M7.2 Nippes Earthquake, Haiti

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PRELIMINARY VIRTUAL RECONNAISSANCE REPORT (PVRR)

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PREFACE

The National Science Foundation (NSF) awarded a 2-year 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 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 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. StEER works closely with other extreme event reconnaissance organizations and the Natural Hazards Engineering Research Infrastructure (NHERI) to foster greater potentials for truly impactful interdisciplinary reconnaissance after disasters.

Under the banner of NHERI's CONVERGE node, StEER works closely with the wider Extreme Events Reconnaissance consortium, including the Geotechnical Extreme Events Reconnaissance (GEER) Association and the networks for Nearshore Extreme Event Reconnaissance (NEER), Interdisciplinary Science and Engineering Extreme Events Research (ISEEER), Social Science Extreme Events Research (SSEER), and SUstainable Material Management Extreme Events Reconnaissance (SUMMEER) as well as the NHERI RAPID equipment facility and NHERI DesignSafe CI, long-term home to all StEER data and reports. While the StEER network currently consists of the three primary nodes located at the University of Notre Dame (Coordinating Node), University of Florida (Atlantic/Gulf Regional Node), and the University of California, Berkeley (Pacific Regional Node), StEER aspires to build a 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 M. Mosalam (co-PI),** University of California, Berkeley, serves as StEER Associate Director for Seismic Hazards, leading StEER's Pacific Regional node and 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, leading StEER's Atlantic/Gulf Regional node and serving as primary liaison to the Wind Engineering community.
- **Ian Robertson (co-PI),** the 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.

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 (available at https://www.steer.network/products).

Citing Images from this PVRR

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ACKNOWLEDGMENTS

This material is based upon work supported by the National Science Foundation under Grant No. CMMI 1841667. 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 Michael Wilson and Lamarre Presuma for direct reporting of eyewitness accounts in the Sud Department within minutes of the earthquake. StEER also appreciates the partnership with GeoHazards International (GHI) under the leadership of Janise Rogers for a similar exchange of information in the Nippes Department. This response benefitted from the continuous exchange of information with colleagues and friends in Haiti, especially from Gefthé Dévilmé of GHI who immediately documented affected communities in Nippes. StEER also recognizes the efforts of Eduardo Miranda and the Earthquake Engineering Research Institute Learning from Earthquakes Program for their engagement and in guidance on the response strategy discussed herein. StEER also apprciates teh background information shared on Nippes and Sud Department by the team from Notre Dame's Integration Lab, including Angelina Soriano Nuncio, Andrew Caffro, Abigail Ginzburg and Lamarre Presuma, who collected valuable baseline data from communities in the affected areas in the summer of 2021, prior to the earthquake.

The sharing of videos, damage reports and briefings via Slack by the entire NHERI community was tremendously helpful and 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

TABLE OF CONTENTS

EXECUTIVE SUMMARY

A magnitude 7.2 earthquake with epicenter coordinates 18.408°N 73.475°W and a depth of 10 km struck 13 km SSE of Petit Trou de Nippes in Haiti at approximately 8:29 am local time, affecting a wide swath of the Tiburon Peninsula, including the Departments of Nippes, Sud, and Grand'Anse. This earthquake resulted from an oblique reverse motion along the Enriquillo-Plantain Garden fault zone, 75 km west of the 2010 Mw 7.0 earthquake epicenter. In addition to widespread destruction in the Nippes Department, the earthquake affected major city centers on the north and south coasts (Jeremie and Les Cayes, respectively), both still recovering from 2016's Hurricane Matthew.

With hundreds of aftershocks in the weeks that followed, collapses and significant damage to the built environment continues to mount. As of August 22, 2021, Haiti's Civil Protection Agency reported 2,207 deaths with 344 still missing. Another 12,268 were injured. Nearly 61,000 homes have been destroyed and more than 76,000 have sustained damages in the three most affected departments. An initial rapid assessment found that 24 health facilities have been affected in the Sud, Nippes and Grand'Anse Departments. Religious institutions, which provide worship, education, and healthcare in many communities, were also significantly impacted.

With the 14 August 2021 earthquake and its subsequent aftershocks affecting three departments of Haiti, the geographic expanse and intensity of this event are actually greater than the 2010 earthquake, exposing a more diverse cross-section of regional construction practices to strong shaking. This resulted in StEER initiating a Tier 2 response and releasing this **Preliminary Virtual Reconnaissance Report (PVRR)** to:

1. provide an overview of the 2021 Haiti Earthquake, particularly relating to the impact of the earthquake on regions still recovering from a major hurricane,
2. assemble information on the seismic hazard and intensity of ground motions,
3. provide an overview of Haitian regulatory environment and construction practices,
4. summarize the preliminary reports of damage to buildings and other infrastructure, including disruption to the community in terms of fatalities and economic losses,
5. establish current conditions in the affected area with respect to access,
6. provide recommendations to inform the continued study of this event by the natural hazards engineering reconnaissance community, which are organized as follows:
    - TOPIC 1: Performance of Post-2010 and Post-2016 Construction
    - TOPIC 2: Performance of Confined Masonry Systems
    - TOPIC 3: Performance of Vernacular Architecture
    - TOPIC 4: Locally Viable, Affordable and Safe Construction Solutions
    - TOPIC 5: Rapid Assessment Capabilities in Data-Sparse Environments

The report concludes with a discussion of StEER's escalation of this event to a Tier 3 response with Field Assessment Structural Teams in support of Topic 5, employing a new hybrid model that teams local data collectors with virtual engineers for a joint assessment effort.

1.0 Introduction

A magnitude 7.2 earthquake with a depth of 10 km struck Haiti on August 14, 2021, at approximately 8:29 am local time, affecting a wide swath of the Tiburon Peninsula, including the Departments of Nippes, Sud, and Grand'Anse. The earthquake, with an epicenter about 129 km west of Haiti's capital city of Port-au-Prince and 37 km northeast of the largest city on the south coast, Les Cayes, caused collapses and significant damage to the built environment, resulting in a mounting toll of deaths and injuries and significant disruption to the country with shaking experienced across the nation. The earthquake was also felt across the Caribbean, including The Bahamas, Dominican Republic, Jamaica, Puerto Rico, Turks and Caicos Islands, United States Minor Outlying Islands, and Cuba (USGS, 2021).

Not counting this event, Haiti experienced eight major disasters that affected more than half of its population in less than 15 years (Marcelin et al., 2016). Haiti tops all countries in recent years in disaster-related deaths, both in absolute terms and in terms of population size (CRED, 2016). Most notable among these is the 2010 Mw 7.0 earthquake that occurred on January 12 (USGS, 2010), which was one of the most devastating earthquakes in recorded history (Eberhard et al., 2010a), with losses exceeding Haiti's 2009 gross domestic product by more than 20% (Eberhard et al., 2010b). While estimates vary to this day, around 300,000 people died, at least 330,000 were injured, and 1.2 million were displaced by the earthquake, with substantial damage and/or collapses in the housing stock (~105,000), schools (~1,300), critical facilities (~50) and government facilities (13 of 15 ministries) (Eberhard et al., 2010b). While minor in comparison to the 2010 event, an earthquake also struck Port-de-Paix in October 2018 (Hu et al., 2018; Rogers et al., 2021).

In the wake of the 2010 earthquake, emerging research needs, and opportunities were identified by the Earthquake Engineering Research Institute (EERI) in a report to the U.S. National Science Foundation (NSF) (Eberhard et al., 2010b). The report underscored that catastrophic loss of life during the 2010 earthquake was directly related to the exceptional vulnerability of the Haitian building inventory, particularly concrete/masonry multi-story dwellings. In that regard, the report highlighted the following needs to reduce future loss of life and economic damage: (1) identify the most vulnerable buildings within large inventories, (2) target limited resources on the essential facilities and networks within a fragile society, (3) find cost-effective retrofit approaches that consider the unique cultural and economic constraints, (4) assess the possibility of using local materials or recycled materials (including debris) as a viable construction material, and (5) develop methodologies to address multi-hazard conditions that exist in Haiti and many countries. The last point proves a key issue that several studies have given the multi-hazard risk of the Tiburon Peninsula extensive attention. Kijewski-Correa (2018) cautioned against an excessive emphasis on heavier concrete slab roof systems to cope with the losses caused by Hurricane Matthew in 2016 that heavily impacted the Sud and Grand'Anse Departments. Such practices create heightened vulnerabilities to seismic hazards in a region with seismic risks comparable to the epicentral region of the 2010 earthquake. This earthquake is thus a sobering reminder of the challenges of navigating the conflicting design requirements of meteorological and seismic hazards, especially in locales with severe economic and material constraints. The affected population is confronted with the compound effects of Hurricane Matthew, this M7.2 earthquake and its numerous aftershocks, and Tropical Depression Grace, which impacted the displaced population just days after the earthquake and further impeded access by search and rescue teams and humanitarian agencies (Fig. 1.1).

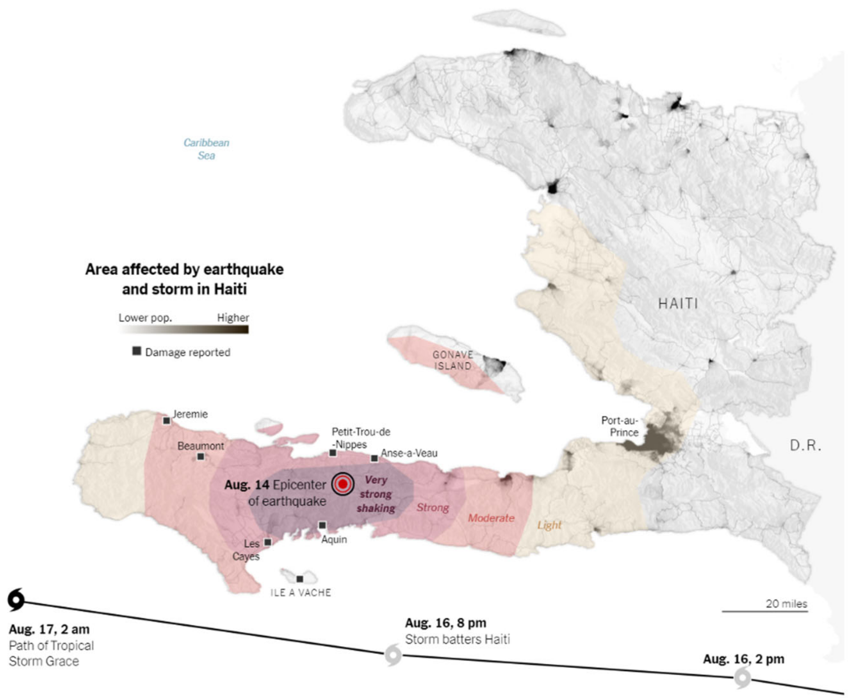

Figure 1.1. Epicenter of the August 14 2021 Mw 7.2 Haiti earthquake, noting earthquake intensity via USGS, population via WorldPop and reported damage via UN OCHA, Reuters and local media, with track of Tropical Storm Grace (Credit: Jugal K. Patel, NY Times).

1.1 Local Context

As the poorest nation in the west, Haiti has faced several development challenges and shocks over its history. This includes the recent disasters and ongoing political unrest culminating in the assassination of its president in July 2021. Non-governmental organizations (NGOs) have expressed concerns that this earthquake is but one more crisis compounding the worsening political stalemate after the president's assassination, COVID-19, and widespread food insecurity (Dupain et al., 2021). As a result, Prime Minister Ariel Henry declared a one-month national state of emergency (OCHA, 2021).

The earthquake significantly impacted two departments (largest territorial divisions in Haiti), namely Sud and Nippes. These departments are subdivided into administrative districts called *arrondissements*, and ultimately into municipalities called *communes.* The Sud Department includes the arrondissements of Cayes, Chardonnières, Côteaux, and Port Salut with the largest city being Les Cayes, while Nippes is divided into Anse-à-Veau, Petit-Trou-de-Nippes, and Baradères, with the largest city being Miragoâne. Overall, Sud is relatively isolated and has an undeveloped road infrastructure. The main road (with over 60 km of paved sections) links Jérémie (in the other affected department to the north, Grand'Anse) to Les Cayes. However, connections to other major cities and Port-au-Prince are limited due to the poor condition of the roads prior to the earthquake. Poverty is high in the Sud with 70-85% of households are considered poor to very poor on established development scales (MSAL, 2020).

1.2 Societal Impact

A United Nations (UN) reconnaissance mission to the affected areas found "less significant damages than initially expected" (OCHA, 2021), based on experiences with the 2010 earthquake, a consequence of the lower density, greater prevalence of single-story construction than in Port-au-Prince, and the fact that many vulnerable buildings were previously destroyed by the 2010 Earthquake and/or Hurricane Matthew. Nevertheless, the earthquake had a significant social impact and public disruption, with PAGER estimated economic losses likely between USD 1 to 10 billion (see distribution in Fig. 1.2). These losses reflect the pre-existing vulnerability in the affected regions. Notably, many communities impacted by this earthquake, including those in Sud and Grand'Anse Departments, were still recovering from Hurricane Matthew which traversed the region on October 4th, 2016, as a category 4 hurricane. The UN estimated that 1.4 million people needed emergency assistance in terms of access to drinking water and sanitation, food, and shelter after that hurricane (MSAL, 2020). Major city centers on the Tiburon Peninsula, including Les Cayes on the south coast and Jérémie on the north coast, both affected by Hurricane Matthew, reported major devastation and widespread collapses of concrete and masonry construction in this earthquake.

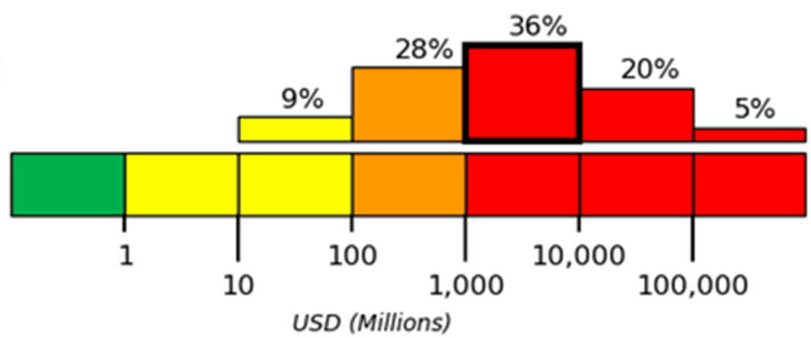

Figure 1.2. PAGER estimated probability of economic losses (USGS, 2021), release date: 2021-08-15 20:31:33 (UTC).

1.3 Loss of Life and Injuries

The full extent of the damage and casualties is not yet known and continues to rise. PAGER estimates are also continually updating but estimate fatalities in the tens of thousands (see distribution in Fig. 1.3). As of August 22, Haiti's Civil Protection Agency reported 2,207 deaths with 344 still missing. Another 12,268 were injured (USA Today, 2021a).

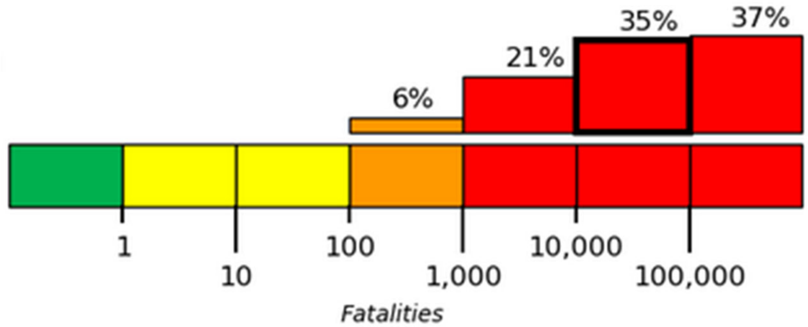

Figure 1.3. PAGER estimated probability of fatalities (USGS, 2021), release date: 2021-08-15 20:31:33 (UTC).

It should be noted that the PAGER predictions reported above were updated versions released more than 2 hours after the earthquake. The original PAGER predictions released immediately after the earthquake had lower probabilities of both economic and loss of life consequences.

1.4 Report Scope

The occurrence of a pair of major earthquakes along the same fault system within a relatively short period, the likely significant loss of life and extensive damage across a large swath of the Tiburon Peninsula, and the complexities of recovery from a multi-hazard sequence (major hurricane followed by a major earthquake) substantiate the need for a **Tier 2 response by StEER** and the formation of a Virtual Assessment Structural Team (VAST). The first product of the StEER response to the 2021 Haiti Earthquake is this **Preliminary Virtual Reconnaissance Report (PVRR)**, which is intended to:

1. provide an overview of the 2021 Haiti Earthquake, particularly relating to the impact of the earthquake on regions still recovering from a major hurricane,
2. assemble relevant information on the seismic hazard and intensity of ground motions in the affected region,
3. provide an overview of Haitian regulatory environment and construction practices in the affected region,
4. summarize the preliminary reports of damage to buildings and other infrastructure, including disruption to the community in terms of fatalities and economic losses,
5. establish current conditions in the affected area with respect to access,
6. provide recommendations to inform the continued study of this event by the natural hazards engineering reconnaissance community.

2.0 Hazard Characteristics

On August 14, 2021, at approximately 8:29 am local time, a magnitude 7.2 earthquake with epicenter coordinates 18.408°N 73.475°W and a depth of 10 km struck 13 km SSE of Petit Trou de Nippes (Nippes Department) in Haiti, see Figure 1.1 (USGS, 2021). The 2010 Mw 7.0 earthquake was located approximately 75 km east of this August 2021 earthquake.

The 2021 earthquake resulted from an oblique reverse motion along the Enriquillo-Plantain Garden fault zone, located 125 km west of the Haitian capital Port-au-Prince. According to USGS (2021), the earthquake occurred at a shallow depth on either a reverse fault striking west and dipping to the north with a component of the left-lateral slip or a fault striking southeast and dipping to the southwest with a right-lateral slip component. The intensity of the 2021 earthquake reached the Modified Mercalli Intensity (MMI) scale IX (Violent) in Les Cayes and MMI VI (Strong) in Port-au-Prince (see Fig. 2.1). By comparison, the epicenter of the 2010 earthquake was much closer to Port-au-Prince (25 km), and its MMI rating was VII (Very strong)[1].

Over 600 aftershocks have been documented by makeshift monitoring networks using inexpensive seismometers (Witze, 2021), causing continued damage and collapse of structures initially damaged by the mainshock. Figure 2.2 displays the locations of some of the most significant aftershocks (Mw 5.0 or greater), the strongest being Mw 5.8 in magnitude and centered approximately 65 kilometers further west on the Tiburon Peninsula.

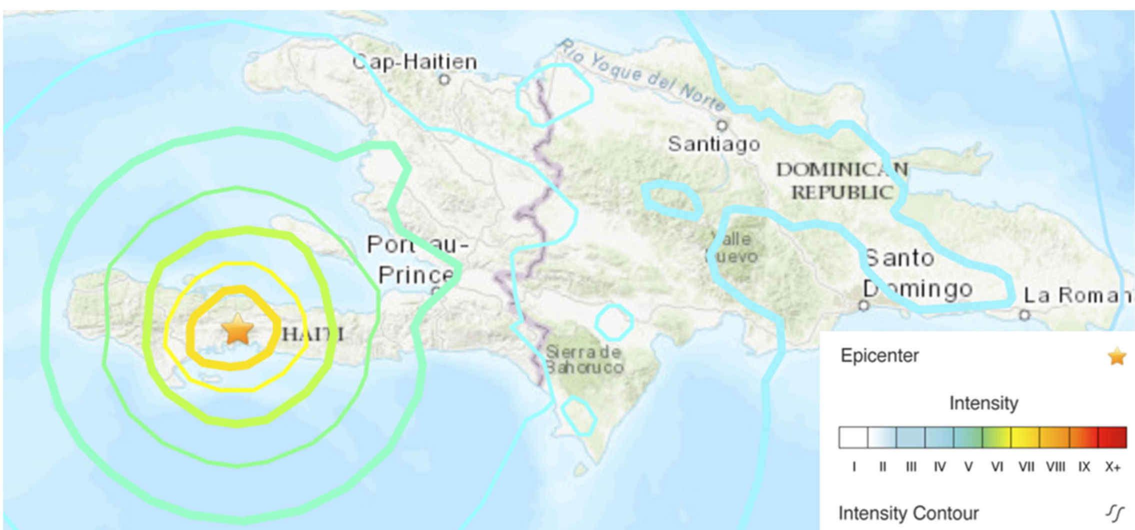

Figure 2.1. 2021 Haiti Earthquake intensity map [Source: earthquake.usgs.gov, Archived from the original on 15 August 2021].

[1] *earthquake.usgs.gov*, Archived from the original on 15 August 2021.

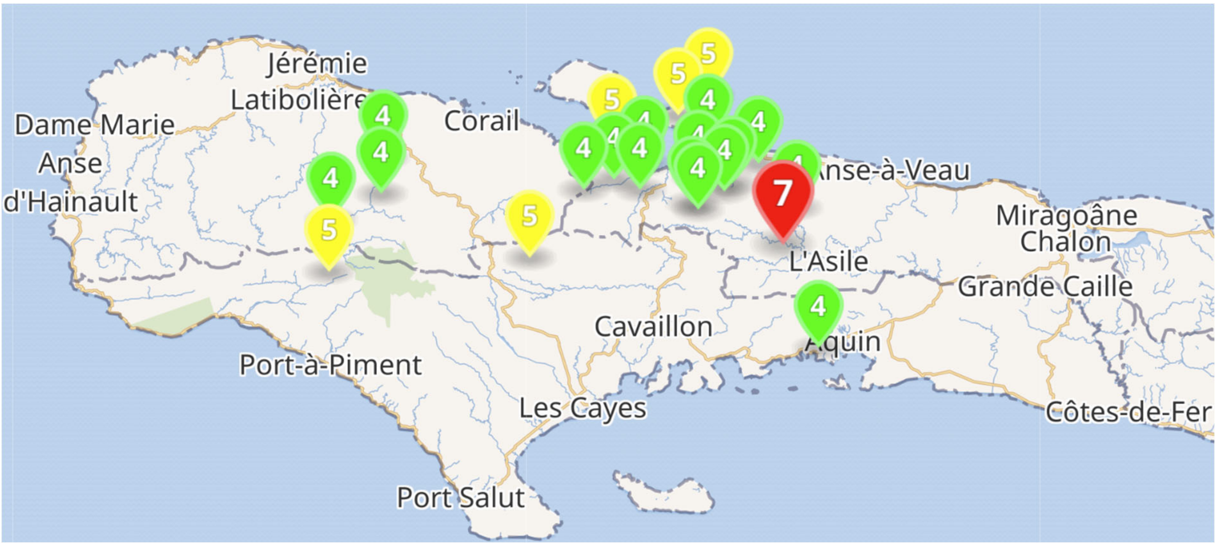

Figure 2.2. 2021 Haiti Earthquake sequence (only earthquakes with magnitudes 5.0 or greater) - Pin color and number correspond to the magnitude [Source: Earthquake.usgs.gov, Archived from the original on 14 August 2021].

2.1 Earthquake Features and Tectonic Summary

There are two major active faults on the Island of Hispaniola shared by Haiti and the Dominican Republic: (i) the Septentrional Fault (SF) and (ii) the Enriquillo-Plantain Garden Fault (EPGF) (Douilly et al., 2017). There is evidence of historical large seismic events close to both the SF and EPGF, which may have ruptured segments of these strike-slip faults (Scherer, 1912; Ali et al., 2008; Bakun et al., 2012). Figure 2.3 presents the geographical distribution of the epicenters and the magnitudes of historical events in the Northeastern Caribbean as reported by Ali et al. (2008), including the 2010 Mw 7.0 earthquake and the recent August 14, 2021, Mw 7.2 earthquake (see Appendix A for source data). Note that the epicenter of the current Mw 7.2 earthquake is on the EPGF and close to the epicenter estimation of the 1770 Mw 7.5 historical earthquake. According to Manaker et al. (2008), the EPGF could produce a Mw 7.2 earthquake if the entire elastic strain accumulated since the last major earthquake was released, based on GPS measurement and earthquake slip vector data analysis of the Hispaniola microplate prior to 2010. Consequently, the 2010 Mw 7.0 earthquake was initially attributed to the rupture of an EPGF segment. However, studies subsequently proved that around 80% of the moment release was from a different fault during this seismic event. Hence, the EPGF was identified as the prime candidate for future earthquakes in the region (Douilly et al., 2017). A recent study by Stein et al. (2021) explores the progressive westward rupture signaled by the 2010 and 2021 earthquakes. From Figure 2.4, it appears that there is a 15-kilometer-long jump or gap between these two earthquakes, one candidate among several for a future large earthquake. Notably, further studies have shown that the 2010 Mw 7.0 earthquake caused stress to the site of the Mw 7.2 earthquake at the Enriquillo-Plantain Garden Fault (Lin et al., 2010; Symithe et al., 2013).

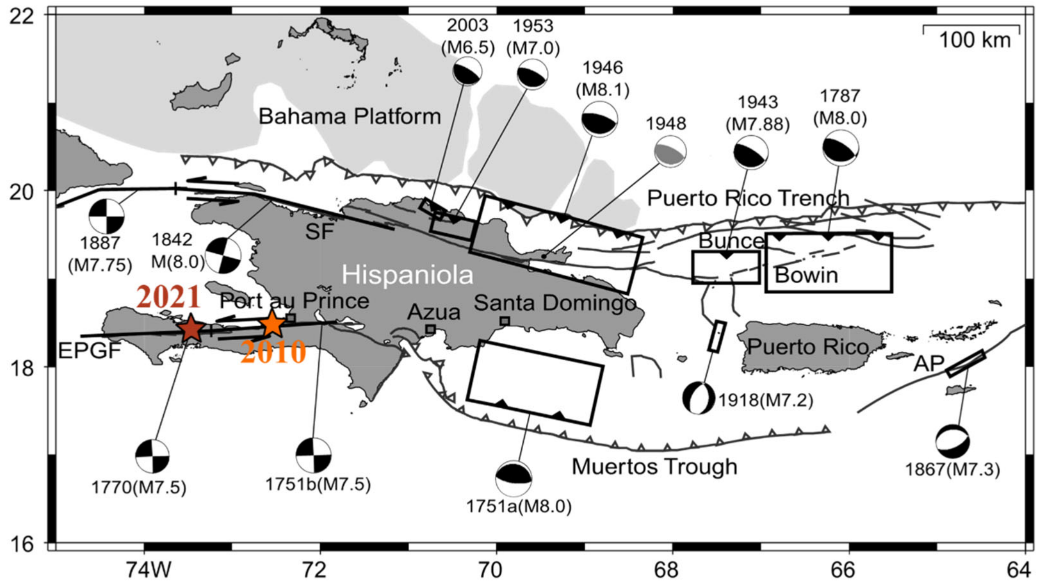

Figure 2.3. 2010 Mw 7.0 aftershocks as well as the 2021 Mw 7.2 aftershocks as of August 17, 2021, and the progressive westward rupture of the EPGF.

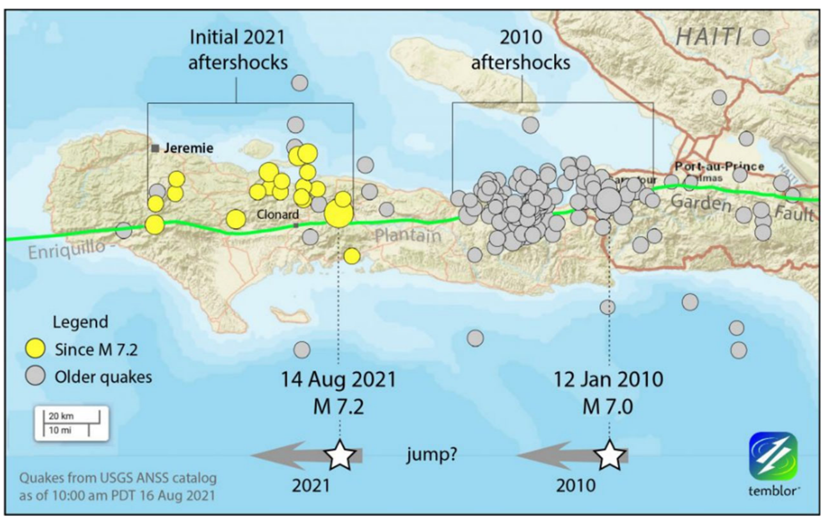

Figure 2.4. 2010 Mw 7.0 aftershocks and the 2021 Mw 7.2 aftershocks along the EPGF with visualization of gaps between the sites of recent seismic activity (Source: [Temblor Inc]).

2.2 Recorded Ground Motions

Following the 2010 Haiti earthquake, USGS and USAID have worked with the Bureau des Mines et de l'Energie (BME) in Port-au-Prince to establish the first national seismic network in Haiti, with over a dozen stations available through various international cooperatives. The network was operational at the time of the 2021 earthquake, with seven USGS stations in a range of (17 to 400 km) from the epicenter. The “Did You Feel It?” (DYFI) system was deployed to tap the information about Haiti earthquakes from the people who experienced it, though knowledge of this platform is not pervasive among the Haitian population. However, over 20 DYFI stations documented this event (see Appendix B). These DYFI ShakeMap stations are displayed and used (together with the Seismic Stations) to generate the U.S. Geological Survey (USGS) Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), and Peak Spectral Acceleration (PSA) shakemaps. An example, Figure 2.5, shows a maximum intensity of IX, corresponding to about PGA of 50%g.

Figure 2.5. Peak ground acceleration (PGA) Shakemap (Source: USGS).

2.3 Response Spectra

Figure 2.6 presents the simplified response spectra at 5 stations gathered from the USGS (2021) (see Appendix C for estimated epicentral distance, with location and PSA, Pseudo Spectral Acceleration, values). The Raspberry Shake Citizen Science Station (R50D4) listed in Appendix C is closest to the epicenter (R_{epi}: 25 km) with available PSA values. At this station the PSA value at T = 0.3 sec was around 0.9g.

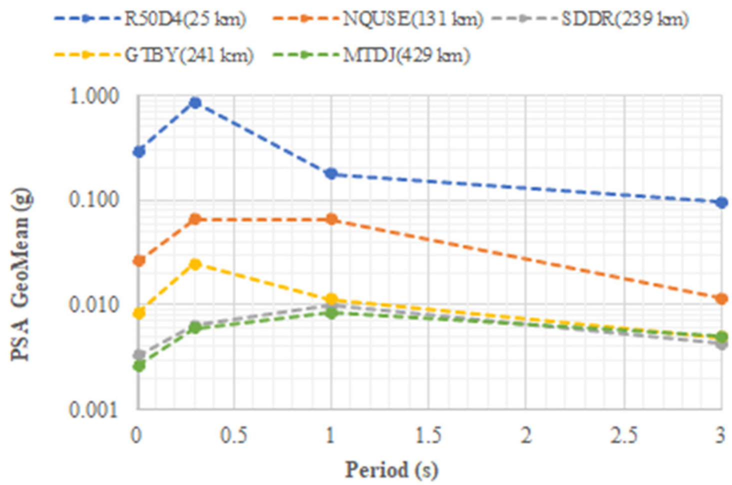

Figure 2.6. Simplified response spectra of the 2021 Haiti Earthquake from five stations with epicentral distances of 25 to 429 km.

2.4 Comparison with Ground Motion Models

Frankel et al. (2011) selected the Next Generation Attenuation (NGA) Ground-Motion Models (GMM) by Boore and Atkinson (2008), Campbell and Bozorgnia (2008), and Chiou and Youngs (2008) to develop seismic hazard maps for Haiti. Figures 2.7a,c,e compare the recorded PGA, Sa(T=0.3s) [Spectral acceleration at T=0.3 sec] and Sa(T=1.0s) [Spectral acceleration at T=1.0 sec] values, respectively, at six strong-motion stations located in Haiti, Dominican Republic, Cuba, and Jamaica during the 2021 Mw 7.2 Haiti Earthquake (Appendix C), against the estimation of the Boore et al. (2014) GMM, an update to the previously used model for the island. Estimates are for stiff soil (V_{S30} = 360 m/sec) conditions, and the Joyner-Boore distance of the stations is approximated here with the epicentral distance. Further, PGA recorded values at 4 strong motions stations during the 2010 Mw 7.0 Haiti Earthquake are included in Figure 2.7a for comparison. Note that most PSA recorded values for both 2021 Mw 7.2 and 2010 Mw 7.0 events fall within the median +/- 1 standard deviation of the GMM estimates, indicating that the observed PSA values are not particularly rare. Figures 2.7b, d, f present the residuals at PGA, Sa(T=0.3s) and Sa(T=1.0s), respectively, to the Boore et al. (2014) GMM versus Joyner-Boore distance. The 2021 Mw 7.2 event, recorded PGA and Sa(T=0.3s) at the closest station, located at around 25 km, are respectively about 60% and 107% higher than the GMM estimate.

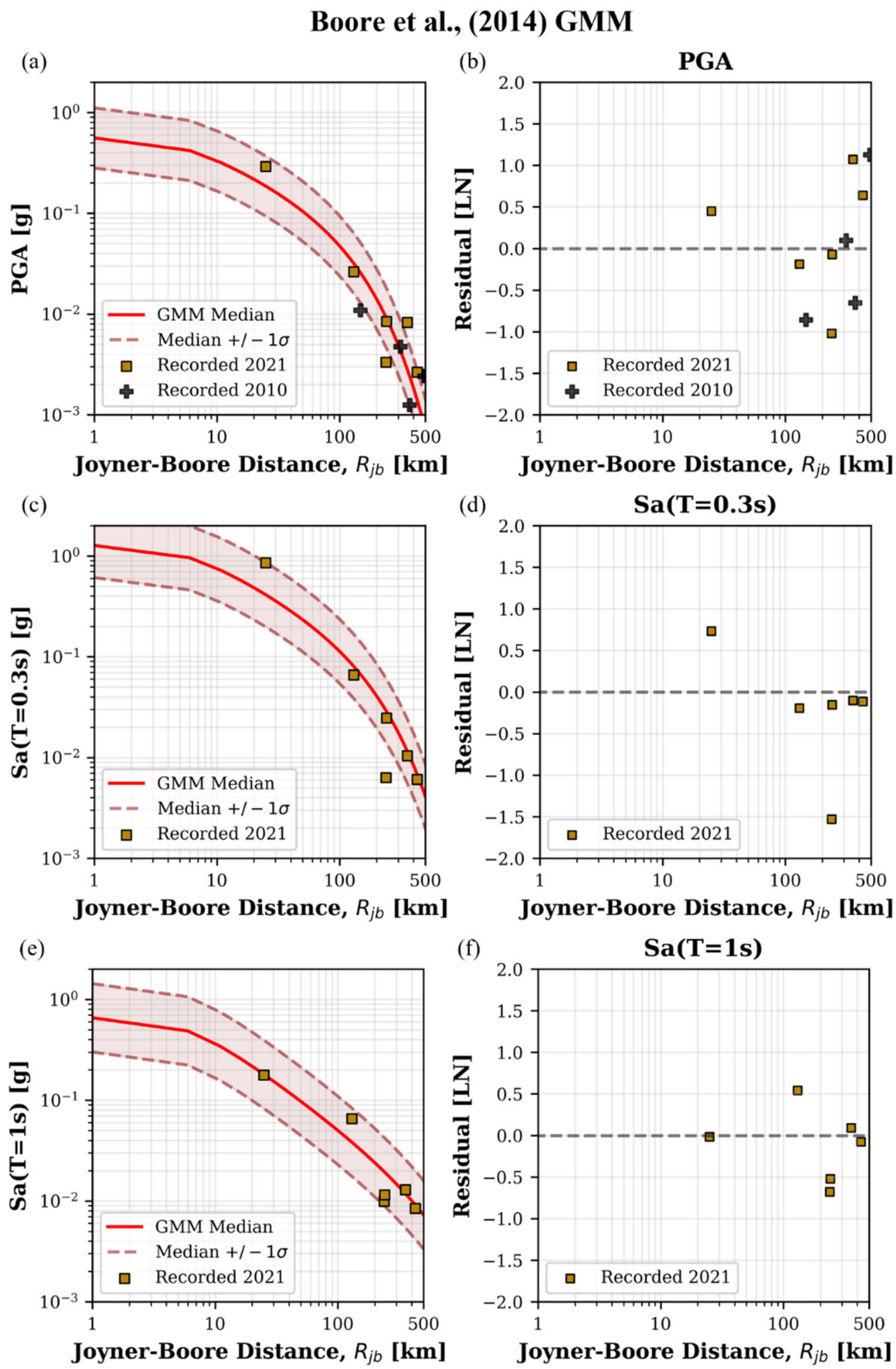

Figure 2.7. Comparison of recorded (a) PGA, (c) Sa(T=0.3s) and (e) Sa(T=1.0s) from established ground motion models with observations from 6 strong motion stations located in Haiti, Dominican Republic, Cuba, and Jamaica during the 2021 Mw 7.2 Haiti Earthquake (Appendix C), with respective residuals in (b), (d) and (f). Comparisons with the 2010 Haiti Earthquake are also provided in (a) and (b).

2.5 Tsunami

A minor local tsunami was generated by the 2021 Haiti Earthquake. Tsunami warnings were issued by both the Pacific Tsunami Warning Center (PTWC) (Figure 2.8) and the National Tsunami Warning Center (NTWC) immediately after the earthquake. It is not known if these tsunami warnings reached the affected population prior to the tsunami arrival, and evidence captured by eyewitness videos indicates that many people did not move inland until after the tsunami wave started inundating the coastline. It is important that communities exposed to near source tsunamis be educated to move inland from the coastline immediately after the earthquake in anticipation of potential tsunami inundation, and not to wait for an official tsunami evacuation message.

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PRELIMINARY EARTHQUAKE PARAMETERS
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  * MAGNITUDE      7.2
  * ORIGIN TIME    1229 UTC AUG 14 2021
  * COORDINATES    18.6 NORTH  73.5 WEST
  * DEPTH          10 KM / 6 MILES
  * LOCATION       HAITI REGION


EVALUATION
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  * AN EARTHQUAKE WITH A PRELIMINARY MAGNITUDE OF 7.2 OCCURRED IN
    THE HAITI REGION AT 1229 UTC ON SATURDAY AUGUST 14 2021.

  * BASED ON ALL AVAILABLE DATA... HAZARDOUS TSUNAMI WAVES ARE
    FORECAST FOR SOME COASTS.


TSUNAMI THREAT FORECAST...UPDATED
---------------------------------

  * TSUNAMI WAVES REACHING 1 TO 3 METERS ABOVE THE TIDE LEVEL ARE
    POSSIBLE ALONG SOME COASTS OF

      HAITI.


  * ACTUAL AMPLITUDES AT THE COAST MAY VARY FROM FORECAST
    AMPLITUDES DUE TO UNCERTAINTIES IN THE FORECAST AND LOCAL
    FEATURES. IN PARTICULAR MAXIMUM TSUNAMI AMPLITUDES ON ATOLLS
    OR SMALL ISLANDS AND AT LOCATIONS WITH FRINGING OR BARRIER
    REEFS WILL LIKELY BE MUCH SMALLER THAN THE FORECAST
    INDICATES.

  * FOR ALL OTHER AREAS COVERED BY THIS MESSAGE... THERE IS NO
    TSUNAMI THREAT ALTHOUGH SMALL SEA LEVEL CHANGES MAY OCCUR.
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Figure 2.8. Tsunami warning issued by the Pacific Tsunami Warning Center (PTWC) (https://www.tsunami.gov/events/PHEB/2021/08/14/21226002/2/WECA41/WECA41.txt).

An eyewitness video captured people running away from inundation due to the incoming tsunami in Les Cayes (Figure 2.9). Evidence of water drawdown and return without causing inundation was noted in Jacmel on the south coast, 63 miles east of the epicenter (Figure 2.10). There were no reports of structural damage, injuries, or deaths due to this minor tsunami inundation. However, there was likely water damage to non-structural components of buildings within the inundation zone. There is also eyewitness video of tsunami inundation in St. Louis Du Nord (https://twitter.com/HaitiInfoProj/status/1049042213290688512).

Figure 2.9. Image captured from a video of people running from incoming tsunami flow in Les Cayes (https://twitter.com/newsistaan/status/1426578163291750406).

Figure 2.10. Tsunami drawdown captured by eyewitness video in Jacmel, 63 miles east of the epicenter per the map above (https://twitter.com/DAVETV_9/status/1426546165810618370).

3.0 Local Codes and Construction Practices

As in many low- and middle-income countries, the adoption, operationalization and enforcement of building codes and standards have historically presented a considerable challenge for Haiti, particularly in privately financed projects. This has been but one of the drivers of vulnerability, particularly in residential construction, compounded further by a lack of land use planning, limited access to finance for construction, frail supply chains, rampant deforestation, and extreme poverty (Burlotos et al., 2020). Though hospitals, schools, churches, and government buildings, particularly those led/financed by foreign partners, have the means to employ higher-quality engineered construction in compliance with the codes and standards in Section 3.1, smaller-scale locally financed construction for residential and commercial occupancies can be assumed as non-engineered construction, often designed by informally trained masons. Larger multi-unit residential and commercial construction may consult a formally trained engineer or architect. This section will outline the nation's codification efforts and the implementation realities.

3.1 Governing Codes and Standards

The 2010 Haiti Earthquake created a strong impetus to raise construction standards, particularly for critical facilities. This manifested in two ways. The first is the release of formal codes and regulations as well as guidelines and standardized designs, many developed through collaborations with various international organizations and partners. The Ministère des Travaux Publics, Transports et Communications (MTPTC)[2] has published the following codes, regulations, and guidelines for construction:

1. Code National Du Batiment d'Haiti (CNBH 2012) - National Building Code of Haiti
2. Règles de calcul intérimaires pour les bâtiments en Haïti - Temporary Rules of Calculation for Buildings in Haiti
3. Guide de Construction de Petits Batiments en Maconnerie Chainee - Construction Guide for Small Reinforced Masonry Buildings
4. Guide pratique de Réparation de petits Bâtiments en Haïti - Practical Guide for Repairing Small Buildings in Haiti
5. Guide de Renforcement Parasismique et Paracyclonique des Bâtiments - Guide for Seismic and Hurricane Building Retrofit

The second is that MTPTC also finalized seismic microzonation maps for Port-au-Prince ("Microzonage sismique de Port-au-Prince, Rapport Synthese" Décembre 2013), while the Comite Interministeriel d'Amenagement du Territoire (CIAT) also produced the "Atlas des Menaces Naturelles en Haiti". The Ministry of National Education and Vocational Training (Ministere de l'Education Nationale et de Formation Professionnelle) has also released standard

[2] https://www.mtptc.gouv.ht/accueil/publications/code-construction.html

plans and guidelines for school construction[3]. These various regulations draw heavily upon international codes and ASCE standards.

Homes are built based on regional practice, often without consulting building codes and with little quality control, unfolding in incremental stages over many years as savings are accumulated; the resulting construction thus has high variability in material quality and workmanship. Noting this considerable vulnerability in the housing inventory, NGOs like Build Change have worked to create standard designs for new construction and guidelines for retrofitting existing masonry construction to achieve life-safety under the design basis earthquake[4], e.g., "Seismic Evaluation and Retrofit Manual" adapting ASCE 31 and ASCE 41 to the dominant unreinforced masonry typologies of Haiti that are not addressed in US standards (Davy et al., 2017). Burlotos et al. (2021) includes further discussion of the tradeoffs in achieving and exceeding life safety standards in Haitian masonry residential construction.

3.2 Dominant Typologies

The following description of typologies in the affected areas is adopted from post-Matthew reconnaissance in the Sud Department (Kijewski-Correa et al., 2018). With lower densities than Port-au-Prince, the affected area is typified by low-rise (1- to 3-story) masonry and reinforced concrete buildings, inclusive of single family residential, commercial, religious, medical, government, and educational buildings. Construction generally adopts one of four typologies: unreinforced masonry (URM), reinforced masonry, confined masonry, and masonry-infilled reinforced concrete frames. Arlotos et al. (2021) discussed that lack of quality control, constrained budgets, and limited technical capacity for aseismic design may result in buildings that blur the lines between these systems in practice. Structures in Haiti commonly display hallmarks of confined masonry but lack sufficient (in number, placement, size, or reinforcement) tie columns to achieve the intended levels of confinement. Ring beams are inconsistently employed in lower-income load-bearing masonry homes with door and window openings rarely confined. Predicting the capacity of typologies along this continuum is further challenged by the variable use of grouting and/or reinforcement (less common) in masonry walls. Material quality is also unpredictable, with concrete commonly hand-mixed and hand-placed and CMU hand-pressed, resulting in wide-ranging quality proportional to cement content, aggregate source, production technique, and curing conditions. The high cost of imported steel restricts the amount of reinforcement used in construction; importing barriers also limit access to alternative building materials, including structural steel, metal building systems, or other non-cementitious materials. Access to quality lumber is equally scarce. In total, these characteristics create significant vulnerabilities in seismic events, as affirmed in Haiti (Eberhard et al., 2010b; Lang and Marshall, 2011; Mix et al., 2011) and elsewhere in the Caribbean (Miranda et al., 2020a, b). It is to be noted

[3] https://menfp.gouv.ht/#/documents/official

[4] https://buildchange.org/resources/retrofitting-guides/

that load-bearing walls in older buildings, like in churches and some hospitals, may employ stone masonry.

Low-rise buildings typically employ shallow foundations (slabs with grade beams, often of stone masonry) to accommodate poor soil conditions and relatively high-water tables, particularly in Les Cayes and other coastal areas. Buildings may be slightly elevated (~0.5 m) in response to frequent flooding in the rainy seasons. Two major roofing systems are common in the affected regions: (1) Corrugated Galvanized Iron (CGI) sheets framed in wood or tack welded steel Hollow Structural Sections (HSS) and (2) concrete slab roofs. Wood-framed roofs are typical in lower-income residential construction where trusses of varying stiffness have been observed, generally toenailed on-site using either dimensional lumber or machete-milled native woods. Middle- and higher-income families and particularly in urban construction may use a concrete slab roof to afford the provision to add floors over time. For confined masonry or URMs, this would be characterized as flat plate construction without the use of any beams to tie the lateral system; Moment Resisting Frames (MRFs) in larger buildings may have beams integrated with the slab floors/roofs. More rural areas are characterized by a mixture of CMU-load bearing walls and vernacular architecture: wattle and daub construction that is wood-framed and infilled with stone bound together with a mix of lime and earth called *clissage.* Reduced seismic mass allowed these structures as well as the historical wooden Gingerbread homes of Port-au-Prince to fare well in the 2010 Haiti Earthquake (Mix et al., 2011).

4.0 Damage to Buildings

Haitian Civil Protection General Directorate (DGPC) reports nearly 61,000 homes have been destroyed and more than 76,000 have sustained damages in the three most affected departments, leaving thousands homeless and creating an urgent need for emergency shelter solutions. An initial rapid assessment found that 24 health facilities have been affected in the Sud, Nippes and Grand'Anse Departments, with 20 suffering infrastructural damages and 4 destroyed. The damaged buildings include residential buildings, hospitals, businesses, schools, and churches.

This section overviews building damage across the Tiburon Peninsula by occupancy and referencing communes when possible (see Figure 4.1). While previous StEER PVRRs normally include assessments of government buildings and critical facilities, their omission herein does not suggest a lack of damage to this occupancy but rather a lack of information on those occupancies. Many of the failures discussed herein are attributed to the complete lack of seismic details in buildings ranging from informally constructed residences to contemporary multi-story buildings in urban centers across the Tiburon Peninsula. There is limited evidence of basic seismic design and construction principles, or uptake of recommendations issued following the 2010 Haiti Earthquake, an observation that is perhaps unsurprising given the context discussed in Section 3.0.

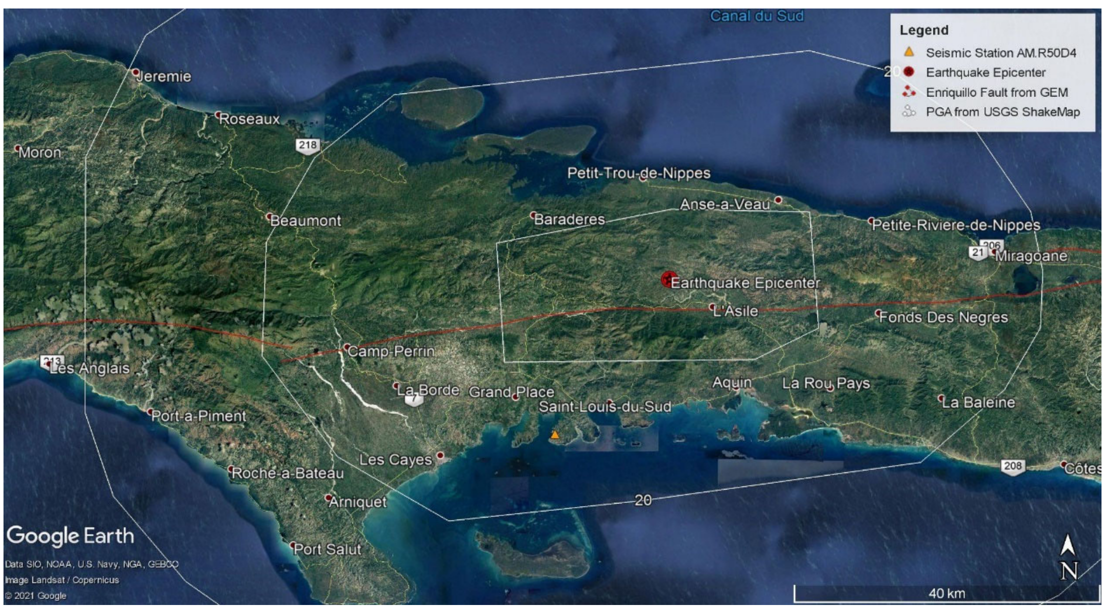

Figure 4.1. Map of epicenter, fault and proximity to a number of discussed communes.

4.1 Single-Family Residential Buildings

Severely damaged and collapsed single-family residences have been reported across the affected area, attributable to the practices and constraints discussed in Section 3.2. Focus herein is placed on representative samples of key vulnerabilities/non-ductile failure modes emerging from early field observations, including in-plane (IP) and out-of-plane (OOP) masonry wall failures, many of which are consistent with the observations following the 2010 Haiti Earthquake (Mix et al., 2011).

In some parts of the developing world, the predominant construction style is confined masonry or relatively small reinforced concrete frames with unreinforced masonry infill, both commonly employing Concrete Masonry Units (CMUs). Adversely, the Haitian situation has the visible appearance of confined masonry but had been built without the necessary seismic details to achieve proper confinement, resulting in thousands of catastrophic failures. Thus, the resulting weakly confined masonry construction performed no more reliably than unreinforced masonry (URM) construction. Meanwhile, the construction of reinforced concrete (RC) frames requires a proper detailed design of the critical areas of beams, columns, and their connections, see Burlotos et al. (2021) for an overview of such requirements in single-family homes for Haitian levels of seismic risk. Observations show no design and implementation of the necessary details for the frame's structural integrity, such as proper geometrical configuration to achieve strong column-weak beam configuration, sufficient confining steel in the beams and columns, and the detailing required in beam-column connections (see Figure 4.2). Thus, the lack of those earthquake resistant details led to brittle failures with low ductility margins that have a crucial impact on life safety. Additional examples of such failures are provided in Appendix D.

Figure 4.2. Example of damaged slab and beam-column connection in Abaka Bay Resort hotel, on the beachfront in Jeremie in Grand'Anse Department of Haiti. (Source: Jesus Chris' Twitter account; Journalist and broadcaster).

Based on VAST observations of Haitian construction, few single-family residences employ masonry-infilled frames. Therefore, in the examples that follow, the presence of columns/protruding longitudinal reinforcement is suggestive of the location of tie columns in what are generally weakly confined masonry buildings.

A common characteristic in Haitian urban construction is iron security bars on windows and doors; shear cracking is commonly visible in URM walls framing these stiff elements, as demonstrated in damaged homes in Figure 4.3 in Les Cayes Arrondissement. Figure 4.3a is a representative example of a single-story construction. On the other hand, Figure 4.3b is representative of the multi-story construction common in urban centers like Les Cayes and Jeremie. In many cases, high shear demands at the ground floor of these heavy, weakly-confined, multi-story masonry homes resulted in soft-story failures (Figure 4.4) and complete pancake collapses with the heavy concrete slab floors/roofs often intact. Exposed reinforcement at the roofline of one such pancake collapse in Figure 4.5 indicates the location of tie columns in this weakly-confined building.

While multi-story URM and weakly confined masonry residences were the most vulnerable, the racking failure in Figure 4.6 demonstrates a number of the common vulnerabilities shared by single-story masonry residential construction in Haiti: (1) heavy concrete slab roof supported by weakly confined load-bearing CMU masonry walls, (2) covered porches supported by concrete columns not tied into the larger structural system, (3) lack of ring beam, relying solely on the slab to engage the system laterally, and (4) openings unconfined but possibly stiffened by security doors and windows. These structural system vulnerabilities are further amplified by the poor quality of the material frequently used in construction. It is also to be noted in Figure 4.6 the elevated stone masonry foundation, which is common in flood-prone areas.

A less common blended typology of load-bearing masonry with upper timber stories has also been documented among older construction in Haiti. The example in Figure 4.7 illustrates an out-of-plane (OOP) failure of stone URM lower level of such a blended typology, revealing details of historical timber construction in this deforested nation. The buildings in the background of Figure 4.7 also demonstrate the low levels of confinement in masonry construction in Haiti, particularly around window openings.

(a)

(b)

Figure 4.3. Shear cracks adjacent to stiff security barred windows in (a) single- and (b) multi-story weakly confined masonry homes in the commune of Maniche in the Les Cayes Arrondissement of Sud Department (Source: Twitter).

(a)

(b)

Figure 4.4. Soft story failures in single family homes in the communes of (a) Maniche (Source: Twitter) and (b) Camp-Perrin (Source: Twitter), both in Les Cayes Arrondissement of Sud Department.

Figure 4.5. Pancake collapse of a weakly-confined masonry house destroyed in Port-à-Piment in the Sud Department (Source: Twitter).

Figure 4.6. Damage of a single-story home in Anse-a-Veau (Credit: Gefthé Dévilmé, GeoHazards International).

Figure 4.7. Example of an OOP failure in blended stone masonry and timber home in Les Cayes (Note poorly confined masonry construction in the background) (Source: Reuters).

Finally, Figure 4.8 provides examples of an alternative single-story residential typology, namely the timber-framed wattle and daub construction typical of older, low-income homes. The lightweight nature of these structures, including the use of Corrugated Galvanized Iron (CGI) roofs, generally mitigates the potential for a complete collapse, though considerable volumes of *clissage* (stone infill) are often lost.

(a)

(b)

Figure 4.8. Examples of damaged wattle and daub construction in the communes of (a) Maniche (Source: Twitter) and (b) Camp-Perrin (Source: Twitter), both in the Les Cayes Arrondissement of the Sud Department.

4.2 Multi-Family Residential Buildings

Major cities like Les Cayes and Jeremie include several multi-story hotels, which may employ non-ductile concrete frames and load-bearing masonry wall systems. Notable failures include the

Hotel Le Manguier and Cayimite Hotel in Les Cayes (Figures 4.9 and 4.10) and the Manolo Inn Hotel in Petite Riviere de Nippes (Figure 4.11). The absence of floor beams is evident in several damaged building photographs, suggesting the structures were flat plate systems supported on a mixture of reinforced concrete columns and load-bearing masonry walls. Damage was also reported to orphanages in the affected area, including Espwa in Les Cayes. Bethesda World Ministries reported that multiple orphanages were severely damaged, and one destroyed (Figure 4.12). See Appendix D for additional examples of damage to multi-family residential construction.

(a)

(b)

(c)

Figure 4.9. Le Manguier Hotel in Les Cayes, (a) before the earthquake, (b) complete collapse after the earthquake, (c) zoomed image of the debris pile showing lightweight CGI roof and multiple stories of pancaked slabs (Sources: Twitter accounts @MurielVeux, @FranzDuval).

Figure 4.10. Cayimite Hotel collapsed in Les Cayes, Haiti, Aug. 14, 2021 (Source: US today).

Figure 4.11. Collapsed Manolo Inn Hotel in Petite Riviere de Nippes (Credit: Gefthé Dévilmé, GeoHazards International).

Figure 4.12. Collapse of the Bethesda World Ministries Orphanage in Ave Des Quatre Chemins, Les Cayes (Source: Orphan Grain Train).

4.3 Commercial Buildings

Failures noted in Section 4.1 would be equally characteristic of commercial construction in Haiti, with a prevalence of small businesses (with small square building footages) often constructed with similar typologies to those used in single-family construction and thus exhibiting similar performance (Figure 4.13). No notable collapses of larger commercial buildings were reported except for one of the Complexe Immaculée de Camp-Perrin, a multipurpose business (grocery, hotel, and restaurant), which suffered a complete collapse (Figure 4.14), as well as a major supermarket in Les Cayes (NY Times, 2021a). See Appendix D for additional examples of damage to commercial construction.

Figure 4.13. Collapse of small business in Petite-Rivière-de-Nippes (Source: npr).

Figure 4.14. Completely collapsed Market Immaculée in Camp-Perrin, Les Cayes, Sud Department, a mixed use structure (grocery, hotel, and restaurant) (Sources: Twitter, Newspaper Le Nouvelliste).

4.4 Hospitals and Healthcare Facilities

Retrofit of hospitals has been a priority even before the 2010 Haiti Earthquake, though the reach of these efforts in the Nippes and Sud Departments is unknown. Reports of damage to hospitals in Sud and Nippes have been noted, but specifics were not yet available at the time this report was released, nor is it clear if these had been seismically retrofitted in any way. The only confirmed reports at this time were the collapse of a dormitory building and cracks in other buildings (e.g., pediatric ward) on the campus of the Hospital Immaculée Conception in Les Cayes (NY Times, 2021a), damage to walls and floors at the OFATMA Hospital in Les Cayes, prompting an evacuation of patients outdoors (Figure 4.15) (Stevenson and Sanon, 2021), and severe damage to Hopital de l'Azile in Nippes (Figure 4.16).

Figure 4.15. Patients being treated in a tent outside OFATMA Hospital in Les Cayes, Haiti after the hospital suffered damages that scared residents (Source: Miami Herald).

Figure 4.16. Severe damage of Hopital de l'Azile in Nippes (Source: Gefthe Devilme, GeoHazards International).

4.5 Schools

Several NGOs are evaluating school performance in this earthquake, including the networks of private (and particularly Catholic) schools, which make up a large percentage of the education system in Haiti. Specific to private schools, on August 24, the Bishops' Conference of Haiti has reported that, in Cayes alone, 73 schools were destroyed and 51 were damaged, in Jérémie, 10 schools were destroyed and 50 were damaged, and in the Department of Nippes, 5 schools were destroyed and 30 were damaged (Le Nouvelliste, 2021a).

Multi-story schools may employ CMU-infill RC frames with columns to support covered porches/walkways, often with elongated floor plans featuring a single row of identical classrooms, partitioned by CMU walls, accessible through outdoor walkways. Figure 4.17 is an example of a complete collapse of such systems at Missionary Oblates of Mary Immaculate in Mazenod, Camp-Perrin (Sud Department). A similar collapse was reported at Alexandre Dumas school in Latibolye, Jérémie, in the Grand'Anse Department.

Figure 4.17. Views of the collapsed seminary school of the Missionary Oblates of Mary Immaculate in Mazenod, Camp-Perrin, Sud Department (Source: Twitter).

The use of vented CMU block or louvered windows over a partial height of CMU infill or load bearing walls is common practice to ventilate classrooms in these buildings; this can create captive/short column effects that resulted in shear failures in the 2010 Haiti Earthquake (Mix et al., 2010). This practice resulted in similar "short column" failures in Sinai National School (Figure 4.18). The same extensive shear cracks in infill walls as well as in RC columns are observed in Boisrond Tonnerre School in Anse-a-Veau (Figure 4.19).

Figure 4.18. Short column effect due to partial height infill walls in Sinai National School in Miragoane (Source: Gefthe Devilme, GeoHazards International)

Figure 4.19. Infill wall damage and short column shear cracks at Boisrond Tonnerre school, Anse-a-Veau, Nippes Department (Source: Gefthe Devilme, GeoHazards International)

Alternatively, classrooms in the more rural areas may be a single-story version of the previously discussed layout, with similar design features. More humble schools may adopt a more open floor plan with weakly confined masonry or URM topped by a CGI-roof. A failure of one such school in Petit Trou de Nippes is shown in Figure 4.20, 13.5 km from the epicenter. Note shear cracking around vented CMU blocks observed in school in Baltazar (Fig. 4.21), where cracking and collapse of weakly confined CMU walls are combined with damage of horizontal and vertical confining elements. Another example of inadequate confinement of a masonry wall in open-plan schools is demonstrated in Figure 4.22 in L'Asile showing poor quality of tie columns.

Figure 4.20. Public secondary school collapsed in Petit Trou de Nippes (Source: Twitter).

Figure 4.21. Severe damage of school in Baltazar (Source: Gefthe Devilme, GeoHazards International).

Figure 4.22. Collapse of weakly confined masonry school in L'Asile, Nippes Department (Source: Gefthe Devilme, GeoHazards International).

4.6 Historical Buildings

The downtown of the major city centers of Jeremie and Les Cayes are characterized by 2 to 3 story historical load bearing stone masonry buildings with elongated floor plans perpendicular to the street. Major damage was reported in this class of construction, as evidenced in Figure 4.23.

Figure 4.23. Collapse of stone masonry historical buildings, downtown Jeremie (Source: CNN).

4.7 Houses of Worship

Haiti Libre (2021) on August 15 reported damage to the St. Louis King of France Cathedral in the commune of Jérémie in the Department of Grand'Anse, damage to six churches in the Department of Nippes, including one that collapsed in the commune of Baradères, and heavy damage to three churches in the Department of Sud. On August 17, Caritas Haiti reported that around 70% of the buildings owned by the Catholic Church (which includes churches, presbyteries, schools, and dispensaries) of the southwest regions have been damaged or destroyed (KTO, 2021). On August 24, the Bishops' Conference of Haiti and Mission Evangélique Baptiste du Sud d'Haiti (MEBSH) each reported 350 churches damaged or destroyed across the Grand Sud region (Le Nouvelliste, 2021a, b).

In the Department of Sud, the damage to churches includes the partial collapse of the Sacred Heart Church in Les Cayes (Figure 4.24, additional images are available in Appendix E), damage to the Cathedral of Our Lady of the Assumption in Les Cayes, the damage to the second church of Dieu des Cayes in Les Cayes (NPR, 2021), the partial collapse of the church of Our Lady of Perpetual Help in Canaillon (Figure 4.25), damage to the church of Our Lady of the Rosary in Port-à-Piment (Boston Pilot, 2021), damage to the Chapel of Saint Eugene, which is part of the seminary school of the Missionary Oblates of Mary Immaculate in Mazenod (Abi-Habib, 2021) (Figure 4.26), the partial collapse of the church in Saint-Louis-du-Sud (Twitter, 2021b), the collapse of the church of Sainte Agnès in Marceline (NPR, 2021), the collapse of a church in Torbeck (Christian Today, 2021), and the collapse of the church of Saint Anne in Chardonnières (USA Today, 2021) (see Appendix E). In the commune of Les Anglais, the church of the

Immaculate Conception has also partially collapsed, killing 17 people, while 2 individuals trapped under the rubble were rescued (Boston Pilot, 2021) (Figure 4.27 with additional images in Appendix E). In the Department of Sud, the church of the Saint Famille in Toirac, Camp-Perrin, partially collapsed, killing an estimated 20 people (Gottesdiener, 2021). Moreover, a church in the commune of Chantal, Les Cayes, has collapsed, killing 21 people (Désir d'Haïti, 2021). The high death rates in churches resulted from the timing of the earthquake when religious celebrations were underway in preparation for a major Catholic feast day. Another major Cathedral, in the Department of Grand'Anse, the St Louis King of France Cathedral in Jérémie, lost its steeple and part of the roof (Figure 4.28).

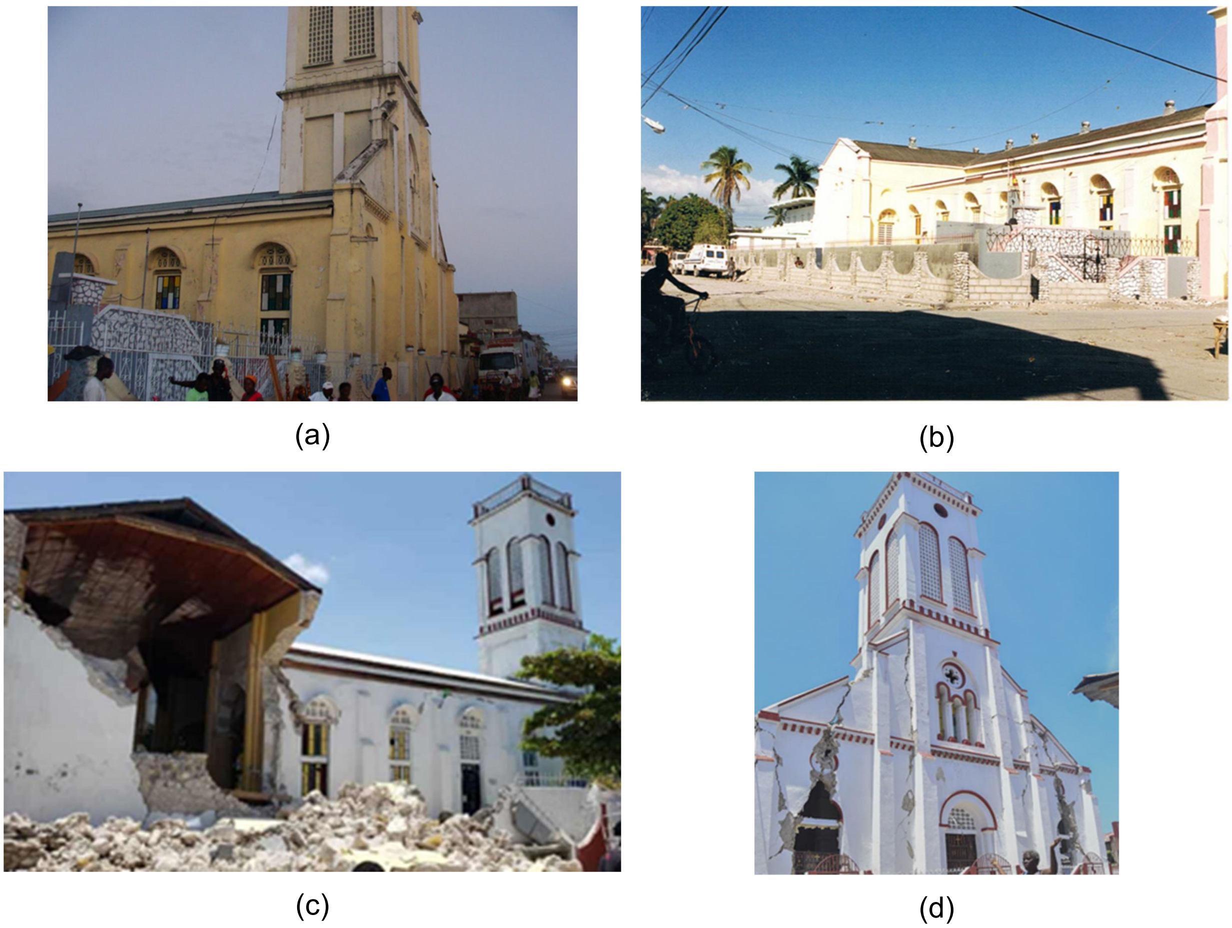

Figure 4.24. Views of Sacred Heart church, Les Cayes; (a) & (b) before the 2021 Haiti Earthquake (Source: mapio.net), and (c) & (d) damaged after the earthquake (Source: Associated Press).

(a) (b)

Figure 4.25. View of the Notre Dame du Perpétuel Secours (Our Lady of Perpetual Help) in Canaillon; (a) before & (b) after the 2021 Haiti Earthquake (Source: Twitter)

Figure 4.26. View of the damage to the Chapel of Saint Eugene, which is part of the seminary school of the Missionary Oblates of Mary Immaculate in Mazenod, Camp-Perrin (Source: NYTimes).

(a)

(b)

(c)

(d)

Figure 4.27. Views of the church of the Immaculate Conception in Les Anglais; (a) (Source: hatianphotos.com) & (b) (Source: haiti.fandom.com) before the 2021 Haiti Earthquake, and (c) (Source: Boston Pilot) & (d) (Source: teleSUR) partial collapse after the earthquake.

Figure 4.28. Views of the St. Louis King of France Cathedral in Jérémie; (a) (Source: Destimap.com) & (b) (Source: Wikipedia) before 2021 Haiti Earthquake, and (c) & (d) partial collapse after the earthquake (Source: Twitter).

In smaller communities, church damages were also reported, including the partial collapse of the parish church in the commune of Corail (The Boston Pilot, 2021) (see Appendix E), the collapse of the Shekinah Free Methodist Worship Center (Stannard, 2021), and the partial collapse of the Baptist MEBSH church of Pestel. In the commune of Maniche, the church of Sainte Rose de Lima partially collapsed following the earthquake (see Appendix E), with subsequent reports that the church is now demolished (Twitter, 2021c). However, the extent to which aftershocks or heavy machinery played a role in that process is unclear. Other heavily damaged churches include the Baptist MEBSH church in Maniche (see Appendix E) and the church of Saint Anne in La Sucrerie Henry in the commune of Aquin (Mona Lisa Lives Here, 2021). Moreover, in the Department of Nippes, the collapse of the church of Saint Peter in the commune of Baradères and severe damage to the Cathedral of Saint Anne in the commune of Anse-à-Veau were reported (Boston Pilot, 2021), as well as the partial collapse of the church of Saint Joseph in the commune of L'Asile (Washington Post, 2021). Imagery for these cases of damages and collapses of places of worship is available in Appendix E.

5.0 Damage to Infrastructure

While the affected area has some grid infrastructure, power, water, sanitation, and communications are often decentralized given the lack of coverage and limited reliability of the grid infrastructure. These decentralized services, including cell towers, were largely uninterrupted by the 2021 Haiti Earthquake as they often rely on their generators for power. However, it was reported that some grid infrastructure was offline in Petit Trou de Nippes, the epicenter of the earthquake (NY Times, 2021a), while water lines burst in Cayes (NY Times).

Concerning roadways, ground instabilities have caused widespread damage, notably National Route 7, which connects the Departmental capitals of Les Cayes (Sud) and Jeremie (Grand'Anse), was cut off due to a landslide at Riviere Glace (Figure 5.1). Landslides also disrupted roadways between Les Cayes and Port-au-Prince (Figure 5.2) and Les Cayes and Camp Perrin (Figure 5.3). Beyond land movement, roadway surfaces were also fractured and damaged (Figure 5.4).

Figure 5.1. Rockslides restrict RN7 (National Route 7) from Les Cayes to Grand'Anse (Source: W10news - Facebook post).

Figure 5.2. Stills of video capturing rockslide blocking road from Martissant to Sud Department (Source: Twitter, click link for full video)

Figure 5.3. Landslide restricting roadway between Les Cayes and Camp Perrin (Source: New York Times)

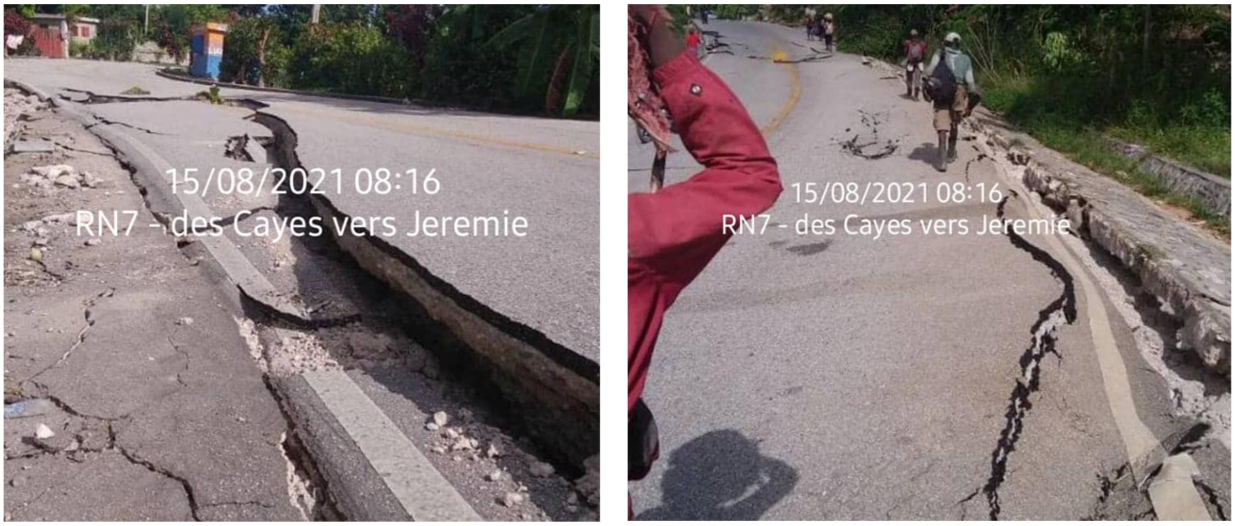

Figure 5.4. Roadway damage in different locations of RN7 (National Route 7) from Les Cayes to Grand'Anse. (Source: Twitter - @RenaldLuberice).

Access between the Sud and Grand'Anse Departments was further hampered by damage to the Dumarsais Estimé bridge over the Grand'Anse River (Bridgemeister, 2021), considerably affecting the delivery of assistance to affected populations in Jérémie (Relief Web, 2021). Fortunately, airports and ports, including Les Cayes Airport (CYA/MTCA) and Jérémie Airport (JEE/MTJE) had no apparent disruptions[5].

[5] https://www.flightradar24.com/data/airports/jee/statistics and https://www.flightradar24.com/data/airports/cya/statistics

6.0 Observed Geotechnical Failures

Beyond the land movements impacting roadways as discussed in Section 5.0, other landslides were reported in the affected region where the Massif de La Hotte mountain range has a high potential for landslides (Figure 6.1). Several rockfalls and landslides are reported in Nippes Department, namely Etang Rey, Petit-Trou-de-Nippes, L'Asile (Figure 6.2), and Brody, as well as in Sud Department along the southwest coast, near Port-a-Piment. A map showing the terrain displacement, ranging from 0.46 to -0.18 m, is presented in Figure 6.3 where the largest displacement is in the vicinity of the epicenter. Reports of liquefaction-induced failures were also noted in the Sud Department. Figure 6.4 illustrates an example of foundation failure in a residential construction in Saint George.

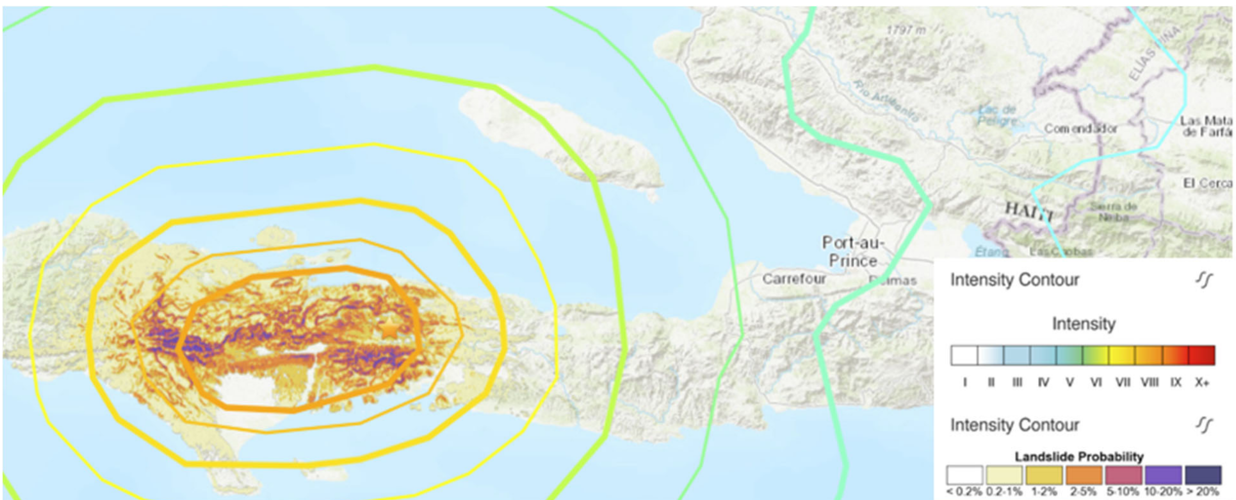

Figure 6.1. Induced landslide probability map (source: USGS).

Figure 6.2. Stills from an amateur video showing the apparent top of a landslide in L'Asile (Source: Michael Wilson, direct communication).

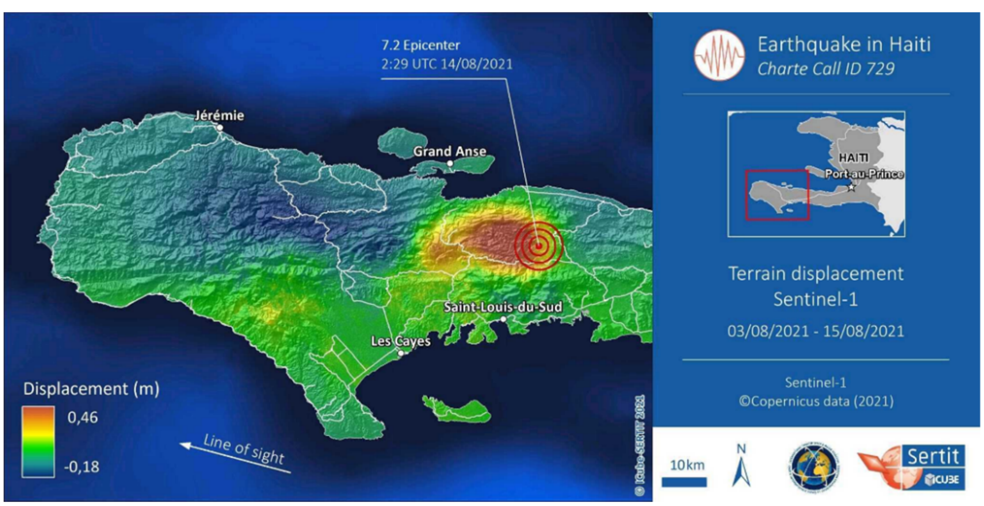

Figure 6.3. Terrain displacement of the 2021 Haiti Earthquake.

Figure 6.4. Foundation failure under small business in Saint George area in southwest Haiti (Source: Twitter).

7.0 Current Conditions and Access

Security Context: Even prior to the 2021 earthquake, Haiti was classified with a Level 4 Travel Advisory by the US State Department due to the ongoing security issues; it was also classified as Level 3-4 with respect to COVID-19 risk due to weak healthcare infrastructure and limited mitigation/vaccination efforts. Gang activity has more critically posed acute security threats and restricted safe ground passage between Port-au-Prince and the affected areas. Prior to the earthquake, passage by regional air was the only advisable route for foreigners. While a truce was struck to allow humanitarian and relief efforts to move by ground from the capital, the ongoing presence of gang activity, the instability heightened by the recent assassination of the Haitian President, and the unpredictable dynamics of the political situation would caution against sending foreign teams into the country. The limited response by many NGOs and international agencies reflects such conservatism in response to these security concerns.

Event-Related Context: As noted in Section 5.0, the major (and only) routes between affected city centers and the capital have been affected; minor routes to rural communities outside of these city centers have also been affected. Given the lack of redundant routes to many of these areas, data collection will be impeded by the quality of roadways in many of the most affected areas. Aftershocks have also continued to disrupt services and collapsed buildings across the Tiburon Peninsula. Further, Haiti has already experienced two storm passages this hurricane season and has the potential for continued exposure.

8.0 Recommended Response Strategy

With the 14 August 2021 Haiti Earthquake and its subsequent aftershocks affecting three Departments of Haiti, the geographic expanse and intensity of this event are actually greater than the 2010 Haiti Earthquake, exposing a more diverse cross-section of regional construction practices to strong shaking. While low- and middle-income countries (LMICs) may struggle to effectively implement sound aseismic design principles, the opportunity to learn what building systems can be effective under the constraints of such contexts can reveal opportunities to reduce seismic risk among the most vulnerable worldwide. Thus, based on the information gathered by this Preliminary Virtual Reconnaissance Report (PVRR), StEER offers the following recommendations for future studies:

TOPIC 1: Performance of Post-2010 and Post-2016 Construction: With the emphasis on improving the seismic resistance of schools and other critical infrastructure following the 2010 earthquake, it is vital to evaluate how structures have been retrofitted or constructed post-2010 using enhanced guidance developed following this event. The extent to which these practices have reached the Sud, Grand'Anse, and Nippes Departments (or not) will further reiterate opportunities to renew awareness of the need for aseismic design across this seismically active country not just in the Port-au-Prince area. Similarly, construction practices adopted following Hurricane Matthew in 2016 may have spurred heavier systems to counter wind uplift only to potentially heighten seismic risk (Kijewski-Correa et al., 2018). Thus, evaluating hurricane-resilient designs built post-2016 for their performance in this earthquake will provide important learnings on construction suitable for this multi-hazard context.

TOPIC 2: Performance of Confined Masonry Systems: Confined masonry has been promoted in Haiti and other LMICs with high seismic risk as a viable typology for residential construction. Unfortunately, this typology has yet to be formalized in many international building codes and standards, though important steps have been taken in this direction by a number of countries. The ability to validate the performance of this construction style in this event, and particularly performance when variable levels of confinement are achieved in highly resource-constrained environments, can press on with the necessary evidence to promote this system globally. As well-confined masonry is equally effective in resisting tensioning and out-of-plane failures of masonry walls under hurricane uplift pressures, the promotion of feasible earthquake-resistant implementations of confined masonry in LMICs in the Caribbean will be advantageous for advancing multi-hazard resilience.

TOPIC 3: Performance of Vernacular Architecture: The challenges of effectively executing concrete and masonry construction in Haiti is well-documented in this report as well as in reconnaissance following past earthquakes and hurricanes. In contrast, vernacular architecture has had mixed and, at times, superior performance. Thus, it is important to document this typology's performance, particularly the contemporary implementations of laterally braced wattle and daub typologies executed by NGOs following Hurricane Matthew, to determine if they can deliver sufficient resistance to seismic hazards.

TOPIC 4: Locally Viable, Affordable, and Safe Construction Solutions: The required cost and technical capacity necessary for aseismic design create barriers for most households in LMICs, leading to the adoption of inferior quality materials, detailing, and unskilled construction methods commonly observed and exploited in natural hazard events. Topics 2 and 3 take important steps toward identifying viable paths forward. Still, more emphasis is needed on identifying more cost-effective, multi-hazard resistant, culturally appropriate, and locally feasible alternative building systems that can be formalized in guidance from government, non-governmental and research/technical bodies. For example, earth-building material made of clay, sand, water, straw, and minimum steel reinforcement constructed without formwork is gaining momentum in some contexts for its proven resistance to seismic forces. While cultural norms will dictate whether this or other low-cost solutions are viable in Haiti, the market of options available for safe and affordable housing in LMICs and particularly Haiti warrants expansion (Kijewski-Correa, 2021).

TOPIC 5: Rapid Assessment Capabilities in Data-Sparse Environments: Rapid loss estimation and impact forecasting tools, including the processing of terrestrial high-definition laser scanning (Moslam et al., 2014) and more globally satellite imagery to assess the potential impacts of a major earthquake, are critical, particularly in settings where construction is not well-regulated and thus highly variable. As these environments often have sparse data, including limited strong motion sensor networks and ground-truth damage assessments, the process of calibrating and validating these tools can be especially challenging but remains an urgent need for marshaling response and recovery efforts. Access to a standardized and unbiased dataset of ground-level observations of building performance can make important contributions to improving the reliability of tools such as PAGER, UNITAR/UNOSAT EU Copernicus EMS Building Damage Grading Products, and iCUBE-SERTIT Building Damage Grading Products, among others; and contributing to improving satellite-based building damage assessment guidelines such as The International Working Group on Satellite-based Emergency Mapping (IWG-SEM) Guidelines for Building Damage Assessment, among others.

Given the magnitude of the 14 August 2021 Haiti Earthquake, the impacts documented in this PVRR, and recommendations for further study articulated above, a Tier 3 response activating Field Assessment Structural Teams (FASTs) would normally be warranted. However, considering the security concerns highlighted in Section 7.0, StEER will instead deploy a hybrid response model:

- StEER has released a custom rapid seismic assessment App in Fulcrum (StEER Rapid Response - M7.2 Haiti EQ - Aug 2021) to enable local data collectors, largely non-engineers, to capture geotagged photographs, basic building information, and audio descriptions of building performance using their smartphones. The App and training guidance is customized for Haitian building typologies and is available in English and Creole at https://www.steer.network/haiti-response.
- StEER has trained and coordinated ongoing data collection by a team from the Sud Department and is collaborating with GeoHazards International, which is coordinating teams of local data collectors in the Nippes Department. StEER has also deployed a local engineer to Grand'Anse Department. All field data collectors are using the same Fulcrum

App to create a common open dataset visualized at https://www.steer.network/haiti-response and accessible at FulcrumApp.com .

- In parallel, StEER is enlisting engineers from its membership, the Earthquake Engineering Research Institute (EERI), the Pacific Earthquake Engineering Research (PEER) Center, and other NGOs and organizations to review the collected records and complete the rapid assessment using the photographs and transcribed audio files, classifying the building typology and damage rating. Through a collaboration with EERI's Learning from Earthquakes (LFE) Program, guidance has been developed to aid engineers in these remote assessments of Haitian construction (see https://www.steer.network/haiti-response). All records will be updated in real-time in Fulcrum as the assessments are completed. StEER remains committed to sharing the collected data with the Haitian government and NGOs responding to this earthquake.
- A high-level review of the data collected in Fulcrum, as well as impressions by the field data collectors, will be compiled and released as an Early Access Reconnaissance Report (EARR), the second StEER product for this event, followed by the dataset curated in DesignSafe.

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Appendix A: Strong Motion Station Records for 2010 & 2021 Earthquakes

Table A1: List of strong motion station records for 2010 and 2021 Haiti earthquakes

Station	Network	Country	Lat. (°)	Lon. (°)	H1 (%g)	H2 (%g)	Z (%g)	EQ Year	R_{epi} (km)	R_{hypo} (km)	$PGA_{GeoMean}$ (g)
R50D4	AM	Haiti	18.225	-73.613	24.42	34.73	21.21	2021	25.0	26.9	0.291
NQUSE	AY	Haiti	18.564	-72.248	2.34	2.96	1.39	2021	130.6	130.9	0.026
SDDR	CU	DR	18.982	-71.288	0.41	0.27	0.21	2021	239.0	239.2	0.003
GTBY	CU	Cuba	19.927	-75.111	0.75	0.95	0.42	2021	240.9	241.1	0.008
KCTB	JM	Jamaica	17.984	-76.817	0.78	0.87	0.24	2021	356.2	356.3	0.008
MTDJ	CU	Jamaica	18.226	-77.535	0.25	0.28	0.2	2021	429.0	429.2	0.003
SDDR	CU	DR	18.982	-71.288	1.03	1.15	0.57	2010	239.0	239.2	0.011
GTBY	CU	Cuba	19.927	-75.111	0.5	0.45	0.24	2010	240.9	241.1	0.005
GRTK	CU	Turks and Caicos	21.511	-71.134	0.13	0.12	0.06	2010	423.0	423.1	0.001
MTDJ	CU	Jamaica	18.226	-77.535	0.31	0.19	0.1	2010	429.0	429.2	0.002

H1, H2: Horizontal components; Z: Vertical component; R_{epi} = Epicentral distance; R_{hypo} = Hypocentral distance.

Appendix B: Additional Ground Motion Stations for the 2021 Event

Table B1: List of USGS seismic stations during 2021 Haiti earthquake

Name	Instrument Type	Source	Distance From Epicenter (Km)	Intensity
Raspberry Shake Citizen Science Station	UNK	AM	17.607	7.8
US Embassy, Port au Prince, Haiti	UNK	AY	126.65	4.5
Mount Denham, Jamaica	UNK	CU	374.405	3.4
Presa de Sabenta, Dominican Republic	UNK	CU	233.946	3.3
KCTB JM	UNK	JM	301.585	4.3
Guantanamo Bay, Cuba	UNK	CU	201.709	3.7
Grand Turk, Turks and Caicos Islands	UNK	CU	412.289	3.8
-	OBSERVED	DYFI	380.655	3.4
-	OBSERVED	DYFI	373.055	2.9
-	OBSERVED	DYFI	330.876	3
-	OBSERVED	DYFI	320.921	3
-	OBSERVED	DYFI	314.646	2.8
-	OBSERVED	DYFI	304.755	4.2
-	OBSERVED	DYFI	303.5	3.2
-	OBSERVED	DYFI	293.578	3.6
-	OBSERVED	DYFI	204.994	4.3
-	OBSERVED	DYFI	8.559	8.8
-	OBSERVED	DYFI	8.278	8.3
-	OBSERVED	DYFI	119.908	3.8
-	OBSERVED	DYFI	121.296	5.5
-	OBSERVED	DYFI	131.122	4.8
-	OBSERVED	DYFI	191.941	2.9
-	OBSERVED	DYFI	308.872	3.2
-	OBSERVED	DYFI	312.07	3.4
-	OBSERVED	DYFI	323.321	2.9
-	OBSERVED	DYFI	313.027	3.2
-	OBSERVED	DYFI	341.534	2.9
-	OBSERVED	DYFI	352.889	2.6
-	OBSERVED	DYFI	362.883	3.1
-	OBSERVED	DYFI	362.941	2.4
-	OBSERVED	DYFI	372.928	2.9

Appendix C: Ground Motion Station Data Used to Construct the Response Spectra

Table C1: List of strong motion station records for 2021 Haiti earthquake for response spectra

Station	Network	Country	Lat. (°)	Lon. (°)	R_{epi} (km)	R_{hypo} (km)	PGA* (g)	Sa(T= 0.3s)* (g)	Sa(T= 1s)* (g)	Sa(T= 3s)* (g)
R50D4	**AM**	**Haiti**	**18.225**	**-73.613**	**25.0**	**26.9**	**0.291**	**0.856**	**0.177**	**0.097**
NQUSE	AY	Haiti	18.564	-72.248	130.6	130.9	0.026	0.066	0.066	0.012
SDDR	CU	Dominican Republic	18.982	-71.288	239.0	239.2	0.003	0.006	0.010	0.004
GTBY	CU	Cuba	19.927	-75.111	240.9	241.1	0.008	0.025	0.011	0.005
KCTB	JM	Jamaica	17.984	-76.817	356.2	356.3	0.008	0.010	0.013	0.032
MTDJ	CU	Jamaica	18.226	-77.535	429.0	429.2	0.003	0.006	0.008	0.005

R_{epi} = Epicentral distance; R_{hypo} = Hypocentral distance; *GeoMean.

Appendix D: Supplemental Building Damage Imagery

	Multi-unit residential collapse in Les Cayes, Sud Department (Source: NYTimes, August 14)
	Multi-unit residential collapse in Les Cayes, Sud Department (Source: NYTimes, August 14)

	Collapse of concrete building in a residential area in Les Cayes (Source: Twitter)
	Soft story collapse of concrete building (Source: Twitter)

	Soft story collapse of concrete building (Source: Twitter)
	Multi-story residential collapse in Aux Cayes (credit: Miriam Frederick, source: WPTV)

	Collapsed house in the commune of Maniche, Les Cayes, Sud Department (Source: Twitter)
	Damage to masonry in the commune of Maniche, Les Cayes, Sud Department (Source: Twitter)

	Damage to infill walls in homes in the commune of Maniche, Cayes, Sud Department (Source: Twitter)
	Damage to infill walls in homes of the commune of Maniche, Cayes, Sud Department (Source: Twitter)

	Collapse of a multi-story house in commune of Maniche, Cayes, Sud Department (Source: Twitter)
	Damage to infill walls in house in commune of Maniche, Cayes, Sud Department (Source: Twitter)

	Damage to infill walls in house in commune of Maniche, Cayes, Sud Department (Source: [Twitter])
	Collapse of masonry building in the commune of Maniche, Cayes, Sud Department (Source: [Twitter])

	Collapse of masonry building in the commune of Maniche, Cayes, Sud Department (Source: Twitter)
	Collapse of wood-framed house in the commune of Maniche, Cayes, Sud Department (Source: Twitter)

	Collapsed masonry home in the commune of Maniche, Cayes, Sud Department (Source: Twitter)
	Damaged houses in the commune of Camp-Perrin, Cayes, Sud Department (Source: Twitter)

	Damaged houses in the commune of Pestel, Corail Arrondissement, Grand'Anse Department (Source: Twitter)
	Collapsed house in the commune of Pestel, Corail Arrondissement, Grand'Anse Department (Source: Twitter)
	Damaged houses in the commune of Pestel, Corail Arrondissement, Grand'Anse Department (Source: Twitter)

	Damage of single-family houses in Petite Riviere de Nippes (Credit: Gefthé Dévilmé, GeoHazards International)
	Damage of single-family houses in Petite Riviere de Nippes (Credit: Gefthé Dévilmé, GeoHazards International)

	Damage of single-family house in Anse-a-Veau (Credit: Gefthé Dévilmé, GeoHazards International)
	Partial collapse of a multi-family RC residential building (Still photo of a footage by Ralph Tedy Erol/AP, Source: NY Times)

	Collapse of a building in Les Cayes (Ralph Tedy Erol/EPA, via Shutterstock, Source: [NY Times])
	Collapsed Manolo Inn Hotel in Petite Riviere de Nippes (Source:Gefthé Dévilmé, GeoHazard International)

	Collapsed building in Saint-Louis-du-Sud (Credit: AP)
	Cayimite Hotel collapse in Les Cayes, Aug. 14, 2021 (Source: US today)
	Collapsed Hotel Les Cayes (Source: Ralph Tedy Erol/AP, Source: Aljazeera)

	Collapsed hotel in Les Cayes front view (Source: Still photo of footage by Ralph Tedy Erol/AP, Source: NY Times)
	Collapsed hotel in Les Cayes (Source: Twitter)

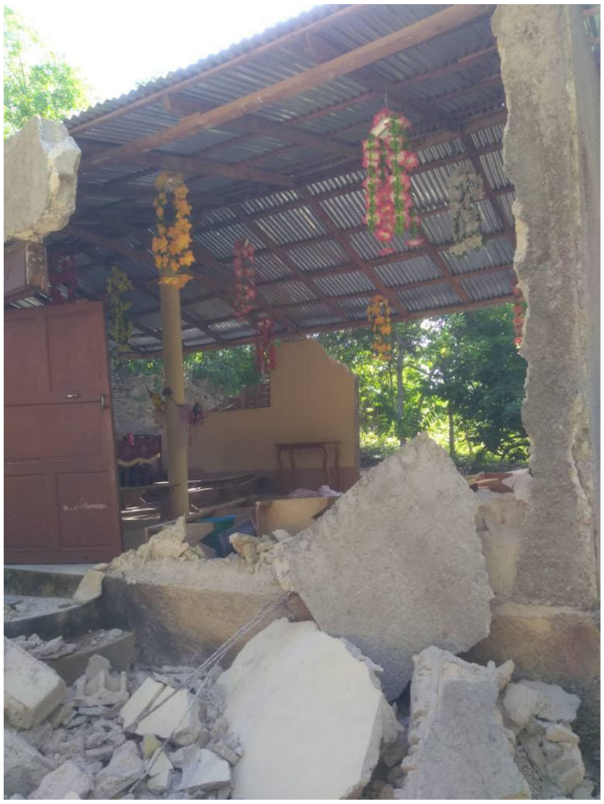
Appendix E: Supplemental Images of Damage to Houses of Worship

	Sacred Heart Church in Les Cayes (Source: Associated Press)
	Sacred Heart Church in Les Cayes (Source: AFPBB News)
	Sacred Heart Church in Les Cayes (Source: The Washington Post)

	Partial collapse of the church of the Immaculate Conception in Les Anglais (Source: teleSUR)

	Partial collapse of the church of the Immaculate Conception in Les Anglais (Source: teleSUR)
	Collapse of the church of Saint Anne in Chardonnières, Sud Department (Source: USA Today)
	Collapse of the church of Saint Anne in Chardonnières, Sud Department (Source: USA Today)

	Collapse of the Shekinah Free Methodist Worship Center in Corail (Source: New Haven Register)

	Collapse of the Shekinah Free Methodist Worship Center in Corail (Source: New Haven Register)
	Partial collapse of the Baptist MEBSH church of Pestel (Source: Twitter)

	Damaged Baptist MEBSH church of Maniche (Source: Le Nouvelliste)
	Damage to the cathedral of Saint Anne in the commune of Anse-à-Veau (Source: GeoHazards International).
	Partial collapse of the parish church in the commune of Corail, Grand d'Anse Department (Source: Twitter)

	Partial collapse of the parish church in the commune of Corail, Grand'Anse Department (Source: Milícia da Imaculada)
	Damage to the church of Saint Joseph in the commune of L'Asile (Source: Washington Post)
	Damage to the church of Saint Joseph in the commune of L'Asile (Source: Boston Pilot)

	Church of Saint Peter in the commune of Baradères before the 2021 Haiti Earthquake (Source: Google Maps)
	Church of Saint Peter in the commune of Baradères after the 2021 Haiti Earthquake (Source: Twitter)
	Church of Sainte Rose de Lima in the commune of Maniche before the 2021 Haiti Earthquake (Source: Worldplace.info)

	Church of Sainte Rose de Lima in the commune of Maniche after the 2021 Haiti Earthquake (Source: Twitter)
	Damage to the church of Saint Anne, in La Sucrerie Henry, commune of Aquin, Sud Department (Source: Mona Lisa Lives Here)

	Damage to the church of Saint Anne, in La Sucrerie Henry, commune of Aquin, Sud Department (Source: Mona Lisa Lives Here)
	Damage to the church of Saint Anne, in La Sucrerie Henry, commune of Aquin, Sud Department (Source: Mona Lisa Lives Here)
	Damage to the church of Saint Anne, in La Sucrerie Henry, commune of Aquin, Sud Department (Source: Mona Lisa Lives Here)

	Damage to the church of Saint Anne, in La Sucrerie Henry, commune of Aquin, Sud Department (Source: Mona Lisa Lives Here)
	Damage to the church of the Sainte Famille du Toirac, in Toirac, commune of Camp Pérrin (Source: Boston Pilot)
	Damage to the church of the Sainte Famille du Toirac, in Toirac, commune of Camp Pérrin (Source: Boston Pilot)