Learning from Earthquakes

The M_w 7.0 Haiti Earthquake of January 12, 2010: Report #1

This is the first of multiple Newsletter *inserts on the Haiti earthquake of January 12, 2010. It summarizes observations from the advance team organized by the U.S. Geological Survey (USGS) and EERI that traveled to Haiti January 26 to February 3, 2010. The multidisciplinary team included Marc Eberhard, University of Washington (team leader); Steve Baldridge, Baldridge & Associates Structural Engineering, Inc.; Justin Marshall, Auburn University; Walter Mooney, USGS; and Glenn Rix, Georgia Institute of Technology.*

In addition to earthquake damage reconnaissance, the team installed four seismograph stations; participated in assessments of numerous buildings, bridges, and port facilities; and trained engineers in post-earthquake damage assessment.

The reconnaissance effort was made possible by the logistical support of the U.S. Southern Command and the officers, soldiers, marines, airmen, and civilians of Joint Task Force Haiti. The institutional support of the U.S. Embassy and U.S. Agency for International Development was also crucial.

Travel funding for the team was provided by the USGS, EERI, Network for Earthquake Engineering Simulation (NEES), Geo-Engineering Extreme Events Reconnaissance (GEER) Association, and Applied Technology Council (ATC).

This insert also includes a section on search and rescue operations by Mikaël Gartner, Donny Harris, Bruce Cook, and Keith Martin, structural specialists with the USAID/OFDA Urban Search and Rescue Team (US-2 / CA-TF2), operated by the Los Angeles County Fire Department.

The EERI contribution was funded by the Learning from Earthquakes project of the National Science Foundation under Award #CMMI-0758529.

Introduction

The M_w 7.0 earthquake that struck the Republic of Haiti on January 12, 2010, is among the most destructive earthquakes in recorded history. As of March 2010, the death toll reported by the Government of Haiti exceeded 233,000, with an additional 300,000 injuries. More than 5 million people live in the area affected by the earthquake, 1.2 million of whom are now in temporary shelters (United Nations, 2010). Humanitarian relief agencies continue to be challenged by the scale of the disaster.

The Republic of Haiti occupies the western third (27,750 km^2) of the island of Hispaniola, located in the NE Caribbean between Puerto Rico to the east and Jamaica and Cuba to the west, and has a total population of approximately 9 million. Its largest city, Port-au-Prince, with an estimated population of between 2.5 and 3 million people, is located 25 km ENE of the epicenter. Haiti is the poorest country in the Western Hemisphere, with an estimated 80% of its people living under the poverty line, 54% in abject poverty (CIA, 2010). In 2008, more than 800 people were killed by four hurricanes and tropical storms that struck during a two-month period.

Seismology

Despite recent seismic quiescence, Haiti has suffered similar devastating earthquakes in the historic past (1701, 1751, 1770, and 1860). Haiti had no seismograph stations during the main earthquake, so it is difficult

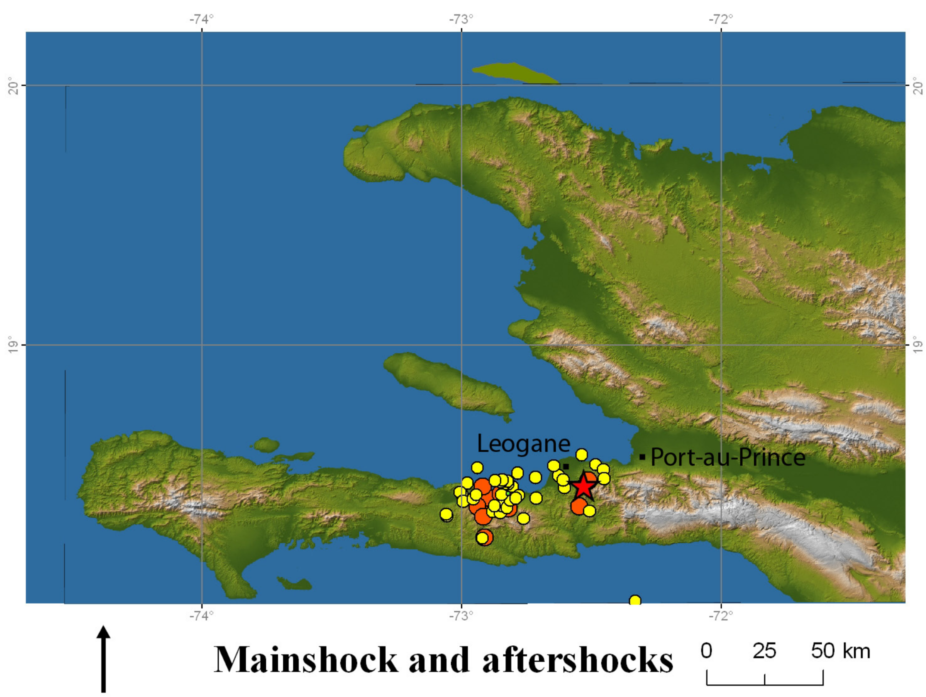

Figure 1. *Topographic map of Haiti with the January 12, 2010, main shock (M7 star) and aftershocks (M5-6 orange and M4-5 yellow) in the first two weeks. Many aftershocks struck 40-50 km west of the main shock, at the west end of the subsurface fault rupture (USGS, 2010).*

to estimate accurately the intensity of ground motions. Nonetheless, the wide range of buildings damaged suggests that the ground motions contained seismic energy over a wide range of frequencies. Another earthquake of similar magnitude could strike at any time on the eastern end of the Enriquillo fault, directly to the south of Port-au-Prince. Reconstruction must take this hazard into account.

Main Shock and Aftershocks. The January 12 quake struck at 04:53 PM local time. The USGS epicenter was 18.457° N, 72.533° W, 25 km WSW of Port-au-Prince on or near the Enriquillo fault (Figure 1). The estimated depth was 13 km, but the lack of local seismic data makes the precise depth uncertain. The USGS assigned a horizontal uncertainty of +/- 3.4 km. The focal mechanism for the main shock indicates left-lateral oblique-slip motion on an east-west oriented fault. The fault ruptured from east to west, away from Port-au-Prince and towards the cities of Léogâne, Grand Goâve, and Petite Goâve. The USGS finite-fault model shows a maximum slip of 5 m up-dip from the hypocenter (Figure 2). The earthquake source zone (the surface area of the fault that slipped) is quite compact, with a down-dip dimension of approximately 15 km and an along-strike dimension of 30 km. This source dimension is about one-third the size of a typical M_w 7.0 earthquake. The earthquake rupture was very abrupt and sharp; maximum moment release occurred in the first 10 seconds of the fault slip.

The four portable seismographs installed by the team recorded a series of small aftershocks. As expected, the ground motions recorded at a hard rock site had a greater proportion of high frequencies than the motions recorded at a soil site. Two of the stations continue to monitor seismic activity.

Surface Faulting. Many crustal earthquakes of M_w 7.0 or greater are accompanied by surface rupture that can be traced for tens of kilometers. However, U.S.-based remote sensing experts have reported no success in identifying surface rupture from satellite imagery. Land-based investigations by other scientists conducted between January 22 and 26 identified only roadway cracking and slumping, no surface ruptures. Our field investigations failed to find any evidence of surface faulting. Numerous cracks in roadways could all be attributed to slumping of road embankments, which rise as much as 3 m (9.8 ft) above the adjoining fields. We concluded that surface faulting is unlikely in the region west of the epicentral zone near the town of Fayette and up to, and including the coastline west of the town of Dufort.

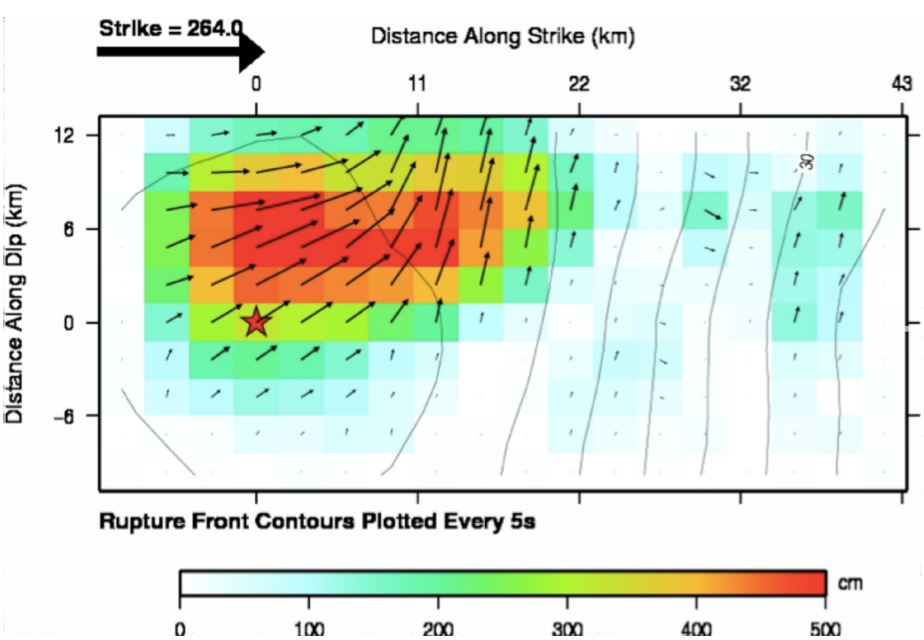

Figure 2. USGS finite-fault model indicates the amount of slip on the fault plane during the earthquake. West is to the right (Hayes, 2010).

Geotechnical Aspects

Soil liquefaction, landslides and rockslides in cut slopes, and road embankment failures contributed to extensive damage in Port-au-Prince and elsewhere. More complete coverage of these aspects can be found in the GEER report, mentioned at the end of this insert.

Liquefaction-induced lateral spreading contributed greatly to the extensive damage in Port de Port-au-Prince, especially the collapse of a pile-supported marginal wharf. The liquefaction features and resulting damage are described in more detail in a subsequent section of this report on the port.

Other less severe liquefaction-related features were observed in the alluvial plain surrounding the city of Léogâne. Figure 3 shows the failure of a structure located about 75 m (246 ft) from the shoreline at 18.446323° N, 72.686259° W. There were several sand boils nearby, the largest of which measured approximately 4 m (13 ft) in diameter. Based on discussions with others who observed this structure (Rathje and Green, 2010), it is likely that a combination of structural and foundation failures contributed to the collapse.

A lack of detailed knowledge about soil physical conditions (lithology, stiffness, density, and thickness) made it difficult for us to assess quantitatively the role of ground-motion amplification in the widespread damage.

***Figure 3**. Combined structural and foundation failure southwest of Léogâne.*

Structures

The earthquake caused extensive damage to buildings throughout the Port-au-Prince region, and in the rural areas and towns to the west of the city. The larger report prepared by this team and available on the web (**http://www.eqclearinghouse.org/20100112-haiti/published-reports**) provides an overview of Haitian building and housing statistics, typical construction practices, and damage to residential construction. It describes the performance of reinforced concrete and masonry structures and illustrates key features with four case studies. Also included is a discussion of prefabricated steel frame performance and a quantitative survey of distributed damage for two sample areas. Below are highlights from the more comprehensive report.

The Haitian Ministry of Statistics and Informatics reported that one-story buildings represent 73% of the building inventory. Most typical one-story houses have roofs made of sheet metal (82%), whereas most multi-story houses and apartments have roofs made of concrete (71%). Walls made of concrete/block/stone predominate in both houses and apartments. A damage survey of 107 buildings in downtown Port-au-Prince indicated that 28% had collapsed and another 33% were damaged enough to require repairs. A similar survey of 52 buildings in Léogâne, the closest large population center to the epicenter, found that 62% had collapsed and another 31% required repairs.

It appears that the widespread damage to residences and commercial and government buildings was largely attributable to the lack of attention to seismic risk in design and construction. In a country as poor as Haiti, typical residences and commercial buildings are constructed informally, with whatever materials and procedures can be afforded. Such structures have not usually been designed formally. For most larger commercial and government buildings that were more likely to have been designed by an engineer, the structural types, member dimensions, and detailing practices were inadequate to resist strong ground motions. These vulnerabilities may have been exacerbated by poor construction practices and difficulties in the procurement of consistent quality construction materials (Figures 4 and 5).

Reinforced concrete frames with concrete block masonry infill appeared to perform particularly poorly. Structures with light (timber or sheet metal) roofs performed better than structures with concrete roofs and slabs.

***Figure 4**. Hand sieving aggregate on site for mortar.*

***Figure 5**. Partial collapse of residential building under construction.*

Figure 6. *Differential damage to two structures across the street from one another in Port-au-Prince: (a) reinforced concrete frame with masonry infill; (b) new Digicel building under construction*

Most multi-story structures appeared to consist of reinforced concrete frames, with reinforced concrete roofs and floors, and masonry infill. The team also found some bearing-wall structures supporting concrete floors and roofs, and occasionally, wood or steel roofs. For structures with low-to-moderate levels of damage, it was often difficult to determine whether the bearing walls were made of concrete, reinforced concrete, or masonry. Only a few of the buildings we observed had any seismic detailing, consistent with the observations of Fierro and Perry (2010).

Figure 6a shows the collapsed Turgeau Hospital, its lateral-force resistance provided by a reinforced concrete frame with masonry infill. As with numerous other structures observed by the team, the columns and joints had little transverse reinforcement. The new Digicel building across the street (18.532729° N, 72.323235° W) appeared to be nearly undamaged, with slight damage to a few windows (Figure 6b). The fundamental period of the Digicel building was likely much larger than that of the hospital, so the seismic demands would have differed; nonetheless, the stark difference in performance suggests that the severe damage to numerous buildings could have been avoided with greater attention to seismic performance.

Since the seismic performance of some buildings was adequate, and a selection of damaged buildings appeared to have had low deformation demands, it is reasonable to conclude that structures designed and constructed with adequate stiffness and reinforcing details would have resisted the earthquake without severe damage (see Figures 7 and 8).

Bridges

There was no evidence of bridge collapses attributable to the earthquake. Most bridges in Port-au-Prince are simple box culverts consisting of 2.0-2.5 m (6-8 ft) deep box girders. However, in several cases the roadway settled differentially between the approaches and the section spanning the culvert. Multi-span bridges on primary routes are engineered structures that had some damage but were still useable.

Port Facilities

The main port in Port-au-Prince suffered extensive damage during the earthquake, inhibiting the delivery of relief supplies. The collapse of the North Wharf appears to have been caused by liquefaction-induced lateral spreading (Figure 9). There were three cranes at the North Wharf, including one 15-m (50-ft) gauge, A-frame container crane, and two rubber-tired mobile

Figure 7. *Collapse was extensive throughout the guest wings of the Hotel Montana, constructed of reinforced concrete with unreinforced infill concrete masonry walls.*

Figure 8*. Areas of the Hotel Montana lobby remained intact. It appeared that this part of the building had reinforced concrete beams and slabs without extensive infill walls***.**

Figure 9. *Fissures caused by lateral spreading at western ends of the North Wharf.*

Figure 10. *Submerged 15-m gauge container crane (foreground) and mobile crane (background)*

cranes. Apparently, two of the three cranes were on the North Wharf at the time of the earthquake and are now partially submerged. Figure 10 shows the A-frame container crane in the foreground and a submerged mobile crane in the background.

The westernmost 120 m (400 ft) of the South Pier collapsed, and approximately 85% of the vertical and batter piles supporting the remaining section were moderately damaged or broken. The remaining section of pier was shut down to vehicle traffic following additional damage during an aftershock. The collapse of a pile-supported pier at the Varreux Terminal resulted in the deaths of about 30 people working on the pier at the time of the earthquake (Figure 11). There was less severe damage, including a small oil spill, at a marine oil terminal located near Port-au-Prince.

Satellite Imagery

A unique aspect of the response to this earthquake is the extensive use of remote sensing data, including satellite imagery and aerial photography, to guide damage assessment and rescue and recovery efforts. The organizations involved in these efforts include ImageCat, the World Bank's Global Facility for Disaster Reduction and Recovery, the Rochester Institute of Technology, EERI, and MCEER. ImageCat, in collaboration with other partners, formed the Global Earth Observation Catastrophe Assessment Network (GEO-CAN). This network is using very high-resolution aerial and satellite imagery to determine which structures have completely or partially collapsed or are heavily damaged. Their findings have been and will be used by the World Bank to help develop plans for the reconstruction effort.

Figure 11. *Remaining portion of pile-supported pier at the Varreux Terminal (source: Chodkiewicz).*

The damage assessment is being performed by volunteer scientists and engineers in government, academia, and private practice who are comparing previous imagery with the high-resolution imagery captured after the earthquake. More than 500 skilled engineering personnel in remote locations have participated in damage assessment to date. They have also used Light Detection and Ranging (LIDAR) technology to create a three-dimensional map of the region to further enhance their knowledge of the damage. An example of the imagery is available in Figure 12. The red areas in the bottom figure indicate structures that have sustained damage discernable from the imagery.

The National Geospatial-Intelligence Agency (NGA) is also using high-resolution aerial images and LIDAR technology. They have created maps of damaged regions and have used LIDAR mapping from flyovers of the area to determine locations where rubble has blocked roads. The data are of sufficient accuracy that they can be used to approximate the volume of rubble that must be removed. Other agencies are developing and using aerial imagery for recovery efforts: the German Space Agency (DLR), Information Technology for Humanitarian Assistance Cooperation and Action (ITHACA), and the United Nations Operational Satellite Applications Program (UNOSAT).

The significant effort devoted to developing imagery evaluation techniques for this earthquake and the collaboration among numerous agencies are testaments to both the magnitude of the event and the possibilities for these technologies in future natural disaster response and recovery.

Figure 12*. ▲Image above shows damage; ▼image below indicates buildings that have been marked as partial or complete collapse in the web-based analysis.*

Search and Rescue

On January 12th USAID/OFDA activated several urban search and rescue (USAR) teams and sent them to Haiti. Two designated USAID/OFDA-supported heavy rescue USAR teams from Fairfax County, Virginia (VA-TF1) and Los Angeles County, California (CA-TF2), composed of 72 personnel, six search and rescue canines, three doctors, and three structural specialists (engineers), and up to 48 tons of rescue equipment, were deployed with USAID/DART. Under the direction of USAID, FEMA also deployed Miami-Dade Fire (FL-F1), City of Miami Fire Department (FL-TF2), and New York City OES (NY-TF1) USAR Task Forces to supplement CA-TF2 & VA-TF1.

The United States USAR teams joined an international effort of more than 40 search and rescue teams from countries as various as France, Spain, the United Kingdom, Iceland, Belgium, South Africa, the Dominican Republic, Taiwan, China, Mexico, Israel, Colombia, Chile, and Russia. Over 134 rescues were made, with 47 made by American USAR teams. Los Angeles County (CA-TF2) made nine live rescues and two assists. Emergency planners and search and rescue experts have cited this event as the most successful operation in recent USAR history.

There were numerous logistical challenges related to transportation, supplies, and communications due to damaged infrastructure and non-existent emergency management. USAR transportation to Haiti was typically provided by military aircraft. Demobilization out of Haiti

***Figure 13**. Three-person rescue in Port-au-Prince store (photo: Gartner).*

***Figure 14.** Humanitarian aid at an orphanage (photo: Harris).*

was typically by commercial airliner out of the Dominican Republic.

Rescue operations were concentrated in the city of Port-au-Prince, with the city divided into sections for more efficient distribution of rescue operations. CA-TF2 was responsible for a section immediately west of the Presidential Palace in downtown Port-au-Prince, with missions at the Hotel Caribe, Hotel Montana, UN apartment complexes, and palace complexes.

Most of the collapsed buildings observed were constructed of concrete/concrete masonry one-way slabs with flush beams supported on concrete columns having minimal reinforcement. Floor slabs had a mix of smooth and deformed reinforcement (see Figure 13). Distribution and size of steel reinforcement in the floor system was typically minimal, with certain buildings having greater amounts of reinforcement based on use. Unreinforced hollow cell concrete masonry had been used to construct internal partitions and exterior walls; frequently the cells were not grouted. The concrete and masonry appeared to be of low quality. Hand tools frequently were sufficient to break through the slabs. USAR equipment supplied in the heavy USAR cache was sufficient to perform breaching and breaking in this type of construction.

Void space, where survivors were rescued, varied in size and configuration, although the brittleness of the masonry walls reduced the formation of void spaces. The walls typically shattered, filling potential void spaces with debris. Floor slabs typically remained intact. Had the walls been grouted and reinforced, the size of the void spaces may have been larger and the probability of rescuing viable victims would have been greater. Had masonry walls been grouted and adequately reinforced, with proper diaphragm connections, there may have been fewer pancake collapses and increased void space.

CA-TF2 utilized locals on several occasions to assist in rescue operations. This allowed operations to be completed faster and involved the people in rescuing their fellow countrymen and women. This was a key element to connecting with the people and at the same time provided an indirect way to control the crowds.

As rescue operations transitioned, USAR structures specialists began assisting the US Army Corp of Engineers (USACE) in assessing structural safety. Using ATC-20, the specialists assessed various hospitals, schools, and structures critical to the humanitarian aid effort.

The secondary mission of the USAR Task Forces was to deliver humanitarian relief to orphanages and hospitals identified by USAID (see Figure 14). Task Force members installed tents and generator power systems, performed structural assessments of buildings, and assisted with medical assessments of orphans.

Social Impacts

The functioning of the government and other institutions was seriously handicapped by the loss of personnel, records, and facilities (Figure 15). Numerous clinics, hospitals, police stations, ministries, schools, universities, palaces, and churches were triply disadvantaged. The absence of social infrastructure has compromised the recovery and reconstruction efforts.

Recommendations

The historic pattern of earthquakes in Haiti indicates that another earthquake of magnitude 7 or larger could strike southern Haiti near Port-au-Prince at any time. Reconstruction must therefore be based on sound, simple, and cost-effective engineering practice for all possible natural hazards. These principles must be clearly communicated to the citizens of Haiti.

The next *Newsletter* report, to be published in May 2010, will have more information on damage and observations on rebuilding. Taken together, these reports can inform recovery and reconstruction decision making.

Additional Information

A much more extensive report from this team is available for download at **http://www.eqclearinghouse.org/20100112-haiti/published-reports**.

Also available for download at the same site are a comprehensive report from the Geo-Engineering Extreme Event Reconnaissance (GEER) Association, a preliminary report from the PEER Center on observations by Eduardo Fierro, and a summary report from MCEER on the damage assessment process.

References

CIA (2010). *The Central Intelligence Agency World Factbook* (**https://www.cia.gov/library/publications/the-world-factbook/index.html)**, Accessed on February 10, 2010.

Chodkiewicz, Scott, USACE, 2010.

Fierro, E. and Perry, C. (2010). *Preliminary Reconnaissance Report – 12 January 2010 Haiti Earthquake*. BFP Engineers, 12 pp.

Hayes, G. (2010). USGS Finite-Fault Model for January 12, 2010, Haiti Earthquake, **http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010rja6/finite_fault.php**

Rathje, Ellen and Russell Green, 2010, personal communication.

U.S. Geological Survey (2010). Significant Earthquakes: Magnitude 7.0 Haiti Region, 2010 January 12, 21:53:10 UTC, **http://earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010rja6/**

Figure 15. *Top: Legislative Palace; middle: Judicial Palace; bottom: National Palace.*