenter (Fig. 2.6). This large magnitude of shaking is consistent with the reported damage to structures.



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012)
Version 6: Processed 2023-03-19T17:13:50Z
△ Seismic Instrument ○ Reported Intensity ★ Epicenter

Figure 2.6. ShakeMap estimated intensities for Balao earthquake (USGS 2023).

2.4. Geophysical Features

The Balao 2023 earthquake happened near one of the main geologic fault systems in Ecuador, the Pallatanga-Chingual Fault. The system starts in the Gulf of Guayaquil and goes through Puna island, La Troncal, Bucay, and Pallatanga. Further north, it joins the inter andean alley reaching the Chingual fault in northwestern Ecuador. This system is considered responsible for spawning the earthquake that caused the total destruction of Riobamba city in 1797. The largest geologic fault system in Ecuador extends about 200 km North-South on the eastern side of the “Cordillera Real" and the deepest earthquakes occur in the subducted oceanic crust with depths larger than 200 km (Rivadeneira et al. 2007).

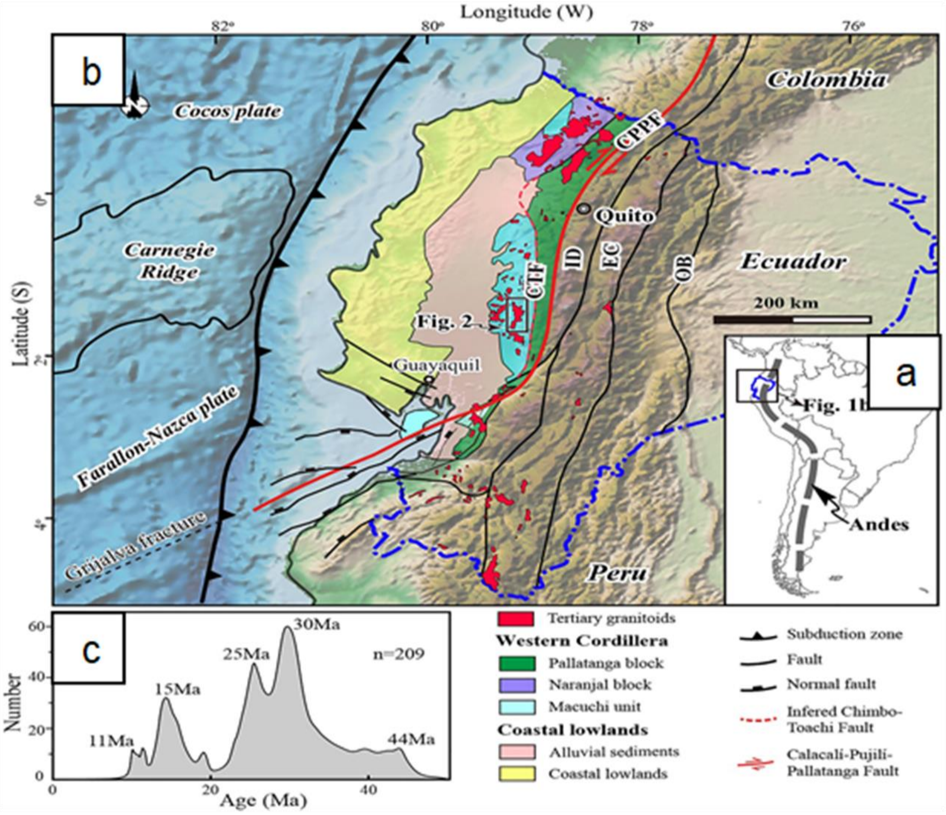


Figure 2.7. Simplified sketch map of tectonic framework and tertiary arc magmatism in the Ecuadorian arc. (a) Outline of the mainland of the South American plate (Liu et al. 2023) (b) Tectonic framework and distribution of the tertiary intrusions developed in the Ecuadorian arc (BGS-CODIGEM 1993); Vallejo et al. (2009). ID: Interandean Depression, EC: Eastern Cordillera, OB: Oriente Basin. (c) Tertiary magmatism tempo in the Ecuadorian arc revealed by detrital zircon age spectrum (Jackson et al. 2019).

The South American arc is the boundary between the subducting Nazca and the South American plates (see. Fig 2.7). The Nazca subduction plate is known to be the reason for the Andes Mountains' uplift and the volcanic activity in the region. The relative northeastern motion of Nazca with respect to the South American plate influences seismic activity in western South America. Crustal and interplate deformations generate predominantly shallow earthquakes (i.e., less than 70 km). Among the most notorious earthquakes in the area were the M9.5 Chile earthquake in 1960 (the world’s largest on record), M8.5 Esmeraldas, Ecuador in 1906, M8.5 Coquimbo, Chile in 1922, M8.4 Arequipa, Peru in 2001, M8 Pisco, Peru in 2007, and M8.8 Maule, Chile in 2010. South America may also experience large intermediate-depth earthquakes up to 300 km depth concentrated in northern Chile, southwest Bolivia, northern Peru, and southern Ecuador as well as deep earthquakes up to 600 km depth concentrated beneath the Peru-Brazil border and Bolivia to central Argentina. In general, deep earthquakes exhibit minor surface effects.

2.5. Recorded Ground Motions

There are eight recording stations from the national accelerometers network (RENAC) around the epicenter of the 6.8Mw Balao earthquake (Fig. 2.8). Each of these stations recorded three components: north component HNN, east component HNE, and vertical component HNZ Fig 2.8.

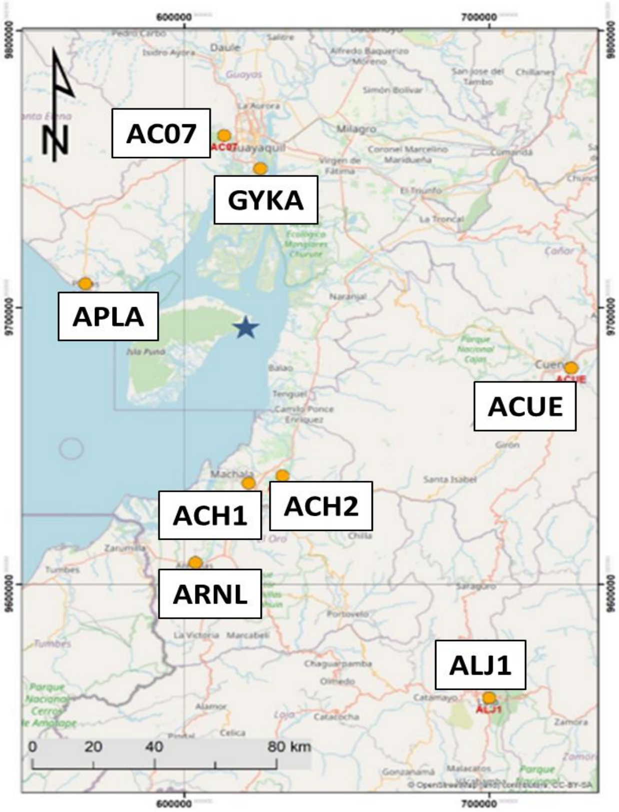


Figure 2.8. National network of accelerometers RENAC (Star indicates the location of the epicenter of the 6.8Mw Balao earthquake) (IGEPN 2023b).

Table 2.2. Acceleration Measurements (Source: IGEPN 2023b).

Station	Component	Peak Ground Acceleration (cm/s^2)	Peak Ground Acceleration (g)	Epicentral Distance (km)
APLA	HNN	162.95	0.17	48.99
ACH1	HNN	317.52	0.32	53.15
ACH2	HNN	148.50	0.15	53.61
GYKA	HNN	194.47	0.20	62.49
AC07	HNE	118.47	0.12	73.17
ARNL	HNN	172.05	0.18	81.68
ACUE	HNE	66.98	0.07	115.00
ALJ1	HNE	47.77	0.05	156.81

The largest records were observed in the HNN components of stations located in Machala ACH1 and Guayaquil GYKA (Table 2.2 and Figure 2.9).

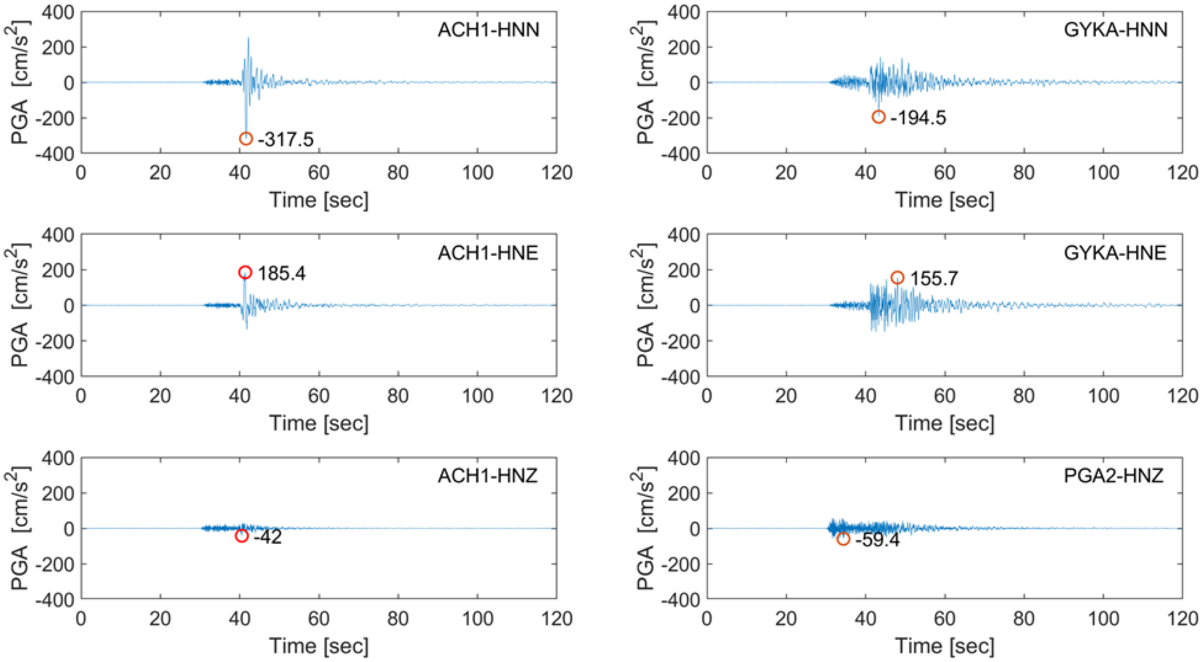


Figure 2.9. Peak ground accelerations of the ACH1 and GYKA stations (IGEPN 2023b).

IGEPN (2023a) also mentions that there is an additional accelerometer station in Machala which registered almost 0.5g. This indicates that there is an amplification effect of the seismic waves in Machala city.

2.6. Response Spectra

Figure 2.10 shows the Fourier Spectra and Response Spectra for the three north (HNN), east (HNE), and vertical components for the stations with higher records (ACH1 and GYKA assuming 5% damping). The maximum spectral acceleration of 934.20 cm/s2 is reached at a period of 0.79 seconds for the N-S component at the ACH1 station while a maximum spectral acceleration of 762.80 cm/s2 occurs for a period of 0.29 seconds for the component E-W (IGEPN 2023b).

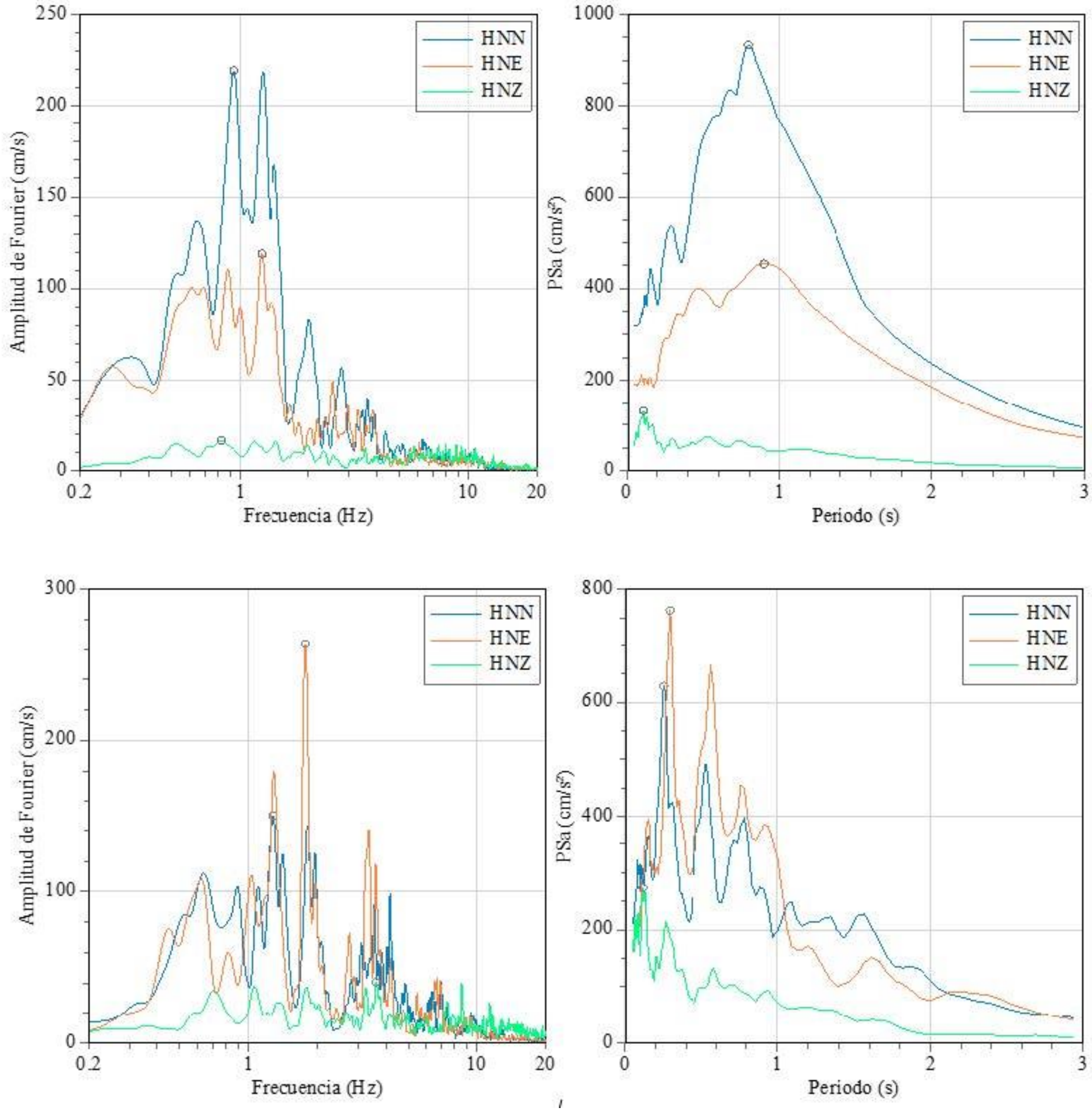


Figure 2.10. Fourier Amplitude and Response Spectra for the ACH1 station (top) and the GYKA station (bottom) (Source: IGEPN 2023a).

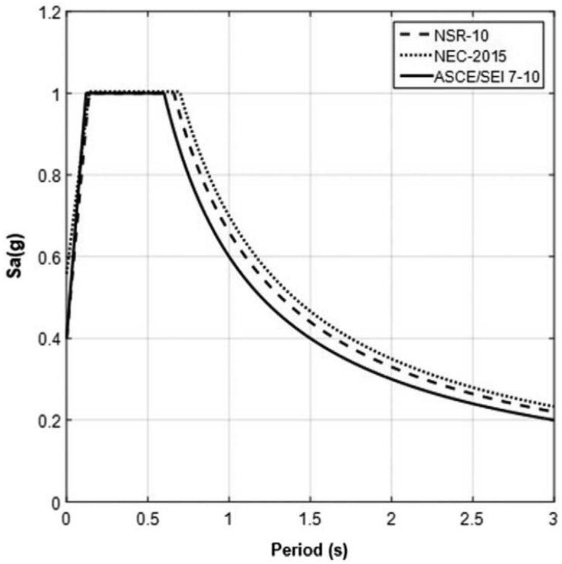


Figure 2.11. Design response spectrum comparison for the three design codes (Arroyo et al., 2018).

Figure 2.11 shows the basic design response spectra from three different seismic codes and standards. According to the seismic map developed by the Ecuadorian Society of Soil Science (Sociedad Ecuatoriana de la CIencia del Suelo 1986), the predominant soil in the gulf is sedimentary. Isla Puná contains sands, silt, clays, and conglomerate while Balao and surrounding areas present mostly limes and clays. Considering a soil type E according to the Ecuadorian seismic normative (NEC), Figure 2.12 shows the design spectra for Balao. The maximum design spectral acceleration is 0.82g (804.15 cm/s^2) which was surpassed by the HNN spectral component in Machala (ACH1) for a period of 0.79 sec (Fig. 2.10 - top).

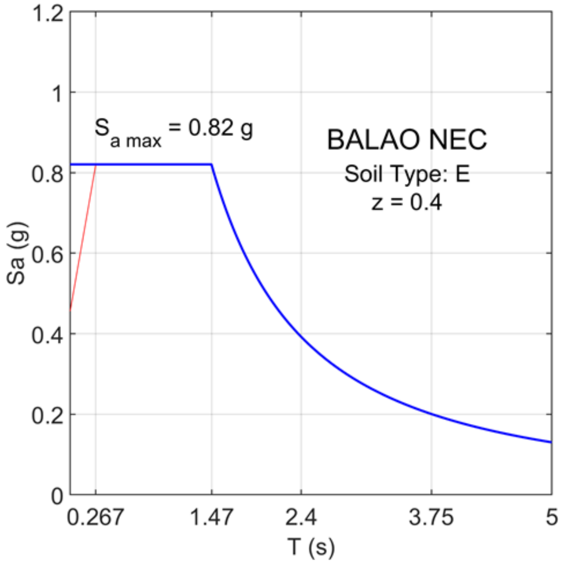


Figure 2.12. Design Response Spectrum for the Balao Earthquake 2023 (NEC 2015).

3. Local Codes and Construction Practices

3.1. Local Codes

Ecuadorian codes started to develop after the devastating consequences of major earthquakes such as the 7.1M that hit Bahía de Caraquez in 1998. This prompted the development of the CEC in 2002 (i.e.,"Código Ecuatoriano de la Construcción") that included basic seismic design guidelines with limited information regarding external loading, structural systems or foundations requirements. Later, NEC-11 replaced CEC to include international updates (i.e., "Norma Ecuatoriana de la Construcción 2011"). Finally, the 5.1M Mitad del Mundo earthquake gave momentum for the development of the NEC-15 (i.e., "Norma Ecuatoriana de la Construcción 2015") which is the current standard and more detailed and restrictive than previous versions (Arciniega and Suárez 2023). The guidelines cover design and construction in different materials such as reinforced concrete, structural steel, and wood. The code covers the following topics: Non-seismic Loading, Seismic Design, Seismic risk, Evaluation and rehabilitation, Geotechnical engineering and foundations, reinforced concrete structures, steel structures, Structural masonry, Wood structures, Two story buildings design, Structures in bamboo, Practical design guidelines, Fenestration components, and Utilities.

Any structures in Ecuadorian territory must follow the minimum requirements established in NEC. The code seeks to achieve structural integrity and functionality (MIDUVI 2023).

3.2. Construction Practices

Ecuador has a total of 3,748,919 buildings distributed across 29 building typologies according to the GEM model (Fig. 3.1). Predominant construction systems are confined non-ductile masonry (50% urban, 45% rural), unreinforced masonry (21% urban, 19% rural), followed by flat slab with reinforced concrete frames in the urban area (12%) and wooden structures in the rural area (10%) (GEM OpenQuake, 2016). The following subsections explain some of the local implementations of these different typologies in Ecuador.

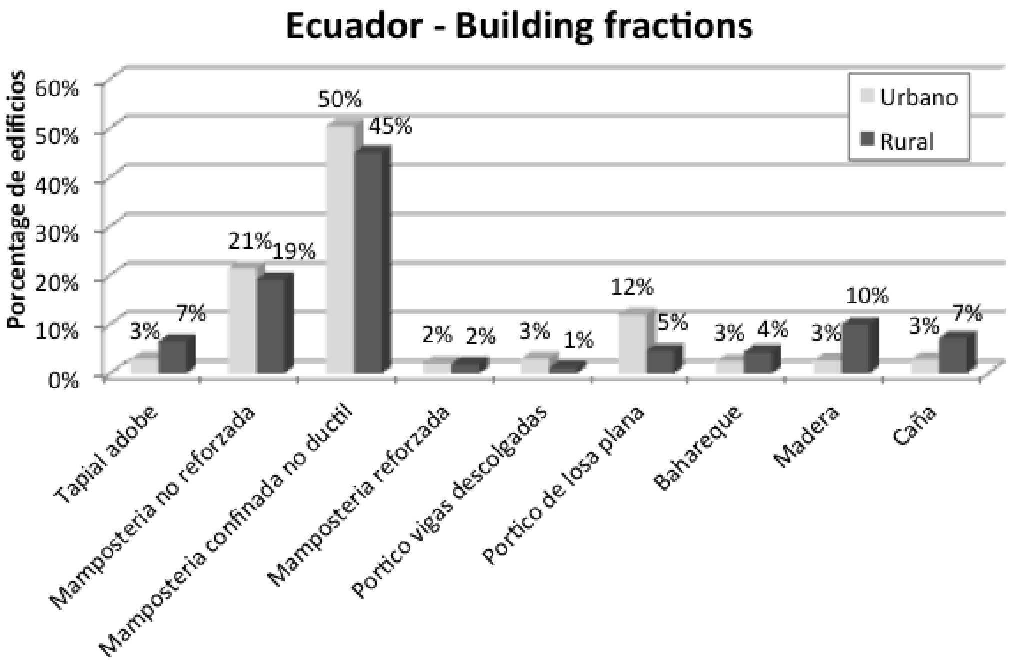


Figure 3.1. Ecuador building typology (GEM OpenQuake, 2016).

3.2.1 Masonry

This system commonly uses RC columns with relatively small dimensions (about 20 cm x 20 cm) and flat slabs at each story. Then, masonry such as artisanal clay bricks or cement blocks, fill the walls. Slender columns, shallow beams, and heavy masonry that are not properly attached to the frames create a very flexible structure with low strength to resist shear forces during seismic events. Figure 3.2 shows four common types of masonry buildings determined based on the material of the wall and the degree of confinement provided by the masonry to the concrete frame (Jiménez-Pacheco et al., 2022):

Figure 3.2. Masonry buildings typology: (a) unconfined adobe masonry, (b) unconfined brick masonry, (c) brick masonry with tie beams, (d) confined brick masonry. (Jiménez-Pacheco et al., 2022).

3.2.2 Bahareque

Figure 3.3 shows a popular construction system, especially in the coastal region. It uses a type of bamboo known as guadua, along with timber, mud, straw, cow manure, and plaster. These are light structures sitting on top of concrete foundations. The system is so popular in the Andean region that there is a more engineered version for the design and construction of single and two-story houses, and it is referred to by the Ecuadorian construction normative (NEC). These types of structures usually perform well during seismic events (INBAR 2016).

Figure 3.3. Non-engineered Bahareque House with substrate exposed by crumbled stucco (Kaminsky 2023).

3.2.3 Clay brick and timber

This structural system combines timber frames with clay or cement blocks as infill masonry. Occasionally this system also includes diagonal timber elements that provide a bracing action increasing the lateral strength (Fig. 3.4).

Figure 3.4. Two-story clay brick and timber building in Manabí. Note the timber framing on the unfinished face creates tall infill panels of irregular width (Google Earth Manabí 2023).

3.2.4 Wood structures

All elements in this structural system (i.e., columns, beams, floors, and partitions) are made of wood. These buildings follow intuitive construction practices where there is no quality control of materials, load paths, or lateral resisting systems (Fig. 3.5).

Figure 3.5. Non-engineered elevated wood house in Pasaje showing typical use of mixed lightweight materials as cladding elements and corrugated galvanized iron roof (Google Earth Pasaje 2023).

4. Building Performance

Tables 4.1 and 4.2 provide a synthesis of the typical performance of other infrastructure classes during this event, organized by class and geography. The subsections that follow present notable case studies. Readers may consult the imagery compiled in the accompanying Media Repository, curated with this report in DesignSafe, to access a richer collection of georeferenced visual evidence cataloged by occupancy.

Table 4.1. Summary of Building Performance by Occupancy.

Single-Family Residential Buildings	**There is** evidence of extensive damage and collapse of several non-engineered buildings. There is the presence of flexible frames with stiff masonry, no seismic gap, and lateral stiffness irregularities.
Multi-Family Residential Buildings	**There is** evidence of extensive nonstructural damage in components such as infill walls.
Commercial Buildings	**There is no** evidence of structural damage in these reinforced concrete structures. Nonstructural damage is concentrated in components such as infill walls.
Healthcare/Medical Facilities	**There is no** evidence of structural damage in these reinforced concrete structures. Nonstructural damage is concentrated in components such as infill walls.
Schools	**There is no** evidence of structural damage in these reinforced concrete structures. Nonstructural damage is concentrated in components such as infill walls.
Government Facilities	**There is** evidence of nonstructural damage in these reinforced concrete structures appearing in components such as infill walls.
Mobile/Manufactured Homes	No observations are available for this class at the time of this report.
Critical Facilities	**There is** one documented case where soil settlements deteriorated the structural foundations of spherical liquid gas storage units.
Historical Buildings	**There is** structural and nonstructural damage reported for about 35 structures including churches, museums, and schools in Azuay. **There is** also a documented case where the partial collapse of a facade from a historical building killed a person in Cuenca.
Religious Institutions	**There is** extensive structural damage in arches and domes as well as partial collapses of facade components. At least 13 churches were damaged in Azuay.

Table 4.2. Summary of Building Performance by province.

El Oro	This province registers **most of the damage** (58% of total damage to residential buildings) from which twenty-four percent collapsed.
Azuay	This province registers 7% of total damage to residential buildings from which thirty-four percent collapsed.
Guayas	This province registers 30% of total damage to residential buildings from which fourteen percent collapsed.
Cañar	This province registers 11 damaged residential buildings from which 5 collapsed

Source: Dirección de Monitoreo de Eventos Adversos (2023)

4.1. Total Collapse of Single-Family Residential Building

Figure 4,1 shows a non-engineered building located in Machala, El Oro, Ecuador near the intersection of Boyaca and Paez streets, located approximately 50 km from the epicenter of the 6.8Mw Balao Earthquake. The structure was at least 50 years old according to local sources (Primicias 2023a), and it featured a mixed structural system with wooden frames and beams on the back side, and flexible RC columns and beams on the front side. There was also stiff clay brick masonry, wooden floors, and concrete slabs. It is obvious from the pictures that there is a commercial shop at the first floor while the upper floor was residential.

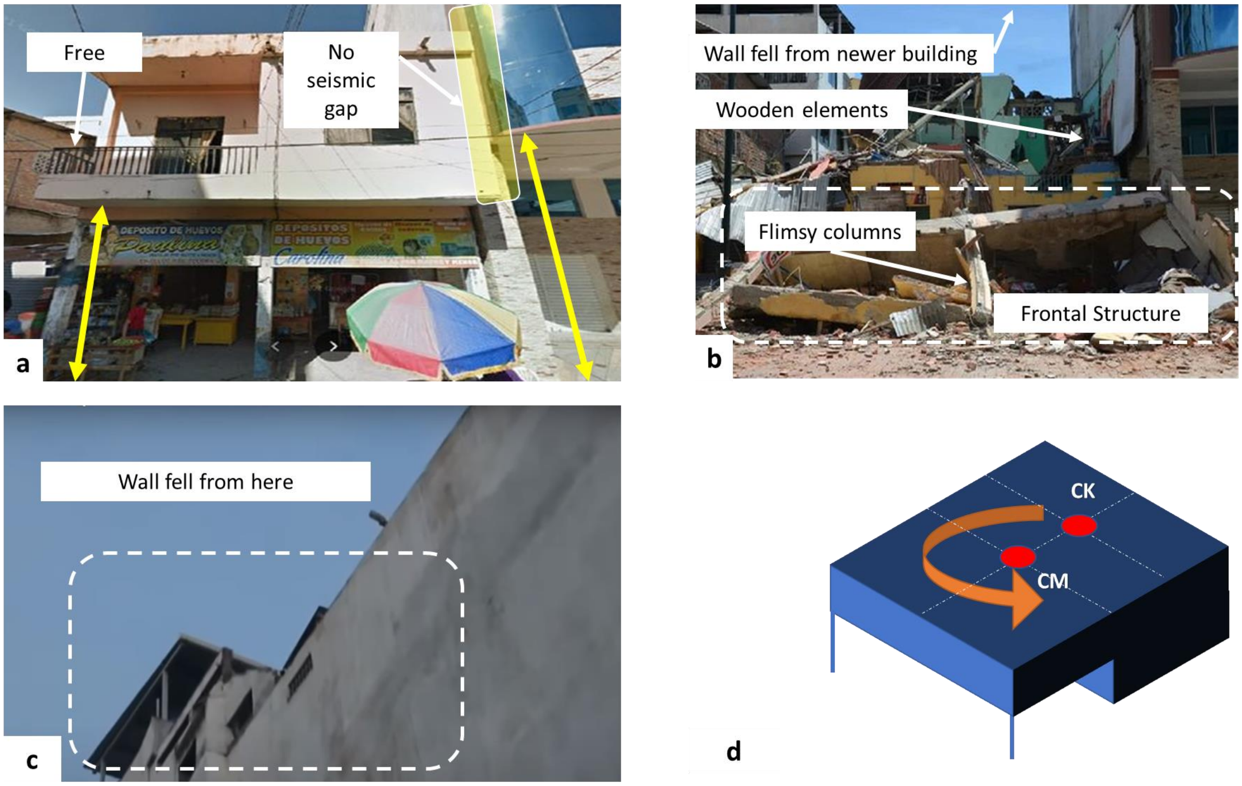


Figure 4.1. Total collapse of a single-family residential building in Machala. (a) Structure before the collapse (El Comercio 2023b) (b) Collapsed structure (Suarez 2023) (c) According to local reports the partial collapse of a brick wall from the fifth story of the neighboring building triggered the collapse of this two-story structure (Primicias 2023a, Endara, A. B. 2023, Arias 2023). The fall of the wall from the neighboring building in combination with stiffness irregularities like the open ground story in the front of the building inducing torsion, lack of seismic gap generating pounding, flexible frames with stiff brittle infill walls that allow large drifts contributed to the collapse of this building. (d) Schematic demonstration of torsional effect induced by stiffness irregularities causing the collapse of a two-story building shown in (a) and (b).

4.2. Partial collapse of Multi-Family Residential Building on top of a Single-Family Residential Building

Figure 4.2 shows three buildings located side by side in Pasaje, El Oro, Ecuador, approximately 50 km from the epicenter of the 6.8Mw Balao Earthquake. The partial collapse of the flexible structure of the building in the middle triggered the full collapse of the smaller non-engineered structure while the building on the right side remains sound. The building in the center exhibits different architectural finishes in the upper stories and the structural system seems discontinuous. This suggests that the upper stories were part of an extension to the original structure. The reinforced concrete building on the right side remains sound.

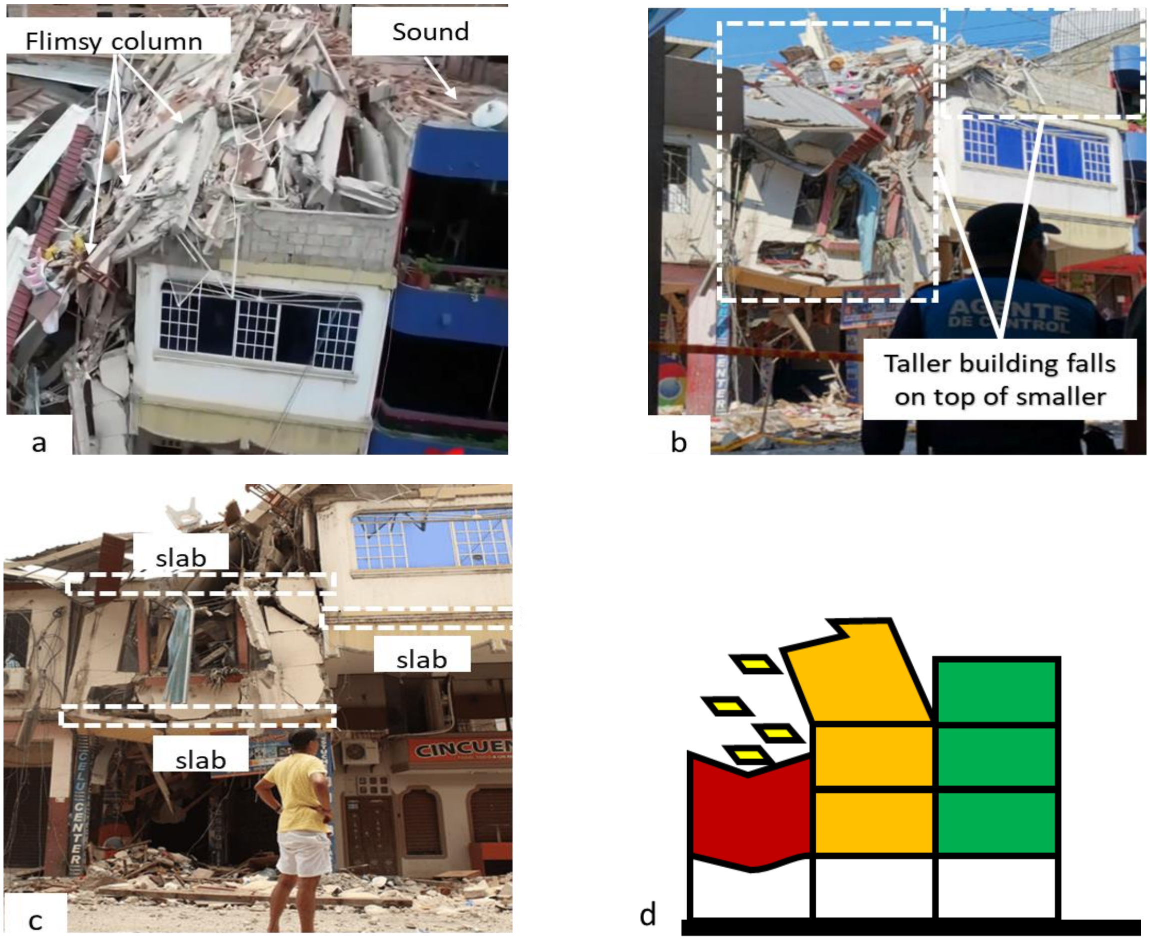


Figure 4.2. Total collapse of a single-family residential building in Machala. (a) Partial collapse of flexible upper stories in the taller building (Ecuavisa 2023). (b) Full collapse of the smaller non engineered building (García 2023) (c) Slabs at different levels could have hit columns in the smaller building around mid height (El Universo 2023a). (d) Scheme of the interaction among these three buildings.

4.3. Single-Family Residential Building with Pre-existing Damage

Figure 4.3 shows a non-engineered single-family building located in Machala, El Oro, Ecuador. While most of the structure is a combination of wooden frames and clay-bricks, the frontal overhang is sitting on top of what looks like reinforced concrete columns. Besides stiffness irregularities, lack of seismic gap and stiff masonry, this building attracts attention due to the pre-existing damage that was captured by google street view in 2015 and remains to date. Apparently, this structure already survived the 7.8Mw Muisne earthquake (400 km from the epicenter) in 2016 which was felt around the country. However, this time (50 km from the epicenter) there were concerns regarding its integrity which prompted the use of emergency shoring whose efficacy could be questioned judging by the picture.

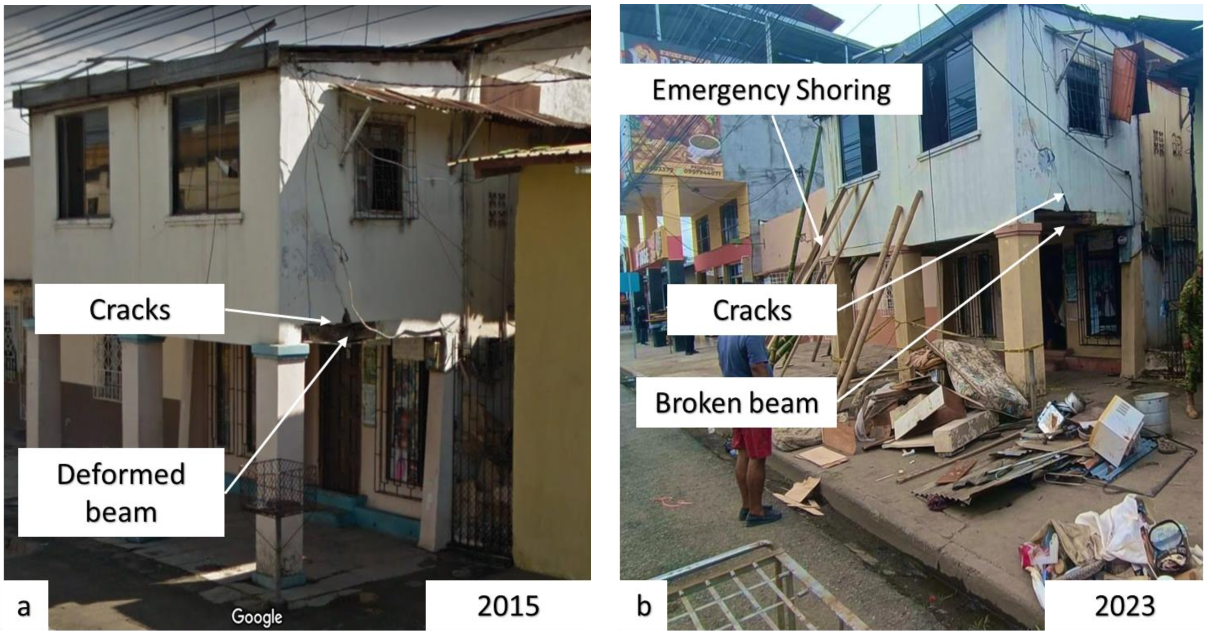


Figure 4.3. Building with pre-existing damage. (a) There is a permanent deformation in one of the beams of the floor system that seems to be the reason for that masonry crack in the right side of the building (Google 2015). (b) There are signs of attempting to fix the crack, but part of the exterior beam seems to be missing / broken Twitter (2023c). However, it appears that the beams' redundancy of the floor system has enabled a redistribution of the loads.

4.4. Single-Family Residential Building Collapse

Figure 4.4 shows a non-engineered single-family building located in Baños, Azuay, Ecuador, approximately 64 km from the epicenter of the 6.8Mw Balao Earthquake. The structure is a combination of very slender columns and cement blocks. This building displays a combination of structural deficiencies such as discontinuous load paths, small cross sections in frames, poor reinforcement in the elements that are intended to work as columns, concentration of the second story mass in one side of the building even when all vertical elements are about the same size.

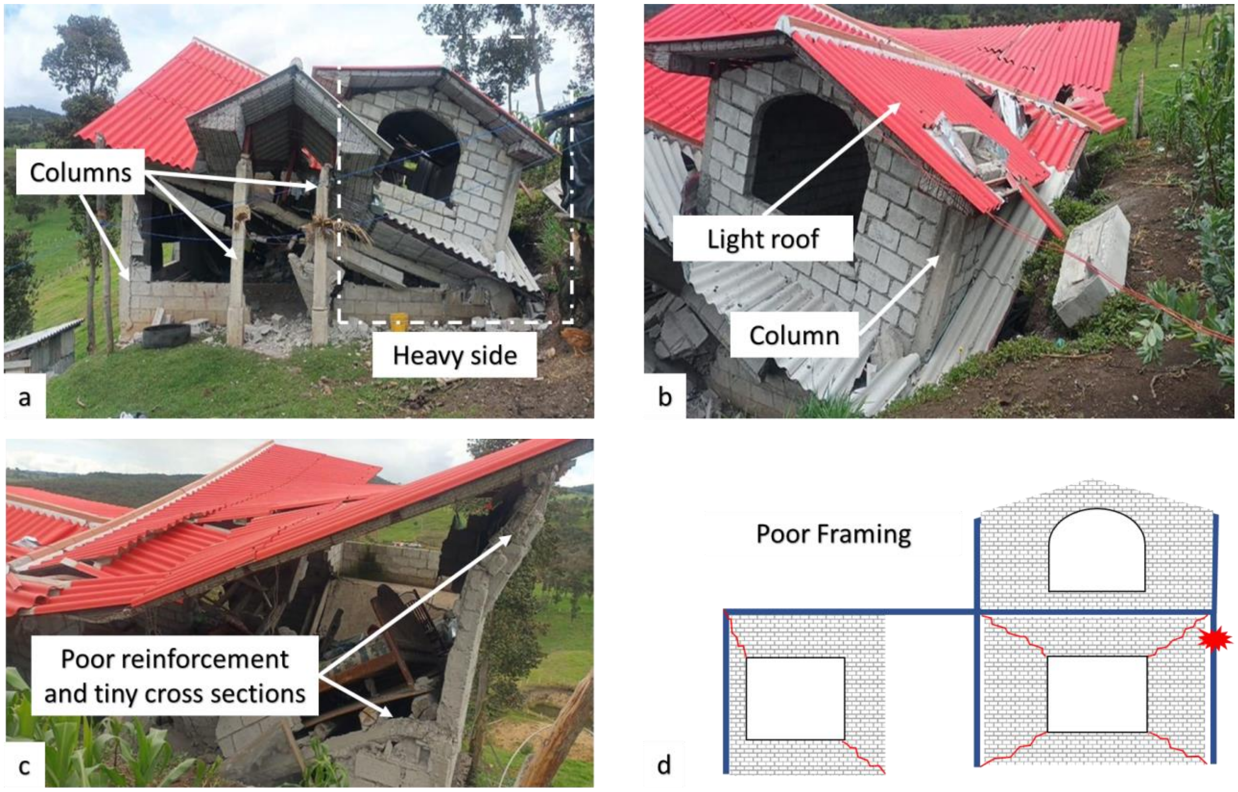


Figure 4.4. Single-family building collapse. (a) Front view shows slender columns and lack of a proper load path with a concentration of mass on the right side of the building (Twitter 2023d). (b) Second floor collapses on top of the first floor even using a relatively light roof (Twitter 2023d). (c) Poor reinforcement, tiny cross sections, and incorrect framing (Twitter 2023d). (d) Sketch of deficient framing leading collapse.

4.5. Structural deficiencies at Pucará church

Figure 4.5 shows a church located in Pucará, Azuay, Ecuador, approximately 75 km from the epicenter of the 6.8Mw Balao Earthquake. The church is one of several churches in need of rehabilitation in Azuay. Many of these churches namely, Baños, Sinicay, San Fernando, Santo Domingo and the Catedral present deficiencies in structural components such as arches, domes, and the structures that hold roofs and towers.

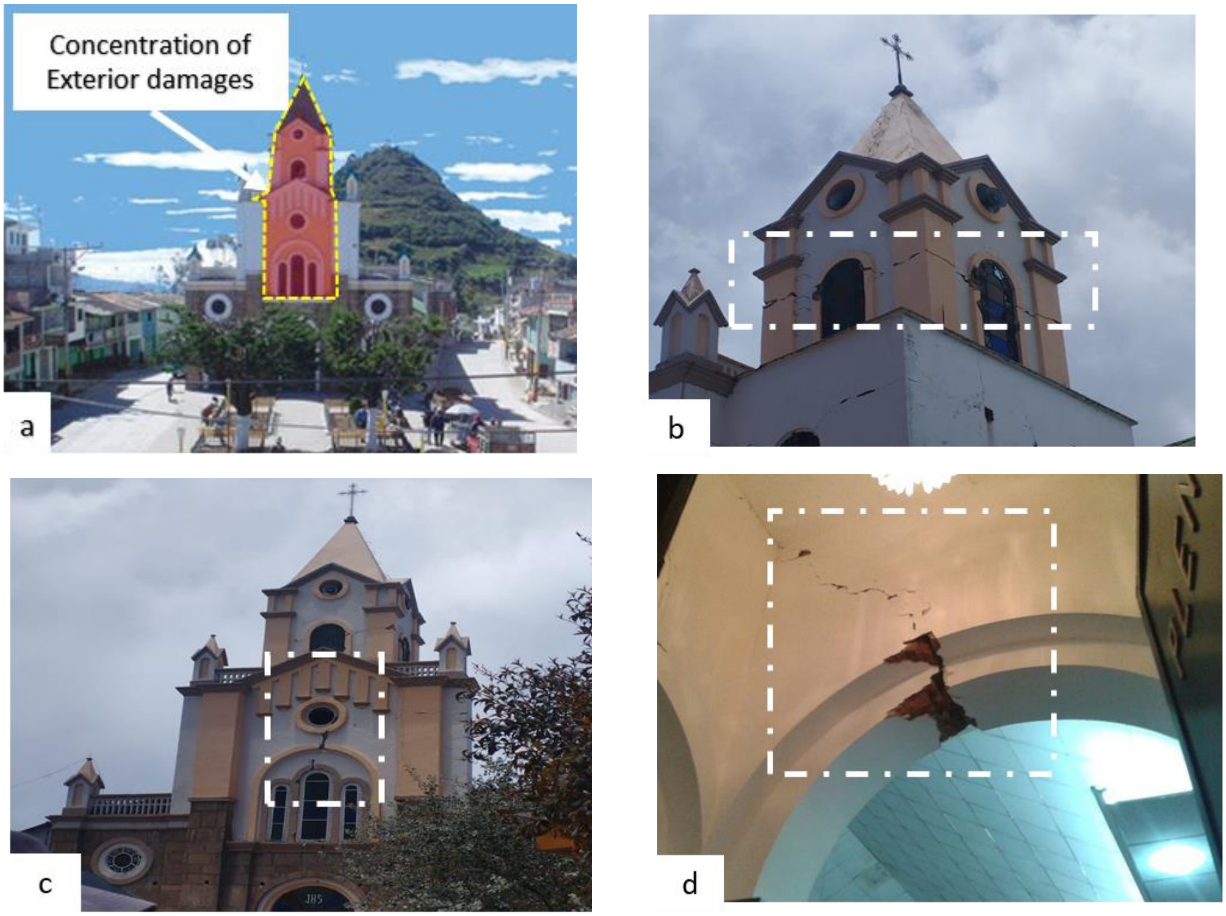


Figure 4.5. Deficiencies at Pucara church. (a) Original structure (Avilés 2023). (b) Cracks in the vertical elements supporting the tower (Twitter 2023e). (c) Cracks in arches at the facade (Twitter 2023e). (d) Interior cracks in arch (Twitter 2023f).

4.6. Piles Failure at the Maritime Museum and Dock

Figure 4.6 shows the marine museum located in Puerto Bolivar, El Oro, Ecuador, approximately 50 km from the epicenter of the 6.8Mw Balao Earthquake. Local news, Primicias (2023b), reported that the steel piles bent and collapsed due to the lateral motion induced by the 6.8M Balao earthquake.

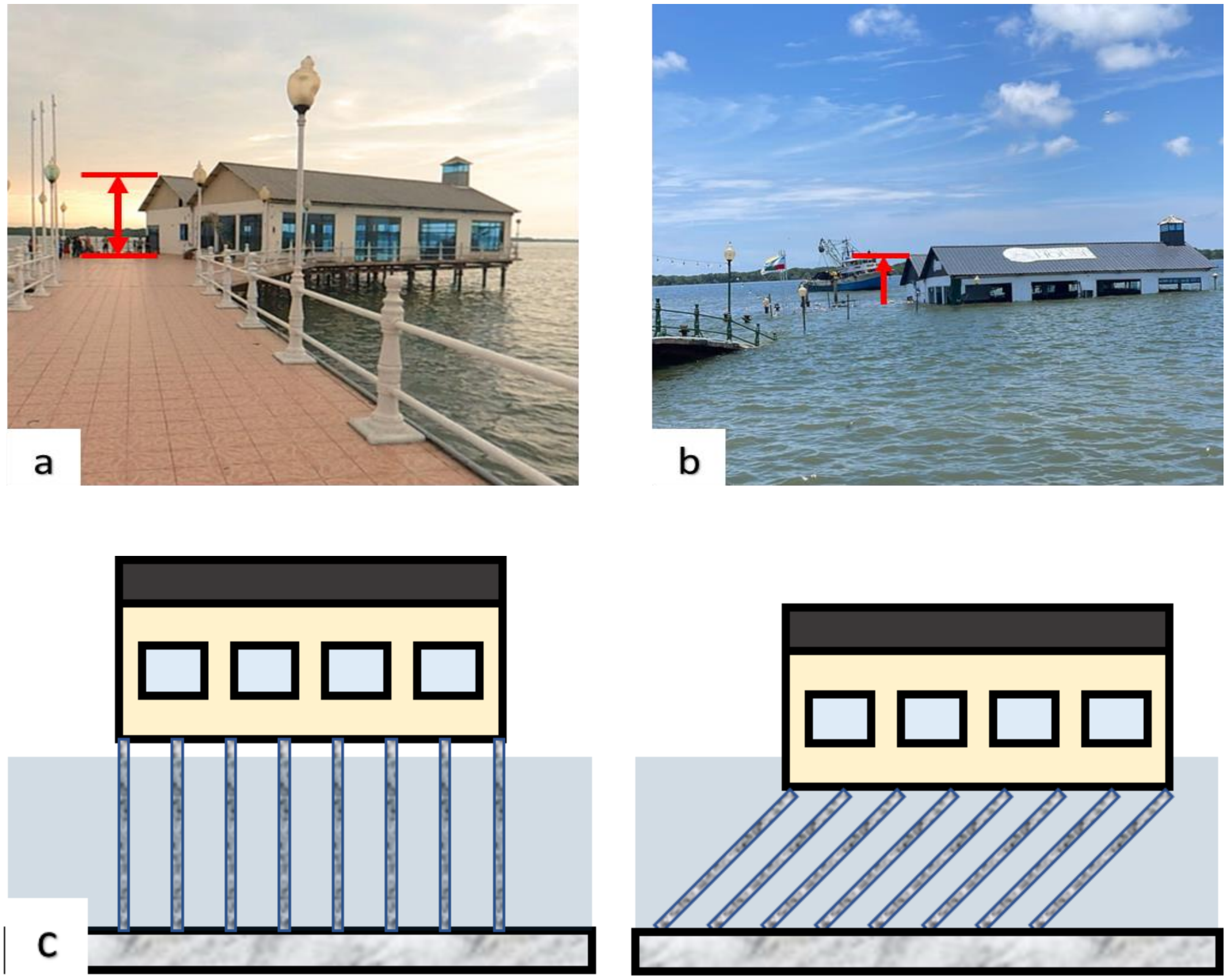


Figure 4.6. Piles Failure at the Maritime Museum and Dock. (a) Marine museum before the 6.8Mw Balao earthquake (Jimenez 2021). (b) Marine museum after the 6.8M Balao earthquake (Twitter 2023h). (c) Sketch of the failure.

5. Infrastructure Performance

Tables 5.1 and 5.2 provide a synthesis of the typical performance of other infrastructure classes during this event, organized by class and geography. The subsections that follow present notable case studies. Readers may consult the imagery compiled in the accompanying Media Repository, curated with this report in DesignSafe, to access a richer collection of georeferenced visual evidence cataloged by infrastructure class.

Table 5.1. Summary of Performance by Infrastructure Class.

Power and Telecommunications Infrastructure	**There are** several reports of power outages due to broken cables, damaged electrical insulators, fallen poles and electric transformers. The damage is concentrated among El Oro, Guayas, and Manabí.
Airports	No observations available for this class at time of this report.
Roads & Bridges	**There were** reports of landslides in Cuenca-Molleturo and Girón-Pasaje routes. El Oro showed cracks in the Balosa route.
Other Lifelines	**There were** interruptions in the data network.
Port Facilities	No observations available for this class at time of this report.
Agricultural	No observations available for this class at time of this report

Sources: Netblocks (2023), CNEL (2023a), Dirección de Monitoreo de Eventos Adversos (2023)

Table 5.2. Summary of Infrastructure Performance by Geography.

El Oro	**There were** 2000 power outages due to broken cables, damaged electrical insulators, fallen poles, and electric transformers. **Highest** interruption in network connectivity, 40.0 % reduction. **There were** reports of disruptions in the water supply
Guayas	**There were** fewer power outages than in El Oro coming from the south and southwest of Guayaquil. Isla Puná had to be disconnected. **Minimal** interruption of internet network connectivity
Manabí	**There were r**eports of power outages from Manta and Portoviejo. **Minimal** interruption of internet network connectivity
Azuay	**Minimal** interruption of internet network connectivity

Sources: Netblocks (2023), CNEL (2023), Dirección de Monitoreo de Eventos Adversos (2023)

5.1. Power Outages & Restoration

Table 5.3 shows the extent of power outages and current state of restoration for the electrical distribution system.

Table 5.3. Extent of Power Outage and Restoration (at time of report release).

	Peak Outage	Restoration Status
El Oro	50%	100%
Azuay	30%	100%
Guayas	-	100%

Source: Dirección de Monitoreo de Eventos Adversos (2023)

5.2. Transportation Disruptions & Restoration

Table 5.4 shows the extent of roadway closures and current state of restoration for the highway network.

Table 5.4. Extent of Road Closures and Restoration (at time of report release).

	# landslides	Restoration Status
Cuenca-Molleturo	13	100%
Girón-Pasaje	9	100%
Riobamba-Colta	1	100%

Source: Dirección de Monitoreo de Eventos Adversos (2023), MTOP (2023)

5.3. Landslide in Cuenca-Molleturo Route

There were thirteen reports of landslides along this route. The more significant ones were at the 74, 93, and 98 kilometer marks. Large rocks and soil filled the road in several locations (Fig. 5.1). A person was reported killed due to a landslide on this route (El Universo 2023b). The Ecuadorian government declared a state of emergency in Azuay.

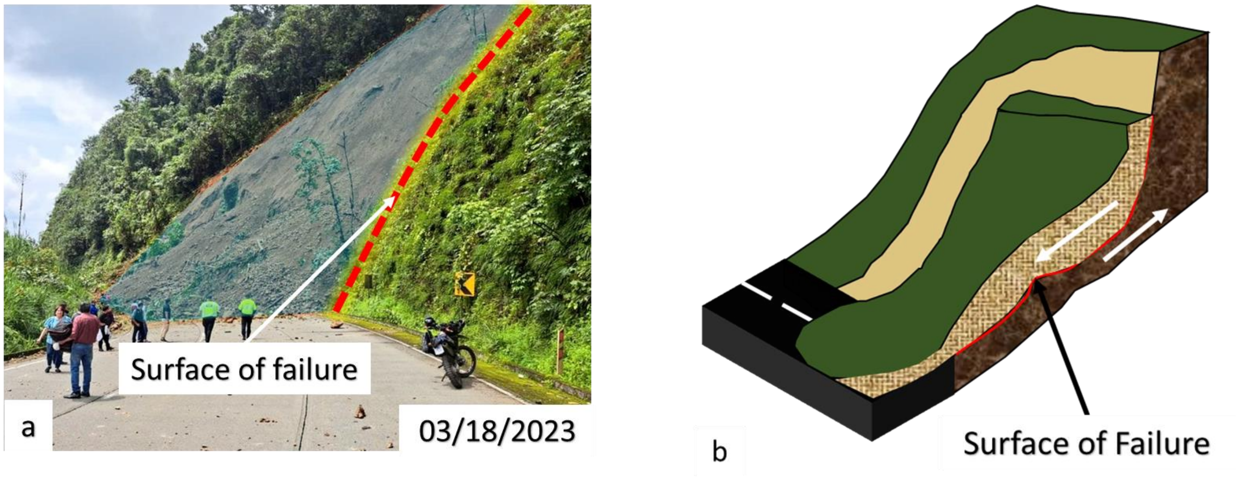


Figure 5.1. Landslide on Cuenca-Molleturo Route (a) Cuenca-Molleturo Route landslide closing 30 m of road (Twitter 2023g). (b) Sketch of the surface of failure generated during the seismic motion.

6. Geotechnical Performance

This section provides a written synthesis of the geotechnical issues noted in this event (Table 6.1). Readers may consult the imagery compiled in the accompanying Media Repository, curated with this report in DesignSafe, to access a richer collection of georeferenced visual evidence.

Table 6.1. Summary of Geotechnical Performance by Province.

El Oro	**There were** reports of liquefaction at Puerto Bolivar, Machala.
Guayas	**There were** reports of liquefaction at Isla Puná, Guayas
Azuay	**There were** reports of settlements in the foundations of the spherical petroleum liquid gas storage units in Cuenca.

Source: Dirección de Monitoreo de Eventos Adversos (2023), MTOP (2023)

6.1.Liquefaction at Isla Puná

There were several reports of liquefaction from Isla Puná, Guayaquil, Guayas which is located in the Gulf of Guayaquil, right next to the location of the epicenter of the Balao Earthquake (Fig 6.1). The community describe it as small water volcanoes. There were no total collapses, but there were at least ten partial collapses reported by Dirección de Monitoreo de Eventos Adversos (2023).

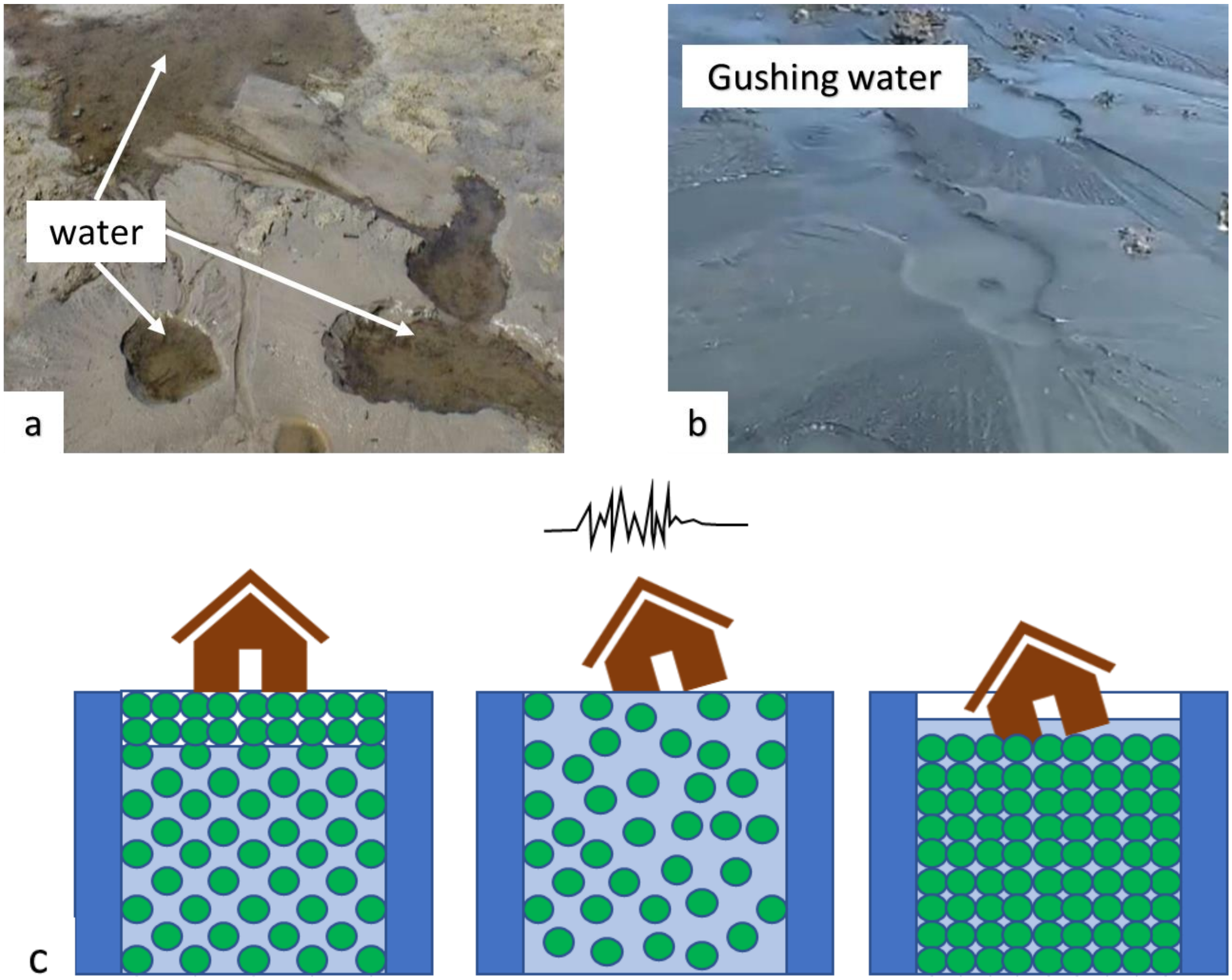


Figure 6.1. Liquefaction at Isla Puná: (a) Water pools due to liquefaction (El Comercio 2023c). (b) Soil fractures surrounding foundations (El universo 2023c). (c) Liquefaction phenomenon sketch.

6.2. Foundation Settlements of the Petroleum Liquid Gas Storage Units

Figure 6.2 shows spherical storage tanks of 3,238 m^3 each for petroleum liquid gas, located in Cuenca, approximately 70 km from the epicenter of the 6.8Mw Balao earthquake. According to government representatives (Transport Manager of Petroecuador), these structures already had settlement issues which were exacerbated by the 6.8Mw Balao earthquake reaching settlements of about 3 cm. The spheres are scheduled to be disassembled and transported to Chorrillos Terminal in Guayas where they will be reassembled.

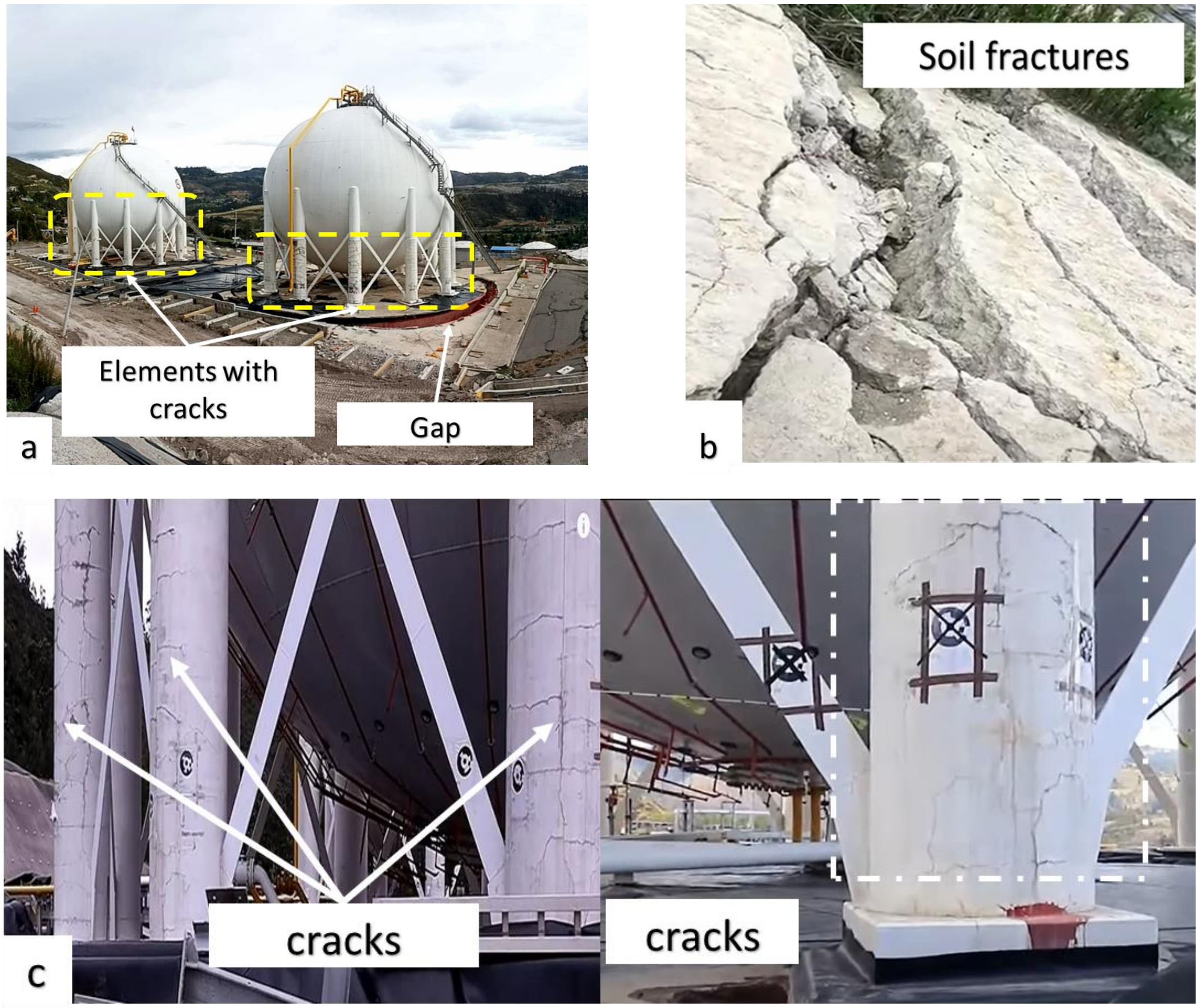


Figure 6.2. Foundation Settlement of Storage units: (a) Spherical Storage unit site (Twitter 2023i). (b) Soil fractures surrounding foundations (Twitter 2023j). (c) Distress in supporting columns due to relative settlements (Twitter 2023j).

7. Recommended Response Strategy

Based on the information gathered by this Preliminary Virtual Reconnaissance Report (PVRR), StEER offers the following recommendations for future study.

Study of alternatives for heavy and brittle infill walls: Most buildings in Ecuador continue to use stiff brick masonry made from either solid clay bricks or cement blocks. These infill systems do not allow the development of the expected in-plane drift of reinforced concrete frames. This problem is of particular importance for non-engineered buildings where the use of extremely flexible frames is widespread. Alternatives must focus on using lighter systems while retaining some of the characteristics that make these stiff infills appealing (i.e., economy, and acoustic isolation). The effects of these systems are easily seen in the partial collapses of at least 10 houses reported in Isla Puná, the government buildings that needed to stop their activities after the 6.8Mw Balao earthquake, and the collapsed structures in El Oro, and Azuay.

Study of structural deficiencies in historical buildings: The number of historical buildings in Ecuador is large and seismic events are deteriorating these structures in some cases and collapsing them in others. Ecuador boasts two cities, Quito and Cuenca that are UNESCO-designated World Heritage Sites. Quito is considered to house the largest collection of historical architecture in Latin America, including magnificent church structures, such as the San Francisco and Santo Domingo monasteries, and the Church and Jesuit College of La Compañía. Cuenca, (official name: the Historic Centre of Santa Ana de los Ríos de Cuenca) retains attributes necessary for the UNESCO designation of its Outstanding Universal Value, having kept its original townscape and urban planning guidelines intact for the past 400 years.

The seismic performance of historic churches shows structural (i.e., cracks in domes, towers, arches) and nonstructural (i.e., falling facade components) deficiencies that seem to be consistent among these structures. Cost-effective and structurally efficient retrofits must be developed to preserve these buildings. In fact, nondestructive evaluation techniques could be used to catalog the mechanical and dynamic properties of the structural components while numerical and experimental models could measure the effectiveness of proposed retrofit techniques. All these studies may lead towards improved retrofit guidelines for these types of structures in Latin America.

Based on the findings of this report, StEER's response to this event will remain at Level 1 with no activation of a Field Assessment Structural Team (FAST). As a result, this PVRR represents the extent of StEER's official response. StEER will continue to coordinate with other organizations responding to this event to encourage consideration of the above recommendations and will monitor their assessments. Should these ongoing efforts reveal new information that would satisfy one or more of StEER's escalation criteria, StEER may re-evaluate its decision and deploy a FAST.

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