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# ARTICLE

# Damage to engineered structures during the 12 January 2010, Haiti (Léogâne) earthquake[1]

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**Abstract:** The purpose of this paper is to first provide relevant information about the historic seismicity of the island of Haiti, the tectonic setting and the identification of the unmapped Léogâne fault which is now believed to have been the main cause of the 12 January 2010 Haiti earthquake. The paper then focuses on the state of construction in Haiti, with particular emphasis given to engineered buildings. The lack of a building code and standards for the design of structures, as well as the fact that seismic forces were not considered in the design of most buildings explains the failure of so many engineered structures. Several examples are given and arranged according to building function. Since the earthquake has occurred, interim measures have been implemented to control construction of new buildings. Some recommendations are given to improve construction practice in Haiti for the reconstruction.

*Key words:* Haiti, Caribbean, Léogâne fault, seismicity, seismic design, earthquake, reinforced concrete, structures.

**Résumé :** L'objectif de cet article est en premier lieu de présenter des informations sur la sismicité historique de l'île d'Haïti, les aspects tectoniques et l'identification de la faille de Léogâne, inconnue jusque-là, et que l'on croie être la source principale du tremblement de terre du 12 janvier 2012. L'état des constructions en Haïti est ensuite présenté avec une emphase particulière sur les constructions issues de l'ingénierie. L'absence de code de construction et de normes de construction des structures et le fait que les forces sismiques sont rarement prises en considération lors du dimensionnement de ces structures sont la cause principale de l'effondrement de tant de bâtiments. Plusieurs exemples sont présentés selon les fonctions des bâtiments. Depuis le tremblement de terre, des mesures intérimaires ont été adoptées afin de baliser les nouvelles constructions. Des recommandations sont données pour améliorer la pratique du génie civil en Haïti pour la reconstruction.

*Mots-clés :* Haïti, Caraibe, faille de léogâne, sismicité, dimensionnement parasismique, tremblements de terre, béton armé, structures.

## 1. Introduction

Though earthquake hazards may not have been on the minds of Haitians, the 12 January 2010, $M_w$ 7.0 earthquake came as little surprise to many geologists and geophysicists. Haiti — and the island of Hispaniola as a whole — lies on the boundary between two major tectonic plates, the Caribbean and North American plates, known to slide past each other at a speed of about 20 mm/year. The earthquake caused significant damage to the cities of Port-au-Prince, Pétionville, and almost entirely destroying the town of Léogâne, at the epicentre, as well as the towns of Miragoâne, Petit-Goâve, and Grand-Goâve, and also causing damage to cities further away such as Jacmel. The official death toll given by the Haitian government was over 200 000 people (CBC News 2011), approximately 7% of the population of Port-au-Prince and 2.2% of the population of the country.

No other event of such moderate magnitude caused so many casualties and such extensive damage. This is because the earthquake occurred in a heavily populated region of a very poor country with substandard building practices, in a city that had not in any way prepared for such an eventually. Only limited information on the seismic hazard was available before the event. Efforts were underway to enhance communication and knowledge about earthquakes, but awareness among the public as well as decision and policy-makers remained low. As a result, mitigation and preparedness efforts were minimal: earthquake threat was not ac-

counted for in construction, land-use planning, or emergency procedures, a situation unfortunately common among earthquake-prone developing countries.

This paper first presents a review of seismic activity in the Island of Haiti, along with details on the seismological characteristics of the Léogâne earthquake. A brief description of widely used construction techniques in non-engineered buildings and resulting damage is then presented, but the focus of the paper, however, is the description of damage sustained by engineered structures (in Haiti, designed by architects and engineers) with the goal of identifying their most common deficiencies. Suggestions for avoiding such catastrophic damage in future seismic events are given.

## 2. Seismicity of the Island of Haiti

### 2.1. Tectonic setting

Haiti — in fact, the island of Hispaniola as a whole — is part of the boundary between the Caribbean and North American plates (Figs. 1*a* and 1*d*). Present-day motion between the two plates is dominated by obliquely convergent, left-lateral strike-slip at rates of 19–20 mm/year (DeMets et al. 2000). This motion is taken up by a series of active faults, which have all experienced large historical earthquakes. At the longitude of Hispaniola, the oblique plate motion is partitioned between thrust

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**Fig. 1.** Seismicity of the Island Haiti and the 12 Jan 2010 earthquake. (*a*) Summary of the present-day tectonic setting of Hispaniola. Black lines show major active faults. Red arrows show GPS velocities with respect to the Caribbean plate. Note the combination of shear and contraction across the plate boundary. Yellow star shows the epicentre of the 12 January, $M_w$ 7.0, Haiti earthquake. White stars show the approximate location of historical earthquakes. Red dashed rectangle shows area of panel (*b*). (*b*) Zoom on the epicentral area showing the deformation caused by the earthquake. Background colors show fringes from radar interferogram calculated by F. Amelung (Univ. Miami) using ALOS/PALSAR data from the Japan Aerospace Exploration Agency (JAXA) (descending track, constructed from images acquired 9 March 2009 and 25 January 2010). Each fringe represents 0.2 m of displacement in the ground-to-satellite line of sight direction. Red arrows show coseismic displacements from GPS measurements. Black rectangle shows surface projection of earthquake rupture for a simple one-fault model, black-white dashed line shows its intersection with surface. Open circles show aftershocks as reported by the U.S. Geological Survey. G = Gressier, L = Léogâne, M = Miragoâne, PaP = Port-au-Prince. (*c*) Schematic north–south cross section perpendicular to the earthquake rupture. The thick vertical black line shows the Enriquillo fault (EF), the red line dipping north shows the inferred earthquake rupture (single fault model; from Calais et al. 2010). (*d*) Overall regional plate tectonic setting of the Caribbean and Central America. The Caribbean plate is moving eastward with respect to both the North and South American plates at a speed of about 2 cm/year. GM = Gonâve microplate. Red dashed rectangle shows area of panel (*a*).
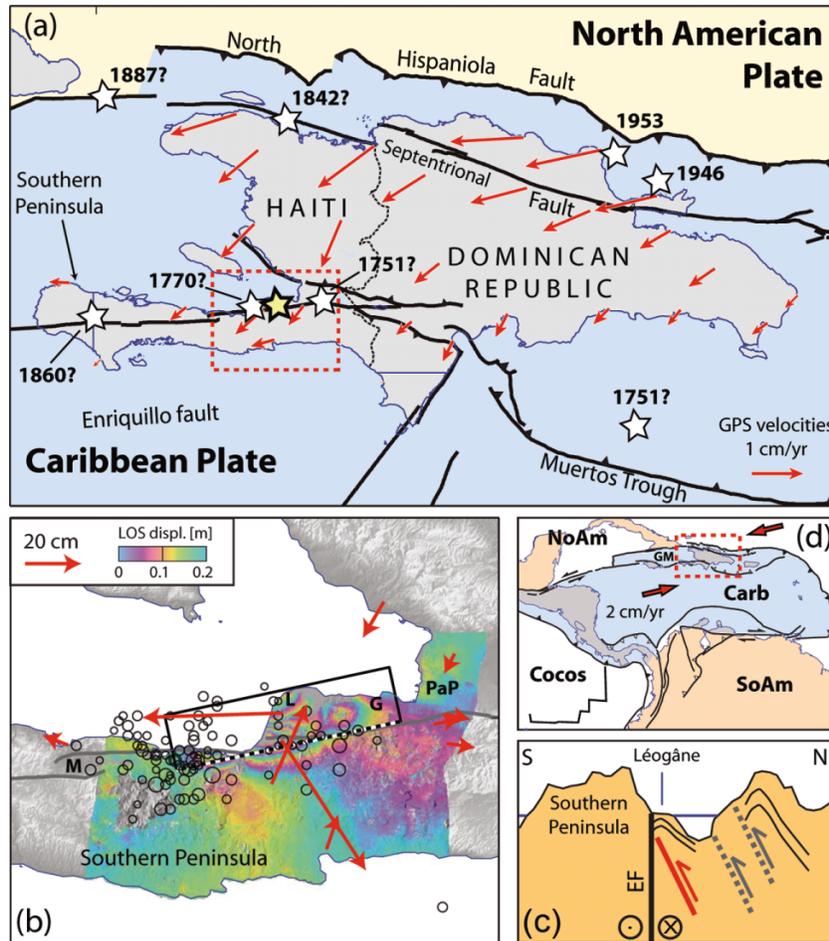


faulting on the North Hispaniola and Muertos trough faults, and left-lateral strike-slip faulting on the Septentrional and Enriquillo-Plantain Garden (EPGF) faults (Calais et al. 2002; Mann et al. 2002). Recent GPS results also indicate significant plate boundary - normal shortening within Hispaniola, mostly affecting the southern part of Haiti (Calais et al. 2010).

Dense GPS measurements recently completed across the island of Hispaniola show a north–south gradient in displacements, reflecting the build-up of elastic strain within the Earth's crust as a result of the overall plate motion. These measurements, when integrated into kinematic block models (Manaker et al. 2008; Calais et al. 2010), indicate that the 19–20 mm/year relative motion between the Caribbean and North American plates is partitioned between 2 to 6 mm/year on the North Hispaniola fault, 6 to 7 mm/year on the Muertos trough, 2 to 12 mm/year on the Septentrional fault zone, and 5 to 6 mm/year on the Enriquillo fault zone.

Additional faults, yet to be identified, are likely to be active throughout Hispaniola — denser geodetic measurements and more geological investigations (on land and offshore) are needed to obtain the complete inventory of active structures necessary for accurate seismic hazard assessment.

Historical archives indicate that the last major earthquakes to strike the Southern Peninsula fault zone in Haiti occurred in the 18th century on 15 September 1751, 21 November 1751, and 3 June 1770 (Scherer 1912), with magnitudes close to — or exceeding — 7 (Bakun et al. 2012). Smaller magnitude earthquakes, which are less well located, occurred in 1701, 1784, 1860, 1864, and 1953 but these were too small to release much of the stress build up in the fault zone. Assuming that the Enriquillo fault zone has been accumulating elastic deformation at a constant rate of 6 mm/year (based on the GPS observations cited above), it had therefore built up, by 2010, a total slip deficit of 1.5 m (0.006 m/year × 250 year).

**Fig. 2.** Column's transverse reinforcement details from (*a*) BAEL 91, (*b*) AFPS 90 (1992), and (*c*) CSA A23.3-04 (2004).
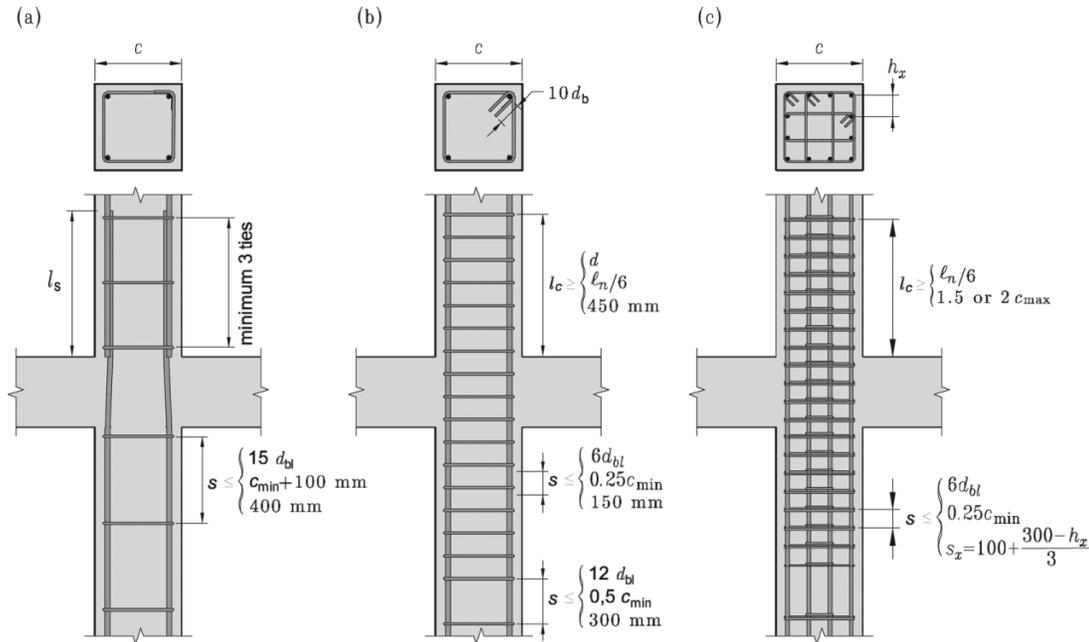


Earthquake scaling laws show that the release of 1.5 m of elastic deformation by sudden fault slip in one single earthquake corresponds to a magnitude of 7.1, very close to that of the 12 January 2010 event.

### 2.2. The 12 January 2010, earthquake

On 12 January 2010, at 21:53:10 UTC (16:53:10 local time), a $M_w$ 7.0 earthquake struck southern Haiti and severely affected its capital city Port-au-Prince as well as neighboring urban centres. It is the largest event to strike southern Hispaniola since the series of 18th century events. The event killed more than 200 000 people, left more than 1.5 million homeless, and caused an estimated US$10 billion in damage, about 100% of the country's gross domestic product. Although there were records of strong ground motion in Haiti at the time of the earthquake, USGS ShakeMap intensity indicate Modified Mercalli Intensity (MMI) VIII to X in Port-au-Prince. Acceleration levels of 0.2*g* to 0.5*g* where derived from liquefaction and lateral spreading studies (Olson et al. 2011) and from damage studies at mechanical and electrical systems (Goodno et al. 2011).

The US Geological Survey (USGS) National Earthquake Information Center (NEIC) determined a moment magnitude of 7.0 and located the epicentre at 13 km depth, ~25 km W–SW of Port-au-Prince (18.44° N, 72.57° W) very close to the Enriquillo fault (http://www.earthquake.usgs.gov/earthquakes/eqinthenews/2010/us2010rja6/). Moment tensor solutions indicated slip on a steeply south-dipping left-lateral strike-slip fault, consistent with the regional trend of the Enriquillo fault, and a small additional component of reverse motion (http://www.globalcmt.org/CMTsearch.html; strike = 251°, dip = 70°, rake = 28°, moment = $4.7 \times 10^{19}$ N·m). Aftershocks followed quickly, with magnitudes up to 5.9 (20 January 2010) and epicentres apparently clustering on the Enriquillo fault (Fig. 1*b*).

This initial information suggested rupture of a segment of the Enriquillo–Plantain Garden fault zone (EPGFZ), a major known regional active fault. The EPGFZ is a nearly-vertical left-lateral strike-slip fault that runs 900 km from the Enriquillo Valley of the Dominican Republic through the centre of the southern Peninsula of Haiti (Mann et al. 1995), accommodating 7 ± 2 mm/year of

**Fig. 3.** Failure of a three-story building with crushing of the second soft/weak strory. (photo: P. Paultre).



relative motion between the Caribbean plate and the Gonâve microplate (Manaker et al. 2008).

### 2.3. The Léogâne fault

In the weeks following the earthquake several research teams were able to gain access to the field in Haiti to study the geological context of the earthquake and further investigate the seismic rupture. Field observations from several independent groups, as well as extensive use of high-resolution satellite imagery found no surface expression of coseismic rupture along the geomorphically prominent trace of the EPGFZ (Prentice et al. 2010). Therefore, despite the fact that the earthquake focus was relatively shallow, the associated rupture remained at depth and did not reach the surface. Surface breaks were all related to secondary effects, such as ground failure, liquefaction, and lateral spreading (Olson et al. 2011). The primary geologic signal directly observable was instead a broad regional uplift well identified through elevated coral reefs along 55 km of coastline from Gressier to Port Royal, with up to 0.64 m of coseismic uplift (Hayes et al. 2010).

**Fig. 4.** Details of a hollow concrete block *hourdis*-type two-way slab system.
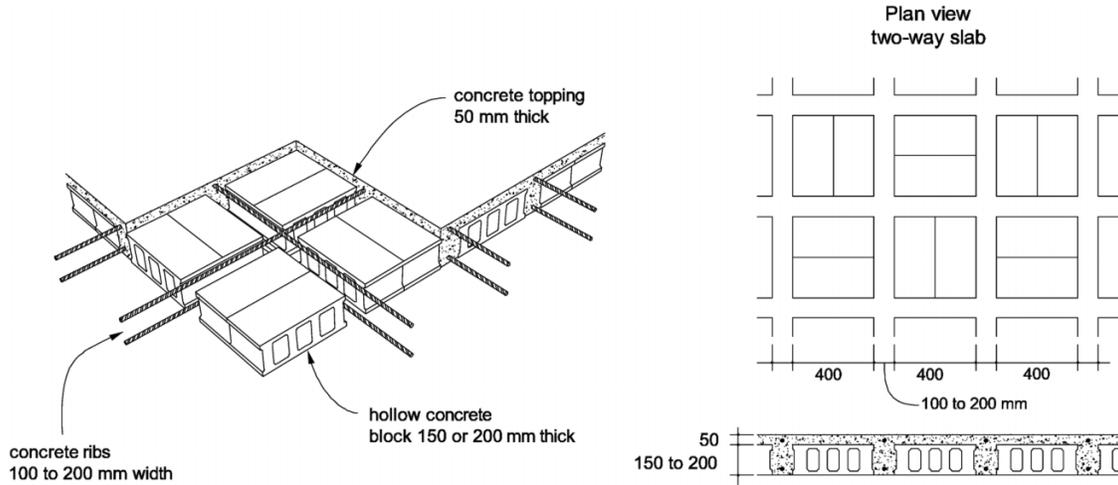


**Fig. 5.** Plan view of the *Palais National*, Port-au-Prince.
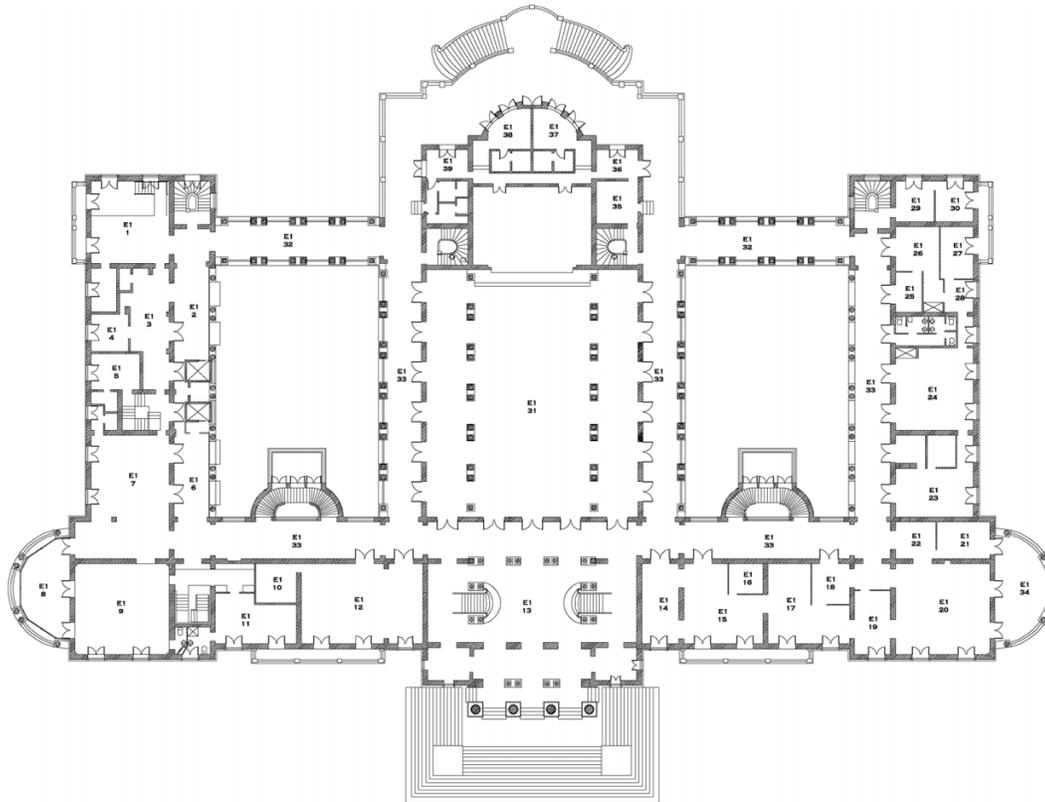


Coseismic ground deformation measurements followed promptly. Field GPS measurements at sites whose position had been determined pre-earthquake showed up to 0.8 m of horizontal displacement in the epicentral area, with measurable coseismic displacements of a few millimetres up to ~150 km from the epicentre. The spatial distribution of coseismic GPS displacements shows a combination of left-lateral strike-slip horizontal motion and north–south contraction. Coseismic ground displacements were also well recorded by synthetic aperture radar interferometry (InSAR), in particular thanks to the Advanced Land Observing Satellite/Phased Array type L-band Synthetic Aperture Radar (ALOS/PALSAR) from the Japanese Space Agency. InSAR data show significant deformation over a ~50 km wide region from Greissier

to Petit Goâve, with up to 0.9 m of ground displacement in a pattern combining horizontal displacement and uplift.

The coastal uplift, seismological, and geodetic data have been inverted by several groups to infer the geometry of the fault responsible for the event and the associated coseismic slip distribution (Calais et al. 2010; Hayes et al. 2010; Mercier de Lépinay et al. 2011; Meng et al. 2012). Although there are differences among results, all show that (1) most of the earthquake was released on a ~30 km long rupture between Petit Goâve and Greissier, extending from 5 to about 20 km depth, and dipping about 60–70 degrees to the north, (2) coseismic slip involved two thirds left-lateral strike-slip motion and one third reverse dip-slip, with two slip patches, an eastern one showing predominately thrust motion

**Fig. 6.** The *Palais National,* top photo before the earthquake (photo J. Raedle, Getty Images) and, bottom photo after the earthquake (photo, P. Paultre).





**Fig. 7.** Failure of lightly reinforced columns in the second story of the *Palais National* (note the absence of transverse reinforcement).
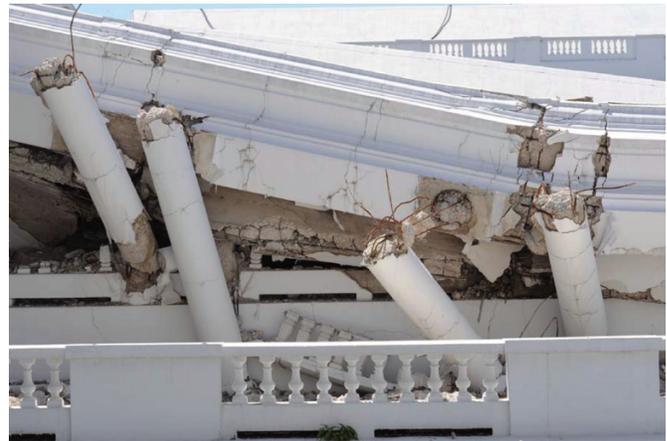


**Fig. 8.** Advanced corrosion of reinforcement in RC walls in the *Palais National.*



and a western one showing predominately strike-slip. The coseismic rupture does not coincide with the Enriquillo fault, contrary to original assumption right after the event, but involves an unknown fault, now called the "Léogâne fault" (Calais et al. 2010).

At the time of these studies, aftershocks of the 12 January 2010, Haiti earthquake had not been precisely relocated so that slip inversions had to rely on the imprecise location of the main shock hypocentre, its source focal mechanism, or geodetic data to infer fault geometries. Recent studies have determined precise aftershocks locations and focal mechanisms (Nettles and Hjörleifsdóttir 2010; Mercier de Lépinay et al. 2011). Douilly et al. (2013) provide the most comprehensive results to date, as they used all available seismic data (on land and offshore). Their aftershock distribution clearly delineates the Léogâne fault (Fig. 1c), with a strike and dip similar to the one inferred from geodetic data alone by Calais et al. (2010).

They also identify a separate aftershock cluster to the west of the Léogâne rupture and offshore, coincident with the mapped Trois Baies reverse fault (Momplaisir 1986), where most of the largest aftershocks occurred. Cross sections through that cluster show that hypocentres align on a plane dipping ~20 degrees to the southwest, consistent with the geometry of the Trois Baies reverse fault, while focal mechanisms show pure reverse motion on NE–SW trending planes, also consistent with the geological characteristics of that fault. Symithe et al. (2013) show that aftershocks on the Trois Baies faults are triggered by the static stress changes imparted by coseismic slip on the Léogâne rupture.

## 3. State of construction in Haiti

It is estimated that approximately 90% of houses and buildings in Haiti are built without the intervention of an architect or engineer. A large portion of these buildings are found in slums built on the mountainside terrain in Port-au-Prince and Pétionville, often on unstable soil foundations.

Rural housing, called *ajoupas*, consists of wattle and daub construction, where a lattice of woven wooden strips is usually covered with wet clay, along with thatch roofs (layered vegetation) or in some cases, tin roofs. They constitute 18% of the housing types and are mostly found in rural areas (92.5%) and in in urban areas (7.5%). A good portion of houses in slums, particularly in flat areas (like Cité Soleil, in Port-au-Prince) are built with recycled wood and tin roofs. As these two categories of construction are very light and mostly one-story high, they did not suffer much damage from the earthquake or cause any loss-of-life. In urban areas, one-storey building types are the most commonly found constituting 72.5% of all constructions. (IHSI 2012). In the Port-au-Prince region, most buildings are one or two-storeys high, made of moment resisting reinforced concrete frames with infill hollow concrete blocks. They are used as residence for single-family and small businesses and they represent approximately 60% of the housing units. Lastly, multi-story buildings and other building types, such as steel industrial buildings, represent respectively 4.8% and 5.1% of the buildings. A small portion of houses found in Port-au-Prince and Pétionville are of the gingerbread style. These one or two storey wood frame houses have high steep tin roofs with intricate and colored wood ornaments. They were built during a flourishing period of Haïti and are located in neighborhoods forming the gingerbread district of Port-au-Prince. They are an original form of architecture developed in Haiti during the 1900–1920 period and were included in 2009, shortly before the earthquake, in the

**Fig. 9.** The Port-au-Prince Cathedral with RC wall details.



World Monuments Watch to "raise international awareness about this unique heritage" (Langenbach et al. 2010).

Gingerbread houses have tall ceilings and doors and large windows to help ventilation in the hot climate and control humidity. They generally have porches around the entire perimeter to provide shade and protect against rain. The common structural features are cross braced timber framing systems filled with brick or clay mortar with rubble stones on the periphery walls. The first storeys were often entirely made of brick walls with steel tension ties at the top of the walls anchored with steel plates at the ends. This type of architecture disappeared around 1925 when the city's mayor, in an effort to prevent the widespread fire damage that had destroyed Port-au-Prince in the past, ordered that all new buildings should be constructed with masonry, reinforced concrete, or iron. This decision saved the city of Port-au-Prince from total destruction from fire due the earthquake, as there is no firefighting capacity in the city. It is, however, also the cause of the significant number of casualties from collapsed poorly constructed concrete and masonry buildings. Although most of the gingerbread houses are severely damaged by termite attacks, they performed relatively well during the earthquake.

## 4. Non-engineered construction

A large portion of the non-engineered buildings found in urban areas consists of confined masonry walls with concrete slabs, often with two or three storeys. This type of construction sustained significant damage during the earthquake and was one of the factors for the high number of casualties. The main reasons for such poor behavior are:

- Confined masonry principles are not properly applied. The wall–column interfaces are flat, whereas they should be irregular hence developing an interaction between the walls and columns;
- Heavy hollow block slabs called *dalles hourdis* are the standard practice (see section below), with cantilever extensions beyond the lower floor walls for sun and rain protection;
- Heavy upper floors, with walls extending to the end of the hollow block slabs that support them delimiting larger floor area than the floor below;
- Poorly detailed reinforcement in columns and beams, with no reinforcement present in the joints. The columns usually have small transverse cross sections (200 mm × 200 mm) and the beams

are typically stronger than the columns, the opposite of the strong-column weak-beam principle used in in modern seismic designs.
- Poor concrete quality, made on site with a mix proportion consisting of 4 buckets of gravel, 2 buckets of sand, 1 bucket of cement, and water at will to obtain certain workability. The sand is usually of very poor quality. Placement of the concrete is poor without vibration, leading to segregation and honeycombing.
- Hollow concrete blocks of very poor quality, often produced by small shops with no quality control, often using recycled materials.

## 5. Engineered structures

There is still no regulating body for the civil engineering and architectural professions in Haiti. Often, the architect also acts as the contractor and structural engineer. To date, there is neither a Haitian building code, nor any standard body regulating construction materials as well as building practices.

In practice, buildings have been built to withstand the vertical loads but not the lateral forces or loads due to earthquakes or wind. Engineers educated in Haiti traditionally studied the French BAEL (Reinforced Concrete Limit State Design) code (BAEL 91) or the ACI code (ACI 1995), concentrating on gravity load design, without consideration for earthquake loads. Structural dynamics and earthquake engineering courses were not part of the civil engineering curriculum. Many engineers and architects, however, obtained their degrees abroad (France, USA, Mexico, Canada, Dominican Republic, etc.); the end result being that each designer used the building codes that they were most familiar with. Also, as continuing education was not available in the country, these codes were often outdated. The reinforced concrete design code most often used is by far the BAEL 91. There are no considerations for seismic design in this code and no definition of any kind of seismic force resisting system is given.

Most engineered buildings are of the rigid frame type with unreinforced infill walls constructed with hollow concrete blocks and one or two-way concrete *hourdis* slabs. Surprisingly, non-engineered constructions and houses used confined masonry construction methods, whereas engineered buildings did not. Figure 2a shows a detail of the transverse reinforcement requirements in BAEL 91. It must be understood that before the adoption

**Fig. 10.** Failure of the Christ Roi church.



**Fig. 11.** Failure of the Canado-Haitien College. The bottom photo shows a *hourdis* slab failure.





**Fig. 12.** Toppling of the hollow block concrete partition walls in the Canado-Haitien College.



**Fig. 13.** Soft/weak failure of the École Hôtelière in Port-au-Prince (bottom picture shows a crushed column with little longitudinal reinforcement and no transverse reinforcement).





of the Eurocode in France, two codes were in use: a code for general reinforced concrete construction (BAEL 91) and a code for seismic design of buildings in seismically active zones (AFPS 90). Seismic hooks and seismic hoops were defined in the AFPS code (Fig. 2b). This is why, for instance, 90° hooks were standard practice in Haiti, because only the general construction code was used. In addition, because of incremental construction, longitudinal

bars in columns were continued just above the joints with only three ties required over the lap splice length (Fig. 2a). This detailing is not allowed in the CSA A23.3 for seismic design (Fig. 2c). Generally, the beams are stronger and stiffer than the columns that have very small (200 to 300 mm²) cross sections. Figure 3 shows a three story building with a soft storey failure. Note the small dimensions of the corner columns (350 to 400 mm for the first story, and 200 mm for the upper storeys).

Two-way slabs, of the *hourdis* type, are used in 90% of floor construction in Haiti. They are built as shown in Fig. 4. In this system, widely used in South America, the Caribbean and Europe, hollow concrete blocks (150 or 200 mm thick) are used as fillers between 100 and 200 mm wide concrete ribs and are covered by a concrete topping (about 50 mm thick). Reinforcement bars are placed along the ribs in one direction or in both directions for

**Fig. 14.** Failure of the Villa Manrese convent. Left photo shows crushing of the first soft/weak story. Right photo shows relocation of plastic hinges in beams with haunches and damage in a weak column.



two-way slab systems. This type of construction is not appropriate for high seismicity regions, and should be replaced by lighter solid one-way or two-way slabs. During ground shaking, the concrete blocks in *hourdis* slabs tend to detach or break apart and constitute a hazard for the occupants.

# 6. Damage to engineered structures

### 6.1. Government buildings

The *Palais National,* the presidential residence, is the most well-known landmark building in Port-Au-Prince. Built between 1913 and 1921, it was designed by Georges Baussan, one of the three architects that developed the gingerbread style houses in Port-Au-Prince. This building was designed by the French Hennebique firm in the early period of the development of reinforced concrete as a construction material. The reinforcement materials are surprisingly varied in form, due to the fact that the construction took place in part during the First World War and that the materials had to be purchased sometimes on the black market (Corvington et al. 2003). It is a moment-resisting frame system with infill unreinforced brick masonry, as well as infill rubble walls. Some infill walls are covered with what appear to be reinforced concrete walls that might have been added later and explained why the building did not collapse entirely. The National Palace is an irregular building in plan with a main part on the front with three aisles perpendicular to the façade (Fig. 5). The building is also irregular in elevation, with heavy mass concentration at the level of the three domes that are located on the front part of the building (Fig. 6). It is the unrestricted motion of the central dome accompanied by the failure of its supporting structure that precipitated the failure of the structures supporting the two lateral smaller domes. The columns are very lightly reinforced with no confining reinforcement as can be seen from Fig. 7. A fact discovered after the failure of the structure is the advanced corrosion of the reinforcement in the oceanfront climate of Port-au-Prince. This corrosion might have been caused also by the use of sea sands (Fig. 8). In the early 1900s, reinforcing steel was obtained outside the country and the bars were usually smooth, with standard 180-degree hooks for anchorage. With the creation of a local steel mill in the early 70s, 300-MPa deformed bars became available.

### 6.2. Churches

Most of the major churches were built in the early 20th century. The most notable one is the Port-au-Prince Cathedral for which construction started in 1883 and was completed in 1912 by the Belgian firm of Perraud & Dumas. The cathedral is an unusual structure for the time, with reinforced concrete walls patented by this firm (Fig. 9). It completely collapsed during the earthquake. Another notable failure is the Christ Roi church, completed in 1908, which is a combination of reinforced concrete and masonry brick walls (Fig. 10).

### 6.2. Schools

It is estimated that 55% of all schools were destroyed or rendered irrecoverable. More than 38000 students, 1350 professors and 150 public servants in the education sector lost their lives in the West department that includes Port-au-Prince. This should never happen and measures should be taken immediately to correct the problem. Figure 11 shows the failure (crushing) of the first story of the Canado-Haïtien College (high-school). The failure of the first floor was precipitated by the soft/weak moment resisting frame with long spans. This configuration was necessary to accommodate a laboratory and an auditorium, while the top floors had stronger moment frames with infill hollow concrete block partition walls to separate classrooms. The building next door, which can be seen in the background in Fig. 11 and is also part of the college complex, suffered repairable damage. This other building had the same type of moment frames and partition walls on all floors, without a first soft/weak story.

Figure 12 shows classrooms in the second building, where the toppling of all the unreinforced partition hollow concrete block walls can be noticed along the corridor crushing the student desks. This type of failure has been observed in a number of schools in the Port-au-Prince area and clearly demonstrates that ducking under the desks as taught to the students in case of an earthquake is not always the safest action to take. Figure 13 shows another soft/weak story failure in the École Hôtelière in Port-au-Prince. The bottom picture clearly shows the insufficient longitudinal reinforcement and the absence of transverse reinforcement in the first story columns. Figure 14 shows the failure of the Villa Manrèse convent, also with crushing of the soft/weak first story

**Fig. 15.** Failure of the front reinforced concrete porch of the Mathon gingerbread-style residence.



and relocation of plastic hinges in the beams with haunches. This soft/weak story problem was found to be one of the main causes of failures during this earthquake.

### 6.3. Gingerbread houses

Most gingerbread houses performed relatively well in spite of pre-earthquake damage due to years of neglect, termites attacks and questionable additions (that change the stiffness and regularity) to the original structures. Figure 15 shows a family house with damage that was caused by the collapse of the heavy reinforced concrete porch that dates to the construction of the house and can be seen in on the left in Fig. 15. This type of timber framing (*colombage*) is very efficient in resisting earthquake forces, as can be seen from this example.

### 6.3. Hospitals

Figure 16 is a striking illustration of the behavior of two recent buildings that were completed at about the same time, shortly before the earthquake, at the end of 2009. The collapsed building in the foreground is the Turgeau hospital. It is a private hospital which was apparently design without consideration for seismic forces. The structure was realized partly with flat slabs supported by columns and infill walls, which is known to be inefficient for earthquake resistance. Just across the street from the hospital, is the Digicel building which survived the earthquake with almost no damage visible from the exterior. Figure 17 shows the Canapé Vert hospital which suffered little damage and was operational after the earthquake. It was located in the heavily-damaged Canapé Vert area, but performed quite well due to a better detailed strong moment-resisting frame.

### 6.4. Commercial buildings and hotels

The Digicel building (background of Fig. 16) is a 12 storey building with one underground level. This building, designed according to the ASCE-07 and ACI codes, has a clearly defined seismic force resisting system consisting of three L-shaped walls at the corners and an elevator core-wall at a distance from the other corner. The Digicel building complex suffered significant damage in two unconnected buildings with no gap between them: a three storey service-parking garage moment resisting frame building and a one storey moment resisting frame parking garage. Most of the damage in these buildings were due to: (*i*) pounding between

**Fig. 16.** Complete collapse of the recently built Turgeau Hospital in the foreground, with the 12-storey frame-wall Digicel building in the background.



**Fig. 17.** The lightly-damaged Canapé Vert hospital.

**Fig. 18.** Shear failure of columns in the parking garage of the Digicel building (note the 90-degrees hooks in right photo).



them and the main 12 storey frame-wall building; (*ii*) to deficient reinforcement detailing (for example, hoops with 90° hooks, see Fig. 18); and (*iii*) to the presence of short columns created by partial height hollow concrete block walls. The most important point however was the significant, although repairable, damage that the beams and columns of the 12 storey frame-wall structure suffered in the top five storeys (Fig. 19 and Fig. 20). Damage to the columns can be attributed to the poor quality of the concrete. Concrete segregation was determined as the problem from the initial visual inspection at the time. Subsequent investigation by the structural engineers responsible for the building repairs determined that only the cover concrete had experienced spalling. The core column concrete was intact and proved very resistant to chipping by mechanical chisel when it was scrabbled one inch behind the steel reinforcement as part of the structural repairs. However, significant damage to the beams connected to the walls is due the rotation demands imposed by the walls. The causes of this damage are discussed by Boulanger et al. (2013a, 2013b) and serve as a reminder that the design of the gravity load system in a well-designed structure with a clearly defined seismic force resisting system is an important task required by the NBCC, but often neglected.

One of the most reported collapse resulting from the earthquake was the Montana Hotel. This luxury hotel was located on a hilltop in the Bourdon area of Port-Au-Prince. Figure 21 shows a portion of the collapsed hotel. It was apparent that the effective cross-section of the columns were much too small (partly covered by thick cement grout), with a very low amount of longitudinal reinforcement, and almost no transverse reinforcement. In addition, this hotel was located in a region of the city where the topography seems to have played a role. Concentration of damaged buildings in a band along the foothill ridge where the hotel is located pointed to possible topographic amplification. Hough et al (2010) and Assimaki and Jeong (2011) reported significant amplification in this zone from the analysis of aftershock recordings. The extensive damage observed at the Montana is therefore probably a combination of poor engineering as well as local seismic motion amplification.

**Fig. 19.** Damaged beam in the Digicel building at wall connection.



## 7. Seismic hazard and design of structures

Shortly after the earthquake, on 9 February 2010 a presidential decree published in the national journal *Le Nouvelliste* (MTPTC 2010) authorized the use of four codes or standards in Haiti: NBCC-05 (NBCC 2005); ACI 318-95 (1995), ASCE7-05 (ASCE 2005), and Eurocode 8 (CEN 2005). A year later, on 15 February 2011, the Ministry of public works, transport and communication published an interim regulation (MTPTC 2011) for construction of new buildings, which included seismic hazard maps. The top and bottom parts of Fig. 22 show the uniform hazard spectral (UHS) acceleration values for structures with periods of 0.2 s and 1.0 s, respectively, for 5% damping. These maps were derived from seismic hazard values developed by USGS (Frankel et al. 2011). As can be observed, most of the territory of Haiti is exposed to high seismic hazard, in particular along the three main fault systems along the south peninsula, in the centre and in the northern part with acceleration values in the order of or slightly higher than values expected in Victoria, Canada. Figure 23 shows the UHS corresponding to ASCE-7 05 and NBCC-10 (NBCC 2010) for Port-au-Prince. Also plotted is the response spectrum of the 23 February 2010 M 4.7 aftershock that was recorded in Port-au-Prince by a seismograph installed by Geological Survey of Canada.

**Fig. 20.** Damage to the bottom of the columns in the upper five floors of the Digicel building.



**Fig. 21.** View of the shopping mall on top of a parking structure of the Montana Hotel. Top photo before the earthquake (source: Internet) and, bottom photo, damage after the earthquake.



The difference between the two UHSs can be explained in part by the facts that mean values of accelerations are used by USGS, while in Canada the GSC used median values to derive the hazards. The NBCC-05 UHS is approximately 10% higher, and a correction factor of 0.9 on the spectral values therefore seems appropriate when using the NBCC-05 in Haiti using the USGS data, as is allowed by government regulation.

## 8. Recommendations

The 12 January 2010 Haiti earthquake was a tragic reminder of the inexorable seismic threat to which the country and the region are exposed. This first part of the risk equation is non-negotiable, as it is driven by the current relative motion between the Caribbean and North American plates. However, much can be done to more accurately assess the seismic threat level. First, through a systematic identification and quantification of potential earthquake sources on land and offshore, to develop better national seismic hazard maps (Frankel et al. 2011). This work requires, among other things, consolidating the Haiti seismic monitoring network. Second, through a detailed seismic zoning of major urban centres and future development areas to quantify site effects (Hough et al. 2010; Cox et al. 2011), provide relevant information to engineers for structural design, and enable better informed urban planning decisions.

The remaining part of the risk equation, the exposure and vulnerability of populations and economic activity, is the responsibility of governments, international agencies and, increasingly, local communities and individuals. Experience and research have given us a broad range of solutions to reduce these factors. These involve proper land-use planning, appropriate use of construction codes, and raising public and institutional awareness through education and research.

Seismic hazards maps are now available for the design of new buildings (see Figs. 22 and 23). Unfortunately, few engineers in Haiti are very familiar with seismic design principles and dynamics of

structures. A number of workshops and seminars have been organised, but what is really required is a new generation of civil engineers with the right curriculum, that includes courses on structural dynamics and earthquake engineering. The following is a list of recommendation that should be implemented as soon as possible:

- Modernization of the university curriculum is required. At the moment, it is heavily oriented towards pure sciences (mathematics, physics, and chemistry) and less on the development of engineering skills. In the current curriculum, the students are trained with too many different codes, leading to confusion while not covering the subject matter deeply. Modern methods of structural analysis are not taught in the different universities and the finite element method, which is sometimes taught, is presented more like a mathematical subject rather than an engineering tool.
- There is a need for an independent regulatory body, similar to the provincial order of engineers in Canada, to control the practice of engineering and architecture in the country. There is also a need for a regulatory board controlling the curriculum of the different private and state universities. At the moment the definition of the curriculum is left to the professors.
- There is a need to provide funding by the government to hire full-time professors in the state university and to develop an embryonic research facility.
- The control of construction materials should be more stringent. The reinforcing steel should meet requirements on yield

**Fig. 22.** Contours of uniform hazard horizontal spectral acceleration at (*a*) 0.2 s and (*b*) 1.0 s (probability of exceedance of 2% in 50 years) for class B as per ASCE 7 and 5% of critical damping.
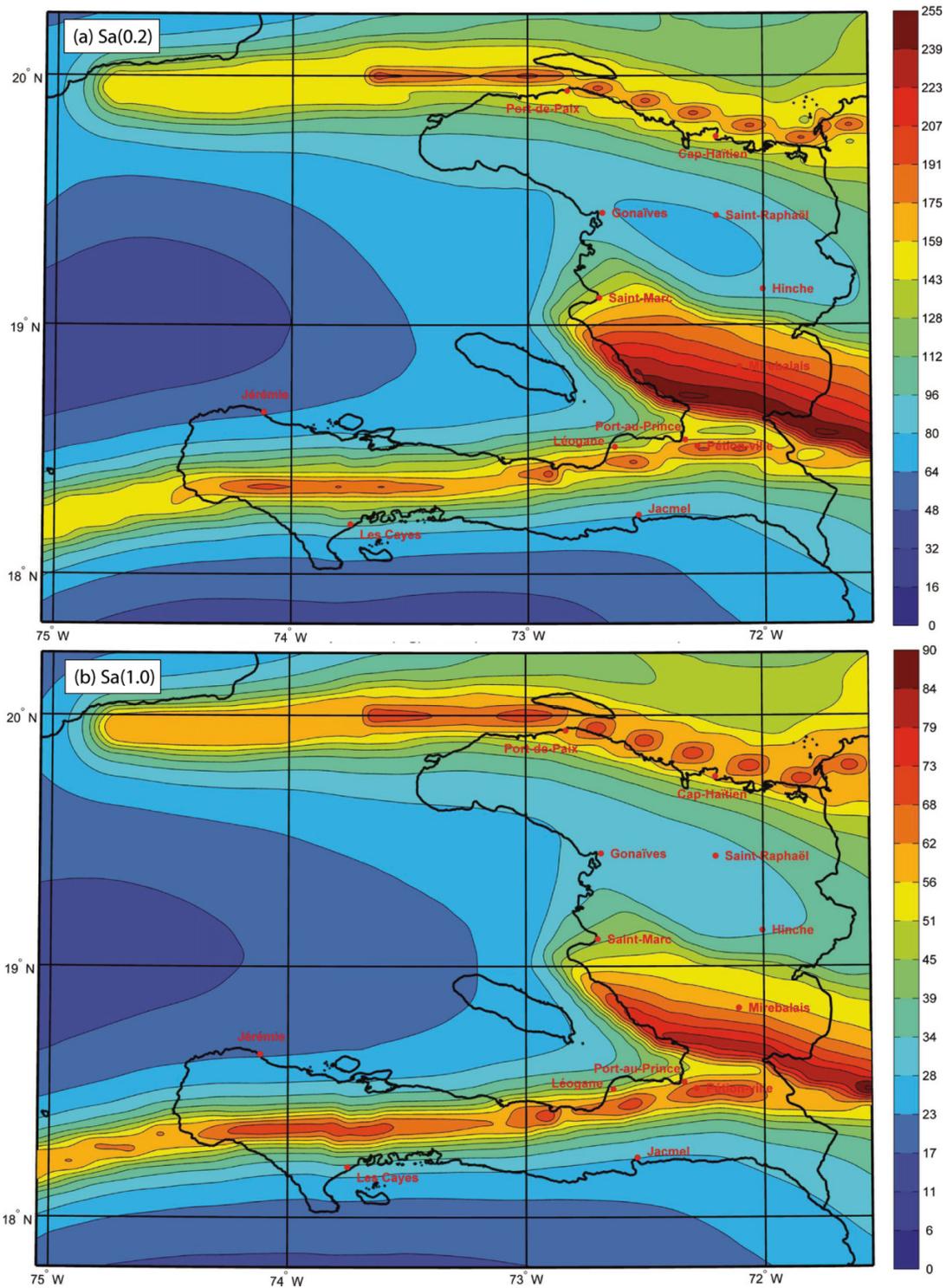
and ultimate strength as well as ductility and technical specifications should be made available by the producer and the distributor to the buyer. Fabrication of concrete blocks should be controlled and supervised by the state, by imposing guidelines and quality control tests.

• Although all new construction needs to get approval from the municipalities, these do not have sufficient manpower to carry out this task, which is relegated to the Ministry of public works,

transport and communication, which also lacks the manpower. There is therefore a need to effectively implement approval of new construction by the different municipalities by trained inspectors.

• The number of casualties in the education sector during the earthquake is unacceptable in any society. Seismic upgrading of all schools is required. Construction of new schools should meet seismic design requirements. In addition, they should be

**Fig. 23.** UHS design values for Port-au-Prince with response spectrum from the aftershock of 23 February 2010.
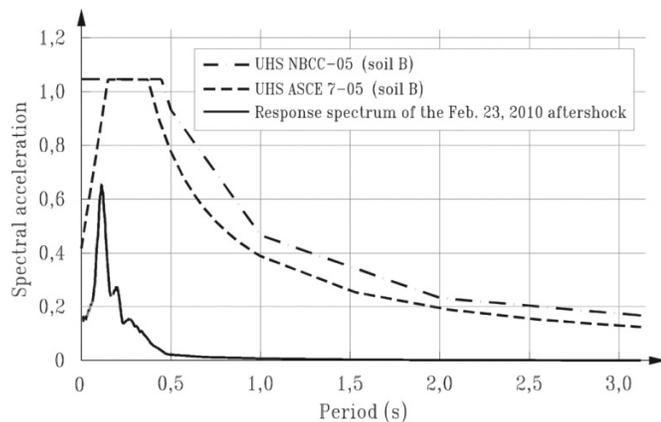


considered as primary buildings to provide shelter in case of disaster.

- Hospitals should be evaluated and rehabilitated. New hospitals, particularly private ones should be designed by engineers that can demonstrate that the design for seismic forces is adequate.
- Cellular telephony towers and buildings should be considered as post-disaster equipment and facilities and should remain operational after an earthquake. Hence all transmission tower and facilities should meet stringent seismic design requirements.

## 9. Conclusions

This paper presented a review of Haitian seismicity as well as the damaged sustained by engineered buildings. Recommendations were made to avoid such a catastrophic level of loss of life and structural damage in the future. Two years after the earthquake, the rubble removal process, the most important step towards reconstruction, is well underway, but still remains a primary objective. A few engineered buildings (hotels, schools and government buildings) are currently under construction, in some cases with international building codes adapted for local seismicity. As the reconstruction efforts go on in Haiti, the key objective for future safety remains education and a strong and sustainable science and engineering foundation in Haiti, so that Haitians themselves can take a lead role in designing solutions adapted to their economy and society. Visitors that come to Port-au-Prince can see thousands of children walking to school each day, and this leaves a strong image of hope for the country.

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