Learning from Earthquakes

The M_w 7.0 Haiti Earthquake of January 12, 2010: Report #2

This second insert on the Haiti earthquake covers engineering failures and the social impacts of the quake. The first report in the April issue covered seismology and geotechnical aspects, primarily. The EERI team responsible for this report, including members from partnering organizations — the Network for Earthquake Engineering Simulation, the Mid-America Earthquake Center, Florida International University, Sherbrooke University, University of Delaware's Disaster Research Center and Western Washington University's Resilience Institute — visited Haiti from February 28 through March 7, 2010. The 18-member multi-disciplinary team included engineers, social scientists, city planners, architects, and geographers. The EERI team worked with the ASCE Technical Council on Lifeline Earthquake Engineering team and, together, the teams visited over 500 facilities and buildings in the heavily hit areas of Port-au-Prince, Léogâne, Petit Goâve, and Jacmel. The EERI team and its partners consisted of Reginald DesRoches, Georgia Institute of Technology (team leader); Susan Brink, University of Delaware; Peter Coats, Simpson Gumpertz & Heger; Amr Elnashi, Mid-America Earthquake Center; Harley Etienne, Georgia Institute of Technology; Rebekah Green, Western Washington University; Martin Hammer, architect, Berkeley, California; Charles Huyck, ImageCat; Ayhan Irfanoglu, Purdue University & NEEScomm; Sylvan Jolibois, Florida International University; Anna Lang, University of California, San Diego; Amanda Lewis, Mid-America Earthquake Center; Jean-Robert Michaud, Boeing; Scott Miles, Western Washington University; Rob Olshansky, University of Illinois; and Patrick Paultre, Sherbrooke University.

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Introduction

On January 12, 2010, at approximately 5 p.m. local time, an M_w=7.0 earthquake struck approximately 17 km west of Port-au-Prince, Haiti, along the Enriquillo fault. The effects of the earthquake were felt over a wide area, including the provinces (known as departments) of Ouest, Sud-Est, and Nippes. The metropolitan Port-au-Prince region, which includes the cities of Carrefour, Petionville, Delmas, Tabarre, Cite Soleil, and Kenscoff. was hit extremely hard. In the city of Léogâne, located on the epicenter, 80% of the buildings collapsed or were critically damaged.

Over 1.5 million people (approximately 15% of the national population) have been directly affected by the earthquake. The Haitian government estimates over 220,000 people lost their lives and more than 300,000 were injured in the earthquake. It is estimated that over 105,000 homes were completely destroyed and more than 208,000 damaged. Approximately 1,300 educational institutions and over 50

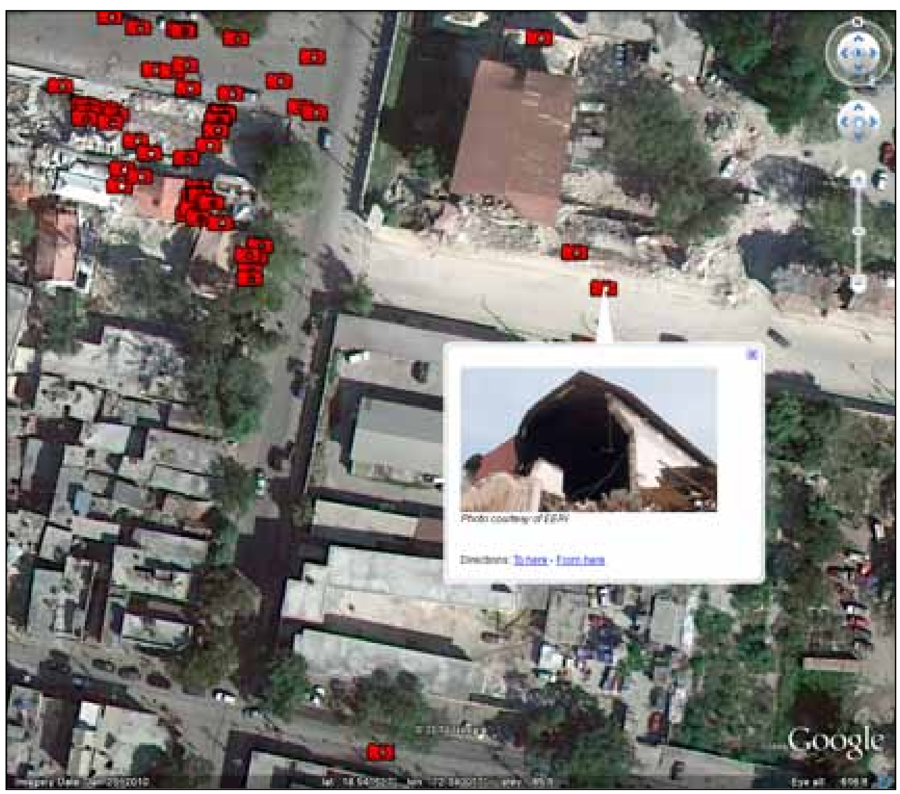

Figure 1. *Georeferenced digital photos taken by the reconnaissance team or donated to EERI are available in KML format at* ***http://www.virtualdisasterviewer.com/vdv/download_photo_kml.php?eventid=7***.

medical centers and hospitals collapsed or were damaged; 13 out of 15 key government buildings were severely damaged.

The Haitian government estimates that the damage caused by the earthquake totals approximately $7.8 billion, which is more than 120% of Haiti's 2009 gross domestic product.

Remote Sensing Data

The Global Earth Observation Catastrophe Assessment Network (GEO-CAN) response after the Haiti earthquake realized a vision many years in the making — that rapid and actionable damage assessment could be completed with remotely sensed data enabled by distributed interpretation in a geospatial environment. Analysis is done through a portal that serves as a "social networking tool" where, after reading a brief training document, hundreds of engineers and scientists provided an assessment of damage by comparing before-and-after satellite images of the affected areas. GEO-CAN allowed for a comprehensive assessment of regional damage and was used in the development of the post-disaster needs assessment. It can serve as a successful model for utilizing remote sensing technologies after a regional disaster.

Within a week, close to 30,000 buildings had been identified as heavily damaged or collapsed. The data were checked independently using field ground surveys conducted by a wide range of organizations. In total, there were over 600 GEO-CAN volunteers from 23 countries representing 53 private companies, 60 academic institutions, and 18 government or nonprofit organizations. Almost 200 members from EERI contributed significantly to the effort. For a complete list of organizations, visit the GEO-CAN community tab at **http://www.virtualdisasterviewer.com/vdv/index.hp?selectedEventId=7**.

All data produced have been made publicly available directly through the World Bank and served in the Virtual Disaster Viewer (VDV), alongside thousands of geo-tagged photographs from the EERI reconnaissance team and various other post-disaster ground field teams (Figure 1).

Many lessons have been learned from the GEO-CAN effort, among them that very high-resolution imagery can be used to provide rapid damage estimates of severely damaged structures where it is difficult to deploy in the field. This has enormous implications for future events where access is restricted or not feasible and immediate information is required. During reconnaissance, it became clear that more damage was visible in the imagery than could be seen on the ground, because damaged structures were behind walls, deep within blocks. Mobilizing hundreds of engineers requires significant resources. Much of GEO-CAN's success is attributable to the generosity of Google, Microsoft, Digital Globe, and GeoEye and the San Diego State University Visualization Center, which not only freely distributed data, but actively served imagery for interpretation.

Most importantly, GEO-CAN is a model for mobilizing volunteers with professional expertise. The GEO-CAN community has conclusively demonstrated that professionals will volunteer in large numbers if the proper IT infrastructure is available.

Social-networking can be used to establish a framework of massively distributed but collaborative environments that can reduce the communication gridlock common in disasters. Future successful deployments will hinge upon harnessing this framework.

Performance of Historic Structures

Historic buildings dating from the time of French colonization to the 1920s predate the concrete-framed concrete block construction that comprises most of the building inventory of Port-au-Prince. Historic buildings fall into three distinct categories: timber frame, unreinforced masonry (URM), and reinforced concrete.

Timber Frame: In Port-au-Prince and other urban areas of Haiti, these buildings were generally constructed between 1890 and 1925. Built typically as residences, the buildings were generally either 1) timber frame with exterior wood siding, or 2) timber frame with masonry infill (known by the French term *colombage*) (Figure 2). The masonry is either fired brick with lime mortar, or irregular shaped limestone with earthen mortar and a lime plaster finish. In all observed cases, the timber frame included diagonal members and interior

Figure 2. *Timber frame with colombage (photo: Martin Hammer).*

Figure 3*. Wood frame building next to collapsed concrete and masonry building (photo: Martin Hammer).*

Figure 4. *Colombage performed well, though the unreinforced masonry wall collapsed (photo: Martin Hammer).*

wooden planks horizontally across the wall framing.

These buildings were either one story or two, with mortared brick or limestone foundations, wood-framed floors, and corrugated steel roofs framed with wood. The most prominent timber frame buildings exhibit ornate carpentry details, and are commonly referred to as "gingerbread," but many simpler buildings utilize the same methods of construction.

Both types of timber frame construction are inherently resistant to earthquakes. The all-wood buildings are light and flexible, and utilize the diagonal members and wood-sheathed walls to resist lateral loads. The colombage buildings are heavier, but dissipate energy through friction between the masonry panels and the timber members, and between the masonry units after their weaker mortar joints fracture. The diagonal wood members provide resistance as well (Figure 2).

The timber frame buildings in Port-au-Prince, Petionville, and the south coastal city of Jacmel performed well, and were often seen adjacent to the site of a collapsed masonry or concrete structure (Figure 3). However, many sustained moderate to serious damage due to the deterioration of wood members from termites or rot. The colombage buildings sometimes expelled masonry panels under out-of-plane loading. Additions made of unreinforced masonry or reinforced concrete usually suffered the most damage (Figure 4).

Unreinforced Masonry (URM): Unreinforced masonry construction predominates among buildings constructed between the late 1800s and the 1920s, often combined with the timber construction described above. The EERI team observed URM residential, academic, religious, and government buildings (Figure 5). The buildings were a combination of rough stone masonry and fired clay brick, with little or no smooth steel reinforcing along building corners or window and door heads. The stone masonry appeared to be the light colored limestone that is commonly acquired in the La Boule quarries in the hills around Port-au-Prince. Some URM buildings, such as the Haitian Ministry of Interior, failed catastrophically (Figure 5) even though the neighboring Ministry of Finance (also URM) suffered far less damage and did not collapse.

The failures we observed generally ranged from diagonal cracking in wall sections to absolute collapse; modes of failure included 1) lack of brick ties or brick headers between brick withes, 2) lack of adequate steel reinforcing, 3) weak stone masonry where it was necessary for structural support, and 4) poor mortar quality due to poor aggregate quality, inadequate cement or lime, or poor maintenance.

For those URM buildings that remain intact or that can be salvaged, it is advisable for an historic preservation and/or structural engineering professional to inspect them in greater detail to determine appropriate preservation and structural retrofit measures. These measures may include doweled through-wall anchors, parallel lateral bracing, or repairs to mortar.

Figure 5. *Unreinforced masonry Ministry of Interior building (photo: Martin Hammer).*

Reinforced Concrete: Many turn-of-the-20th-century structures built in the manner prevalent in Europe at the time were precursors to what is now the most common form of construction in Haiti. At the time these were built, it was unique to construct an entire building with poured-in-place concrete. This building type included two of the best known landmarks in Haiti, the National Presidential Palace and the National Cathedral (Figure 6), both of which collapsed catastrophically.

Each of these buildings had unusual footprints that militated against any effort to sustain seismic forces. Each building also included large concrete domed structures, which apparently contributed to their collapse. In the case of the National Presidential Palace, an eyewitness reported that the second story rocked until the central core collapsed vertically, followed by the front section of the east and west wings. This indicates that the second story acted as the soft story between the rigid first floor and the massive concrete dome and roof structures. The strength and hardness of these domes was evidenced by their showing no apparent cracking after falling one story.

While the National Cathedral did have a light steel roof structure, it also had two large concrete domes on top of its towers, making them top heavy. In addition to collapses, the damage that we observed included severe shear cracks in columns and out-of-plane collapses of concrete walls.

Petrographic testing of concrete from both samples (services donated by Simpson, Gumpertz and Heger) revealed that the concrete aggregate is of relatively high quality and contains approximately 30% volcanic materials. There is no evidence that marine aggregate was in either of these buildings. We observed excessive corrosion of the steel reinforcement in both buildings, but given the results of the petrographic testing, it appears that it was the result of the carbonation of the aged concrete rather than the use of poor aggregate.

According to our observations, the following are possible primary modes of failure: poor weight and wall distribution for seismic loading; corroded steel reinforcement as a result of aged carbonated concrete; and inadequately ductile concrete members to sustain repetitive stressing.

Engineered Buildings

Given the absence of building codes and record keeping, and the widespread practice of uncontrolled construction, it was not always possible to establish whether a spe-

Figure 6. *Collapsed roof, interior of National Cathedral, Port-au-Prince (photo: Martin Hammer).*

cific building was engineered. We decided that "modern engineered buildings" were those with regular structural framing layouts, estimated to be built after the 1950s, and deemed to have received some degree of care by a structural engineer during design and construction. "Engineered" does not mean designed for seismic loading. While modern commercial, industrial, and essential buildings are the most likely structures to be engineered, several low to mid-rise office, residential, and school buildings were also considered to be engineered.

Most of the early generation Haitian engineers and architects were educated in France and were familiar with the French building design codes (AFNOR). By the 1960-70s, these engineers were teaching at the university level using the French code. Earthquake provisions were not present in these codes, and moment-resisting frames were the favored structural system. A small number of Haitian engineers were educated and trained in North America, and were familiar with the Canadian and U.S. design codes.

Since the 1950s, reinforced concrete has been the material of choice and many construction practices that do not consider seismic loads were established at that time. Concrete is usually hand-mixed on site for smaller engineered buildings and is typically of poor quality. Lately, in prominent engineered buildings such as those at the Digicel compound (Figure 7), ready-mix concrete is used. There is only one Haitian contractor who uses ready-mix concrete consistently; no information is available about the practice of international contractors.

In older engineered buildings, smooth reinforcing bars were used, and transverse reinforcement was observed to be 5-6mm diameter wires with unacceptably large spacing, particularly in columns. In newer construction, deformed bars were also observed. Ductile detailing was absent in the damaged and exposed structural members in both older and more recent construction.

Figure 7. *The 12-story Digicel building with RC dual (frame-wall) structural system (photo: Anna Lang).*

In the past, the Ministry of Public Works controlled building permits, along with plan and design reviews, but the jurisdiction now lies with municipalities. Local engineers indicated that this transfer of jurisdiction led to reduced control over design and construction.

Reinforced Concrete Buildings: Reinforced concrete buildings with moment-resisting frame structural systems (RC-MRF) and unreinforced hollow concrete masonry unit (CMU) infill walls dominate the engineered buildings. A small number of dual-system buildings with RC MRF and structural walls were also observed.

The typical floor system is RC slab with beams. RC dual-systems are observed to have sustained less damage, on average, than the RC-MRF buildings. In several buildings recently constructed, seismic design guidelines such as those provided in U.S. design codes and ACI-318 were followed. However, the application of seismic design principles was due to individual initiative and not because of consensus or governmental action.

Critical structural damage was mainly due to absence of proper detailing in the structural elements, with failure of brittle columns as the main cause of collapse. Some structures had soft-story issues. The quality of concrete varied from weak (typical) to good (rare), verified by preliminary tests. Both smooth and deformed reinforcing bars were observed in structural elements exposed due to damage.

The Digicel building is the tallest engineered building in Port-au-Prince. One of its L-shaped structural walls can be seen along the left corner in Figure 7. Three such walls are present at as many corners of the building. The fourth corner has a large atrium with deep beams. An elevator core wall is near the atrium corner. The building performed well with light structural and some nonstructural damage. Spalling of concrete was visible in some columns, top and bottom; some beams in the upper floors suffered severe spalling and, in a few places, buckling of longitudinal bars. Adjacent three-story RC-MRF buildings were severely damaged.

In the Petionville area, several modern engineered buildings were inspected. One of the hotels, a RC-MRF with reinforced CMU infill walls, suffered damage in its infill walls and a few captive columns at the ground story (Figures 8 and 9). Another RC-MRF hotel under construction (with three stories completed and three more to go) sustained no damage (Figure 10),

***Figure 8**. Reinforced CMU wall from a hotel in Petionville (photo: Amanda Lewis).*

***Figure 9** (**left**). Damage in a column due to captive condition, Petionville hotel (photo: Ayhan Irfanoglu).*

while an older construction RC-MRF multi-story hospital building adjacent to it collapsed totally.

The new U.S. Embassy building, located near the airport in north-eastern Port-au-Prince and reportedly designed to load levels equivalent to those for U.S. seismic zone 4 with near-source consideration, did not sustain any structural damage.

Steel Buildings: A small number of steel industrial buildings were inspected. A single story steel building with corrugated roof and side sheathing at the fuel port sustained no damage. In another steel building that houses an apparel manufacturing company, neither the structural steel framing nor the CMU block infills sustained any damage. The structure had a light, corrugated sheet metal roof. The steel framed warehouse at the main port of Port-au-Prince sustained heavy damage due to lateral spreading. When the seaside supports of the transverse frames were displaced outward, the frames buckled at the roof (typical) as did the seaside columns.

***Figure 10**. Garage of hotel under construction, sustained no damage (photo: Ayhan Irfanoglu)*

Low-Rise Buildings and Homes

The most prevalent building type in Haiti, particularly in the Port-au-Prince region, consists of non-engineered, lightly reinforced concrete frame structures with concrete masonry block infill. They are constructed with unreinforced concrete block walls framed by slender, lightly reinforced concrete columns. Other types of masonry, including fired clay brick, are not used.

Floors and roofs are reinforced concrete slabs, typically four to six inches thick with a single layer of bi-directional reinforcement. Concrete blocks are commonly cast into the slab to minimize the use of concrete. Corrugated steel or fiberglass over a sparse wood frame is also a common roofing method.

These buildings are used for single family dwellings and small businesses, and are usually one or two stories, though three stories are not uncommon. The familiar soft-story design, whereby the ground level is dedicated commercial space and upper floors are residential apartments, is not prevalent in Haiti, as most people live and work in different geographical areas. Soft stories are a problem, however: large openings for windows and reduced wall area caused numerous floor collapses, both at the ground level and at floor levels above.

Many residences are constructed over a significant length of time as the homeowner acquires funds or the family's needs expand. Most are designed and constructed by the owner or a local mason. Residents sometimes squat on land, public or private, to be near family, friends, or their employment. These unauthorized developments, known by the French term *bidonville*, are found on hillsides surrounding Port au Prince and Petionville, as well as in low-lying coastal areas such as Cite Soleil (Figure 11).

Perimeter foundations are typically 1m deep and assembled with stone or rock rubble and lightly cemented mortar. Because the bidonville residences are usually constructed on hillsides, stone foundations commonly serve as either a retaining mechanism on the upslope or are elevated on the down-slope to create a level floor. These foundational elements regularly exceed 2m height on steep inclines. A layer of concrete is poured over the foundation to provide a finished surface upon which the building's walls are constructed.

Construction Materials and Procedures: Concrete masonry blocks are commonly manufactured at or near the construction site. Type I Portland cement is used for all construction elements, including masonry blocks, foundation and wall mortars, roof and floor slabs, and columns and beams. Concrete mix proportions regularly lack sufficient cement and have a high water con-

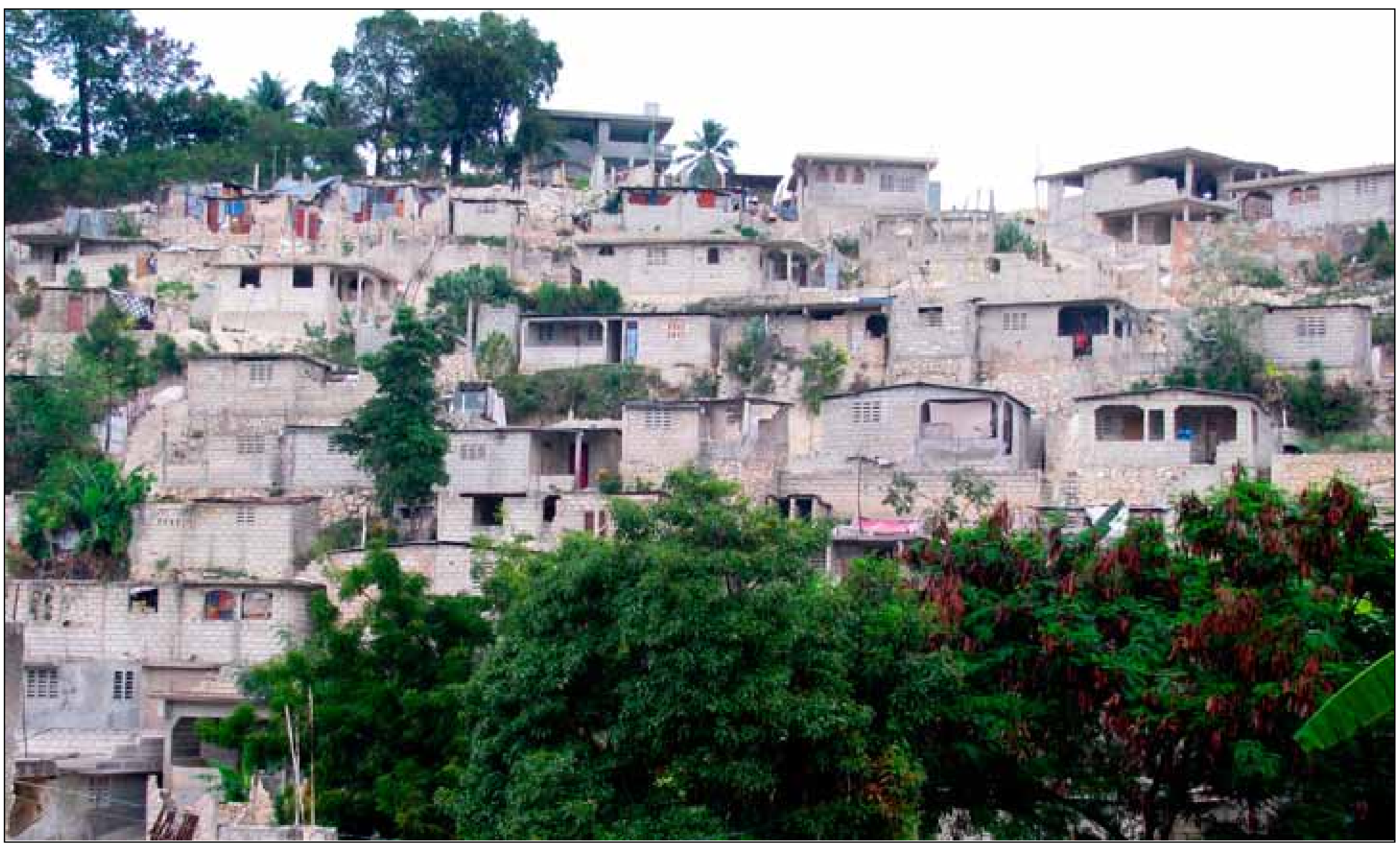

Figure 11. *Typical residential bidonville in the hillsides above Port-au-Prince (photo: Anna Lang).*

Figure 12. *Typical construction of a residence, showing a rock rubble foundation, confined masonry construction technique, and reinforced concrete slab. Note blocks added to the top of the walls and reinforcement emerging from the slab, ready for construction of another level (photo: Anna Lang).*

tent for workability and reduced cost (see Figures 12 and 13).

Aggregate is obtained from nearby limestone quarries and gradated on-site. The largest quarry, La Boule, produces a light colored weak limestone. Despite a recent ban on the this aggregate for its weaknesses, its use persists. Other stronger smooth aggregate originates in riverbeds in the hills around Port-au-Prince. While the use of corrosive beach sand was prevalent in the past, we observed no evidence of its present day use.

Masonry walls are typically 2.5 m high with a single-wythe staggered block arrangement. Walls are constructed directly on top of a finished foundation or floor slab; no mechanical connection is made. Typical block dimensions are 40 cm long, 18.5 cm high, and 14.5 cm wide. Mortar for the block walls is mixed on-site, typically on the ground. Horizontal bed joints are commonly 2 cm thick; vertical beds vary from 0-2 cm. Walls vary in length from 2-4 m and are commonly bordered by lightly reinforced concrete columns. Wall slenderness did not appear to be problematic: most have a height-to-width ratio less than 1.0. Slender reinforced concrete columns that border the walls are typically 25-35 cm wide. Column depth is no less than the masonry unit width. Longitudinal reinforcement usually consists of four #3 or #4 bars; transverse reinforcement is typically #2 bars, spaced between 6-12 inches with no decrease in spacing at column ends. Transverse ties are not bent beyond 90 degrees and smooth or ribbed reinforcement is used. The use of smooth bars in new construction was largely abandoned after the year 2000.

Poured-in-place concrete is not typically consolidated, so there are large air pockets and a lack of bond with the reinforcement. Further, the lack of sufficient cement in the concrete mix reduces bond strength.

Roof and floor slabs are commonly poured after the wall panels are already constructed and, regrettably, the walls are typically not assembled to the full height of the roof or floor. Rock or masonry debris is added later to fill in the gap between the top of the walls and the bottom of the slab. Subsequently, masonry walls are typically not load-bearing — gravity load is carried only by the slender concrete columns. For future construction of

Figure 13. *Lack of sufficient cement bond, smooth reinforcement, and insufficient detailing (photo: Anna Lang).*

Figure 14.*Typical out-of-plane failure of an infill masonry construction (photo: Anna Lang).*

additional levels, longitudinal reinforcement of the columns commonly extends through the slab thickness, but without additional connection detailing.

Performance of Infill Masonry: When these building types were excited during the earthquake, lateral load transfer primarily occurred at the column-slab connection. The walls are typically not load-bearing, and their strength capacity was reduced by a lack of friction between the blocks. Interaction between wall panels and columns resulted in localized damage, notably in the columns. Lateral capacity of the slender columns was generally insufficient to resist acceleration demands on the structure. P-delta effects ensued, proliferating collapse. Overturning and out-of-plane failures of wall panels were commonplace and caused the majority of complete structural collapses (Figure 14). Even when they didn't contribute to building collapse, these out-of-plane wall failures caused innumerable injuries and deaths.

Performance of Confined Masonry: Confined masonry structures generally sustained little or no damage during the earthquake (Figure 15). A seemingly minor variation in the construction sequence resulted in very different behavior. The confined masonry construction technique is similar to infill masonry, but walls are assembled first and then used to form the columns. If masonry blocks are staggered within the column cavity, a secure connection develops between the masonry wall and the columns. Instead of two structural systems acting independently, confined masonry performs as a singular system whereby lateral load is transferred from the column-slab connection to the walls directly. Though the walls are not load-bearing and therefore do not develop full capacity, they still contribute to the lateral resistance of the overall structure through the mechanical connection with the columns. Though of poor quality, this connection was sufficient to develop one-way bending and arching of the wall, greatly reducing out-of-plane failures during the earthquake.

Hospitals

According to the World Health Organization (WHO) and Pan American Health Organization (PAHO),

Figure 15. *In foreground, new wall under construction shows staggering of blocks within the column cavity; this mechanically locks the masonry wall to the columns, causing them to act as a unit. In background, a typical one-story CM residence (photo: Anna Lang).*

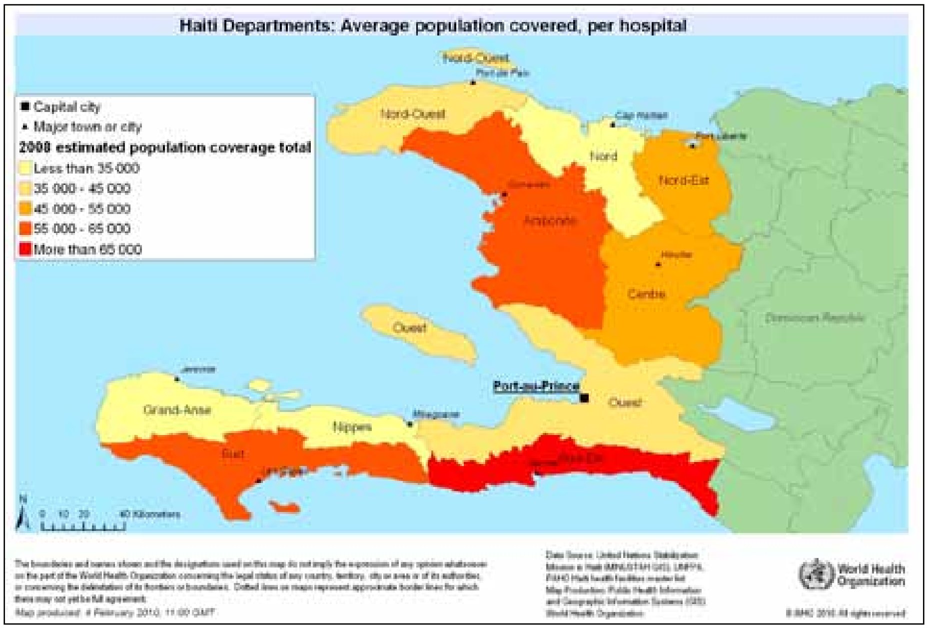

Figure 16. *Average population covered per hospital by Haiti Departments, from web page* ***www.who.int/hac/crises/hti/maps/haiti_population_per_hospital_district_4feb2010.JPG****.*

prior to the earthquake there were 594 primary health care centers; 30 reference communal hospitals (30-60 beds each); six centers for integrated diagnostics; ten department hospitals (with 150 beds each); and three university hospitals (1,500 beds total. See Figure 16). In addition, numerous nongovernmental organizations (NGOs) in Haiti provided health care services, training for health care providers, and advice to Haitian health care administrators. PAHO had a core staff of 52 before the event, and sent an additional 60 people with expertise in disaster management, logistics, epidemiology, communicable disease control, and water and sanitation.

Hospitals suffered damage similar to that sustained by other engineered structures mentioned above. In addition nonstructural damage, many hospitals were unusable due to a lack of power and water. In the aftermath of the earthquake, there were approximately 91 functioning hospitals in Haiti. Of these, 59 were in the metropolitan Port-au-Prince area and included four public hospitals, 34 NGO or private hospitals, and 21 field hospitals. Fifty-six of the 59 hospitals had surgical capacity. In a Special Report dated 16 February 2010, PAHO stated that, "Haiti's Ministry of Health lost more than 200 staff members in the earthquake," many of them in the collapse of the Ministry of Health building.

It was reported that patients were reluctant to enter hospital buildings, due to fear of collapse during aftershocks. Consequently, almost all healthcare services were provided in tents, even seven weeks after the event. All facilities (public and private) were providing services to patients, free-of-charge. At least one private hospital was not paying its staff, due to lack of income. Both public and private hospitals were eager for written recommendations regarding seismic retrofit and upgrade. They intended to use the recommendations, along with data regarding patients served for free, in proposals written to NGOs for future funding.

Water/Wastewater

The public water system suffered only minor damage to most facilities. The day following the earthquake, most of the pipeline breaks were isolated, and it took less than a week to restore service. The Centrale Autonome Metropolitaine d'Eau Potable (CAMEP) reported eight to ten pipeline breaks in their 70 km of pipe. This is a very low break rate, considering the extent of other types of damage. The Port-au-Prince water system lost five employees in the earthquake, and over 50% of their paying customers. As a result, they have inadequate revenue to cover payroll.

The biggest issue following the earthquake was getting potable water to the displaced population, an estimated one million people. People could not stay in their houses, either because they had collapsed or because they feared potential collapse in aftershocks. Many of these people were in temporary tent camps distributed throughout the city. At the time of our visit, foreign emergency re-

Figure 17. *Emergency water tank (photo: Rebekah Green).*

Figure 18. *Sediment and debris (mostly plastic bottles) build-up in drainage channel at highway overcrossing (photo: Anna Lang)*

sponse organizations and NGOs had set up portable treatment equipment at selected locations and were treating water drawn from the public water system. A German group set up a major temporary treatment facility near the airport, and distributed potable water by tank trucks supplied by the local contractors. Starting on January 19, water was being distributed to 500 sites that had plastic tanks and bladders (Figure 17).

In general, the earthquake had limited direct impact on the drainage system. In a limited number of cases, the facilities themselves were damaged by landslides, collapse of embankments, and differential settlement. In some cases, buildings collapsed into drainage channels and blocked them. In other cases, garbage and debris filled the channels (Figure 18). There were reports of septic systems that were not working as a result of differential settlement of connecting pipelines.

The only wastewater treatment plant in the country, located at the National Hospital, was not operable at the time of the earthquake. There was no apparent damage, although it was difficult to tell, as it had not been in operation. A significant issue following the earthquake was dealing with the waste generated by the large displaced population.

Ports

Autorite Portuaire Nationale (APN) operates several facilities in Port-au-Prince. It is the largest and busiest container port in Haiti, handling about 1,200 containers per day, according to APN officials. The port consisted of two separate waterfront facilities designated as the North Wharf and the South Pier. These facilities had seven berths constructed between 1978 and 1980, and included two roll-on/roll-off (Ro-Ro) berths.

The North Wharf was a pile-supported marginal wharf 1,500 feet long and 68 feet wide, supported on 20-inch square pre-stressed concrete piles with five vertical and two batter piles per bent. A 110-foot-by-40-foot Ro-Ro pier was adjacent to the east end of the North Wharf. Both collapsed into the bay during the earthquake, primarily because of liquefaction-induced lateral spreading of the backfill soils (Figure 19). There may also have been corrosion and prior damage that contributed to the damage. Two

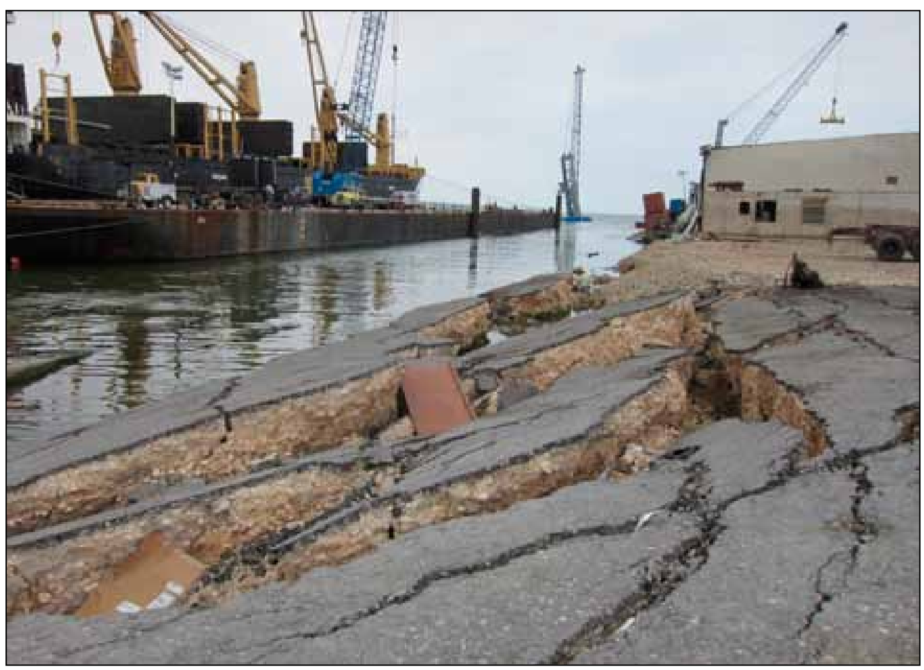

Figure 19. *Liquefaction-induced lateral spreading damage to the APN North Wharf. Note the barge on the left was used to replace the North Wharf for post-earthquake recovery efforts. The mobile container crane is shown in the water at the west end of the submerged wharf (photo: Stu Werner).*

Figure 20 (a) ▲ and (b). ► *Residents living in or next to damaged homes (photos: Rebekah Green).*

large warehouses (each approximately 500 feet by 135 feet) were located in the backland of the wharf and were heavily damaged by the lateral spreading. A gantry container crane and a mobile container crane along the North Wharf were partially submerged due to the collapse of the wharf structure.

The South Pier was a 1,250-foot-long finger pier connected to a small island by two small bridges extending perpendicular to it. It was supported on 45 bents with 20-inch square prestressed concrete piles. Each bent consisted of two vertical piles and four batter piles. It was heavily damaged during the earthquake, with the westernmost 400 feet collapsing, and with 90% of the remaining piles (mostly the batter piles) requiring repair of the pile-deck connection. There was evidence that some of the piles were already damaged before the earthquake due to corrosion or overloading.

The main access road to the port was heavily damaged by lateral spreading due to liquefaction of the foundation soils. Liquefaction induced settlement and lateral spreading was seen in many backland areas, and resulted in differential settlements adjacent to culverts, roads, and utilities.

Recovery efforts to restore port operations began two days after the earthquake, and were carried out around the clock by a U.S. military task force. Initially, three landing beaches were constructed for use in supporting immediate emergency relief efforts. Shortly thereafter, a fourth beach was constructed for transport of additional humanitarian and commercial cargoes.

On February 13, a barge with a shoreline access ramp was anchored offshore just north of the South Pier, and was used as a temporary wharf to increase cargo unloading. On February 27, a second barge and shoreline access ramp was anchored just south of the North Wharf to provide an addition temporary wharf facility.

The U.S. military also began efforts to repair the uncollapsed segment of the South Pier by constructing a reinforced concrete cap to encase the upper few feet of the severely damaged piles. This was expected to be completed in early April. APN is planning to rebuild the North Wharf facilities to bring the port back into full operation.

Social Impacts

The earthquake affected all segments of Haitian society: the government, the commercial sector, churches, civil society, United Nations operations, and international NGOs. Approximately 150,000 Haitians left the country; some needed support from government and civil society services in the countries to which they emigrated. At least 500,000 people abandoned damaged urban areas to find shelter in the more rural departments (jurisdictions) of the country. This influx of people exacerbated already critical demands for food and services.

About 1.3 million people now live in tents and informal shelters in the Port-au-Prince metro area. One count estimates 465 camps for internally displaced persons (IDP), which fill most public and private open spaces. Residents have also pitched tents in their yards or blocked off some streets to allow tents adjacent to their damaged

Figure 21. *Champ de Mars IDP camp near the Presidential Palace (background) in downtown Port-au-Prince (photo: Rob Olshansky).*

homes (Figure 20). Most IDP camps were created spontaneously by individuals, with subsequent water, food, sanitation, and shelter support from NGOs (Figure 21). Many in the Port-au-Prince metro area are still without weather-resistant shelters.

A damage assessment of 140 housing units conducted by an NGO found that 30-40% of the units were safe for re-occupation, but residents did not want to re-occupy their homes, either because of aftershocks or a desire for better access to service distribution points. The resistance to re-occupying structurally sound residences placed additional pressure on the IDP camps. At the same time, the UN and Haitian government indicated that a substantial proportion of the population continues to live in or adjacent to unsafe buildings.

The earthquake exacted heavy casualties on the Haitian national government and UN personnel, which reduced the institutional knowledge needed for the recovery process. In the 13 severely damaged or collapsed government buildings were lost innumerable government documents and an undetermined number of government officials. The UN headquarters building collapsed, killing over 100 employees, including the UN mission chief.

Approximately 50% of schools in Port-au-Prince were damaged (Figure 22); an estimated 400 or more tents are needed for temporary learning spaces.

Much of Haiti's economic activity is located in Port-au-Prince, where the majority of the earthquake's impact was felt, and the city also generates about 85% of the government's revenue. About 30,000 commercial buildings collapsed or were severely damaged by the earthquake. Many businesses have had to move into tents or operate on the streets, adding to or replacing street vending that was common prior to the earthquake. Nearly all of Haiti's garment plants, which account for most of the country's exports, are in Port-au-Prince. One factory employing 4,000 collapsed, while others suffered severe damage. Many jobs have been lost, increasing the pre-earthquake estimate of roughly 70% unemployment.

Organized religion is an essential and central component of Haitian culture and social service provision. The earthquake destroyed many church buildings, including two of Haiti's most important cathedrals: Holy Trinity Church and Cathédrale Notre Dame in central Port-au-Prince. The principal churches in Léogâne and Petit Goâve — St. Rose de Lima and Notre Dame — were also destroyed. A number of key church officials, including the Catholic Archbishop and Vicar General, and volunteers were killed.

Figure 22. *Damaged school in Port-au-Prince (photo: Rebekah Green).*

A significant number of church-affiliated schools, universities, and hospitals were destroyed or damaged, and numerous additional undamaged structures have been evacuated as a precaution. Many cultural institutions operated by these organizations are now closed, including museums, music centers, libraries, historic sites, and community activity centers.

Because churches are among the most trusted institutions in Haiti, many of them became sites of IDP camps. Churches have also expanded their social services and become focal points for the delivery of food, water, medical care, and shelter materials, sometimes through affiliated international aid and development organizations. Because of damaged buildings, services are being held outdoors in difficult circumstances. Importantly, churches continue to support rural Haitians but are hampered by impacts in the Port-au-Prince area and damage to buildings in their rural centers.

Figure 23. *Displaced Iron Market vendors selling goods in downtown Port-au-Prince (photo: Scott Miles).*

Recovery Efforts

Following the earthquake, lead UN and NGO agencies initiated regular "cluster" meetings across a variety of sectors involved in relief and recovery activities. This cluster method — developed by the UN and non-UN humanitarian partners in 2005 as a means of improving coordination, predictability, and accountability in humanitarian response — has helped to designate response standards and better coordinate activities in Haiti regarding such matters as food, shelter, sanitation, and debris removal. For example, the UN Shelter Cluster has set the goal of providing weather-resistant shelter material by May 1, 2010, through coordination of over 50 agencies. The Shelter Cluster has also identified a common transitional housing design and has worked with the Haitian government to identify five sites for transitional housing or IDP camp relocation.

The Haitian government asked the UN to institute a post-disaster needs assessment (PDNA) process to develop a reconstruction plan and estimate associated funding requirements. This process, coordinated by the UN, World Bank, Inter-American Development Bank, and European Commission, had begun at the time of our reconnaissance. The PDNA's proposals for recovery were presented to an international donors conference on March 31 in New York, and a multi-donor trust fund was requested to facilitate recovery. At the same time, the Haitian government is proposing a Haitian Reconstruction Commission, chaired jointly by the Haitian Prime Minister and a foreign government representative, who was confirmed on March 31 to be Bill Clinton.

Numerous foreign governments have been involved in relief and recovery activities. Those we observed included debris clearance and security by the U.S. and Canadian military; damage assessment

Figure 24. *Cash-for-work for clearing debris from neighborhood school in the Nerette neighborhood of Petionville (photo: Rebekah Green).*

by the U.S. Army; management of IDP camps by Canada, Colombia, and Germany; tarps provided by USAID, Canada and France; and cash-for-work programs jointly supported by the UN, USAID and the Government of Haiti.

Many NGOs have been operating in Haiti for years and have been able to apply their local experience to relief and recovery activities. However, while some NGOs are participating in cluster meetings, relative coordination between NGOs and with other stakeholders was difficult to assess.

Despite the widespread damage in the Port-au-Prince metro area, the formal and informal economy is operating, albeit at reduced levels. Street markets survived the quake, and many new markets have appeared in and adjacent to tent camps (FIgure 23). In the Port-au-Prince metro area, it was common to see street vendors selling everything from art, clothing, and baby products to salvaged construction material, tarps, and mobile phone charging services. We observed use of social networks outside of Haiti to obtain tents or tarps and remittances. About a third of Haitians relied on remittances before the earthquake. Subsequently, one microfinance institution reported a doubling of processed remittances.

The formal commercial sector is engaged in business continuity activities. Additionally, some foreign businesses are supporting recovery. For example, a major cell phone service provider was reportedly organizing volunteers and providing resources such as limited free service to all Haitian customers. This commercial enterprise was also paying a former market vendor to organize the repair of Port-au-Prince's historic Iron Market (*Marche de Fe*), with market vendors as volunteers and using company-procured materials. This company and associated NGOs were involved in community development work prior to the earthquake.

Microfinance institutions (MFI) had a prominent role in Haiti prior to the earthquake, with about 20 institutions operating about 250 branches or credit centers. MFIs will play an important role in post-earthquake recovery. The majority of MFI credit centers are located outside of Port-au-Prince and thus can assist with rural recovery issues and migration pressures. MFIs were up and run-

Figure 25. *Limited equipment available for debris removal (photo: Rebekah Green).*

ning within a few days after the earthquake, reportedly faster than commercial banks. One particular MFI is currently offering mobile banking, micro-loan restructuring, micro-loans to new clients, cash-for-work towards shelters, and adult education opportunities.

Significant Recovery Issues

Through interviews and field observation, we identified several enduring recovery issues, four of which are presented below.

Debris removal and management: The Early Recovery Cluster is actively planning and implementing a plan for debris removal, with a current focus on roads and drainage ditch clearance. However, the amount of debris exceeds available resources for removal (Figures 24 and 25). The availability of heavy equipment is extremely limited in Haiti, with only two Haitian government agencies operating it; private sector equipment is very expensive. Foreign militaries provided heavy equipment for early debris removal (Figure 26), but many are now pulling out of Haiti. Although some heavy equipment is being donated locally and internationally, the problem of disposal remains.

Safe shelter: The most immediate shelter issues are fourfold.

- First, a wide range of response actors are calling for continued procurement of weather-resistant shelter materials — tarps and plastic sheeting — for emergency and temporary housing.
- Second, the U.S. Army estimates that about 9,000 people are exposed to high flood hazard; immediate mitigation is required for the roughly 150 IDP camps that are exposed to some flood and/or landslide hazard during the current and next rainy season.
- Third, over 20 IDP camps have been identified as congested, exacerbating safety and security concerns for residents. Some shelter transition has begun to one UN coordinated site.
- Lastly, it is critical to better understand how many houses can be re-occupied and how to support their re-occupation. The importance of assessing longer-term shelter needs and the costs of providing them will increase as recovery continues.

Figure 26. *Canadian forces clearing debris of church in the town square of Léogâne (photo: Rob Olshansky).*

Land tenure: Government officials acknowledged that the earthquake may have destroyed the already incomplete set of land ownership records in their possession. Squatting was common before the earthquake and has expanded considerably since, with tent camps and new homes set up on property owned by other private individuals, organizations, and the government.

Land ownership issues will be complicated by a paucity of mortality records for residents and landlords and difficulty in assessing whether properties have been abandoned. As a result, not only will it be difficult to identify owners and renters in order provide them with reconstruction assistance, but it will also be difficult for the government to acquire and redevelop land parcels. Identification and purchase or lease of sites to support transitional or permanent housing in areas of heavy damage will be challenged by legal and funding constraints, as well as a shortage of suitable sites.

Capacity building: Significant knowledge and skills were lost with the many people killed in the earthquake. Schools, universities, government agencies, and NGOs were damaged physically and socially. Regaining human capacity remains a critical issue.

A wide range of stakeholders are planning various training programs for Haitians. For example, the Haitian government and NGOs are training locals to assess buildings. These efforts will need to expand to other areas, such as safe building construction, marketable job skills, and education.