Seismic risk assessment for Northern Haiti based on geotechnical investigation and building typologies

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ABSTRACT

Northern Haiti is vulnerable to damage from potential earthquakes that can result in catastrophes nearing or exceeding the 2010 event. The Septentrional-Oriente Fault Zone passing close to the major cities including Cap Haitien, Ft. Liberte, and Port de Paix, was a significant contributor to historical seismicity within the region, including the 1842 M8.1 Cap Haitien Earthquake that led to approximately 5,000 deaths. Given the history of this fault and its tectonic setting, there is significant potential for future strong ground motion and widespread death and destruction. To address the seismic vulnerability of Northern Haiti, a comprehensive risk assessment of the building population was conducted. The key components of the program included: a) performing geotechnical investigation to develop microzonation maps for the major cities; b) performing surveys of areas to collect exposure data for the sites; c) extrapolation of collected data to cover the entire effected areas; and d) performing probabilistic risk analysis to estimate fatalities, financial cost, and the number of required temporary housing for the area. The results of the study can then be used by the government and international agencies to allocate resources to focus and maximize the outcome of earthquake risk mitigation program.

INTRODUCTION

Northern Haiti is a vulnerable area that has close proximity to a major fault and has experienced very large earthquakes in the past. The geophysical study investigated the seismic risk for the cities of Cap-Haitien, Ft. Liberté, Ouanaminthe, and Port de Paix. The results of the study can then in-turn be used by federal and local government and other stakeholders to allocate sufficient resources to undertake seismic retrofitting of the most critical and vulnerable structures, and to develop contingency plans (such as temporary housing and emergency centers) in preparation for future earthquakes. The key components of the study comprised: a) Seismic hazard: identify relevant earthquake scenarios and develop maps of the study area that depict earthquake-related ground shaking corresponding to these scenarios; b) Building typologies: Site visits to the four cities in were undertaken to collect data regarding the construction type and number of occupants; c) Building vulnerability. Using available data, fragility parameters were developed for common building types. The available literature data were adjusted to account for local conditions in Northern Haiti.; and d) Loss estimation; the seismic demand, exposure, and fragility data were synthesized to produce estimates of the human and physical losses that would occur in each of the project cities for the scenario earthquake.

SEISMIC HAZARD FOR NORTHERN HAITI

Overview. The Caribbean island of Hispaniola includes the countries of Haiti on the west and the Dominican Republic on the east. The island sits on the boundary of the Caribbean and North American tectonic plates (Figure 1). The Caribbean Plate subducts beneath the North American plate east of Hispaniola, where the plate boundary is marked by a subduction zone and a chain of volcanic islands. The northern border of the Caribbean Plate is delineated by two left-lateral transform fault zones coincident with the northern and southern borders of Haiti. These fault zones are designated as the Septentrional-Oriente and Enriquilllo-Plantain Garden fault zones. Displacement rates along these two faults are approximately 12 and 8 mm per year, respectively. The M7.0 January 2010 Port-au-Prince Earthquake occurred as a result of movement along Enriquillo-Plantain Garden Fault Zone. This earthquake occurred had an epicenter near the city of Leogane and a focal depth of approximately 13 km. As a result of this earthquake, approximately 300,000 people were killed. Although this was a large earthquake, it had minimal impact on northern Haiti due to the relatively soft nature of the rocks and high attenuation rate.

The Septentrional-Oriente Fault Zone passes very close to the cities of Cap-Haitien, Fort Liberte, Port-de-Paix, and Ouanaminthe. This fault is considered to be a significant contributor to historical seismicity within the region, including the 1842 M8.1 Cap Haitien Earthquake. The earthquake occurred on May 7 and led to approximately 5,000 deaths. There is significant potential for future strong ground motion and tsunami with an estimated recurrence interval of 1,000 years for M8.5 earthquakes.

Probabilistic seismic hazard assessment has been performed by the United States Geological Survey (Frankel et al., 2010; Frankel et al., 2011) to predict levels of bedrock shaking corresponding to a 2,475 year return period; see Figure 2 for 0.2-s bedrock spectral acceleration (S_s). To predict ground surface shaking, bedrock shaking levels are combined with knowledge of the near-surface soil stiffness to perform a site seismic response analysis.

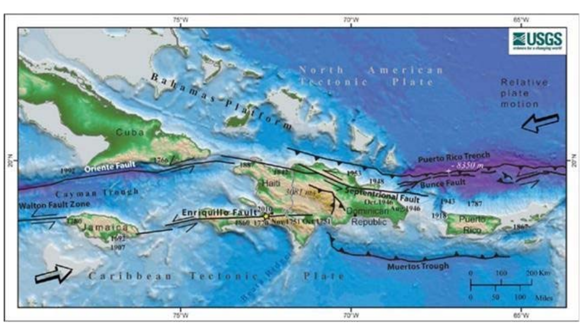

Figure 1. Tectonic setting of Haiti (USGS, 2015)

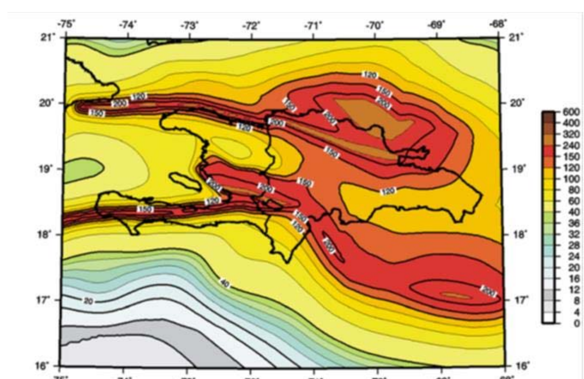

Figure 2. Bedrock S_s acceleration, (Frankel et al., 2010; Frankel et

al., 2011)

Microzonation study. A field study was conducted in December 2014 to measure shear wave velocity throughout the four cities described in this study (Kalinski et al., 2015). Shear wave velocity was determined using the Spectral-Analysis-of-Surface-Waves (SASW) method. The SASW method is a simple method to develop soundings of shear wave velocity versus depth. The SASW method involves the use of an impulsive seismic energy source and a pair of receivers spaced an equal distance apart in a straight line. When the ground is impacted, surface waves are generated. As they pass the two receivers, the energy recorded at each receiver is analyzed for spectral content. Differences in phase between the two receivers are calculated at each frequency, and this information is used to calculate variations in surface wave velocity with wavelength in the form of a dispersion curve. Since shorter-wavelength velocities only depend on shallow material and longer-wavelength velocities depend upon deeper material, variations in velocity with wavelength are indicative of variations in shear wave velocity (vs) with depth.

For this study, sites were identified on aerial photos. Testing was completed at 61 sites, with more sites in the larger city of Cap Haitien (Figure 3). Locations were selected due to the need for large, open spaces for testing and selected to represent a cross-section of different soil types and soil stiffness. Coordinate information was obtained by GPS. The data were synthesized to obtain the site contour plots for the localities. For Cap Haitien (Figure 4), site classes from B to D were measured. Site Class B was found in higher elevations northwest of the city, while site class C was found at lower elevations and to the east of town. Site Class D was found in the lowest lying area along the river. The shape of the site class map for Cap Haitien is consistent with results reported by Bertil et al. (2014) but the shear wave velocities reported herein are slightly higher than those reported by Bertil et al.

Figure 3. Map of SASW Test Locations Cap-Haitien

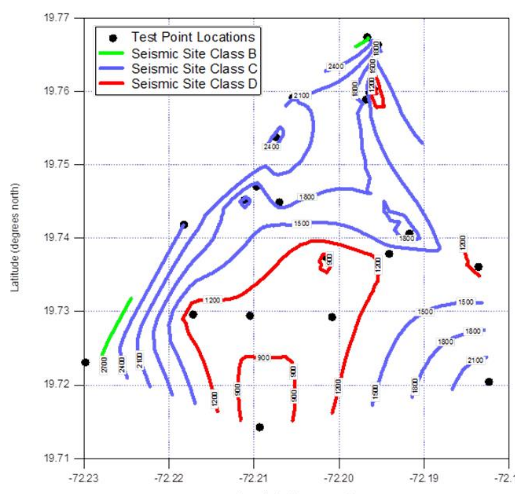

Figure 4. Map of V_{30} for Cap Haitien

Seismic design parameters. Seismic site class is determined in terms of shear wave velocity, and is used to calculate ground surface design levels of ground shaking. Seismic site class is a relative description of the stiffness of the soil or rock column within 30 m of the ground surface. ASCE 7 (ASCE, 2010) as referenced by the IBC states seismic site class ranges from A to F. The resulting values for v_s' determined from analysis of the field surface wave data were contoured for each of the cities. Next, using the shear wave velocity and site class, a site class was assigned to each of the tested sites. To calculate ground shaking, the bedrock MCE spectral values are multiplied by acceleration and velocity coefficients F_a and F_v to account for the stiffness of the soil profile, and then reduced by a factor of 2/3 to convert MCE to design ground surface spectral values S_{Ds} and S_{D1}. Short- and long-period MCE spectral acceleration were determined based on GPS location using the USGS database. Using this information, ground surface design spectral acceleration values were determined. The distinct data were synthesized to obtain the site contour plots for the localities. These contours were then superimposed on the map of the site to present the short period and 1-sec seismic design parameters for the sites; see Figure 5 and Figure 6 for Cape Haitian.

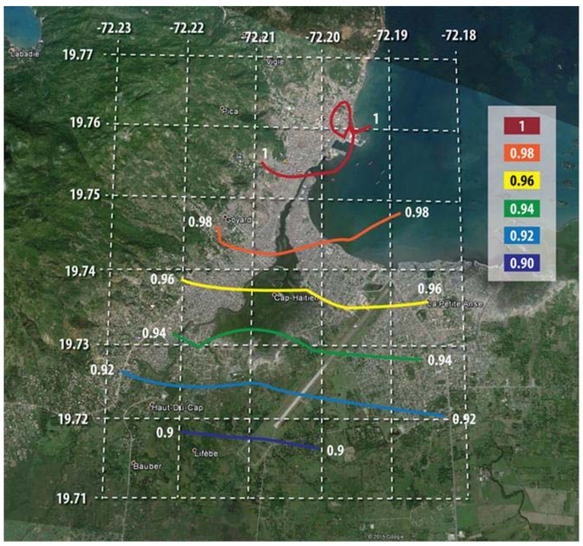

Figure 5. Map of S_{DS} for Cap Haitien.

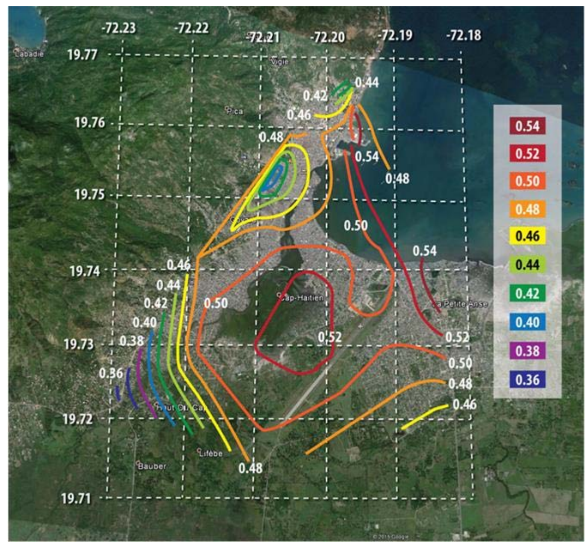

Figure 6. Map of S_{D1} for Cap Haitien.

SURVEY OF BUILDINGS

Overview. A data collection template was developed for use by field surveyors. For each city data were collected in blocks from representative zones which can be extrapolated to building city wide. As an initial step, a spreadsheet was developed for use by the field personnel in their data collection. The spreadsheet allowed for the consistency and uniformity of collected data in various locals and among different field surveyors. Data were collected and recorded electronically to minimize human error. The data collection template followed the procedure suggested by FEMA P154 (FEMA, 2014) and was designed to allow for rapid screening of buildings while allowing for collection of sufficient data that can be used in risk assessment studies. Data collection included the following: a) Buildings coordinate (latitude and longitude) system, b) City and zone, c) Building footprint, number of stories, Occupancy type, lateral system, and construction material, and d) Number of occupants.

Data collection process. For large cities, it is impractical to collect data for each individual building. Instead, data are collected for a small percentage of buildings to represent the city as a whole. For each city, the developed and mostly populated area was divided into a number of zones. The number of zones for each city represented the diversity in construction, topology, and occupancy For Cap Haitien (see Figure 7) , 28 zones were selected because this is a large metropolis, densely populated and with a diverse group of building construction. For other cities, eight zones were chosen per city.

Given the large size of zones, it was impractical to collect data for each structure within a zone. Instead, each zone was divided into a number of blocks. The blocks were selected such that the pool of the buildings in each block was representative of the zone as a whole. Using Google map tools, the approximate area of each zone was estimated. Furthermore, using satellite imaginary and local-based knowledge, the number of each of the blocks in a given zone was estimated. As an independent check, for each city, the total population was estimated by summing the product of population in a given block and the number of that type of block estimated in that zone and summed over all zones. This aggregate value was within a few percent of the listed population of that city.

Analyses of surveyed data. A total of 1,458 buildings were surveyed. Of the surveyed buildings approximately 66% were one-story units and 27% were two-story buildings. Over 96% of buildings can be classified as residential/small business. In Haiti, this is a common occupancy where a portion of a residential dwelling is designated for running a small business. Moment frames (concrete) and bearing wall (concrete or masonry) are the primary lateral load resisting system for these buildings. Masonry and concrete comprise approximately 2/3 and 1/3 of building material for these structures; see Figure 8. The masonry unis are unreinforced and in many cases are constructed with stone and rubbles. As such this type of construction is inferior to typical unreinforced brick or block construction. To reflect this feature, a higher risk factor will be assigned to these buildings

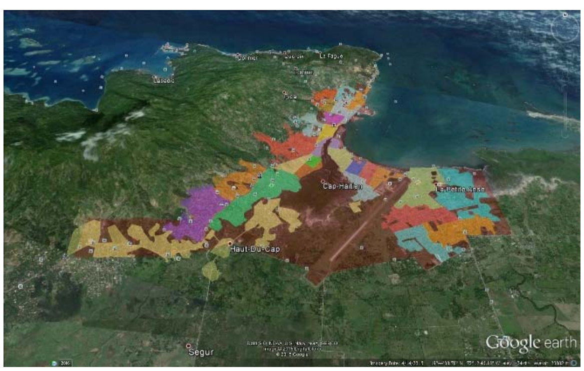

Figure 7. Division of city into zones, Cap Haitien

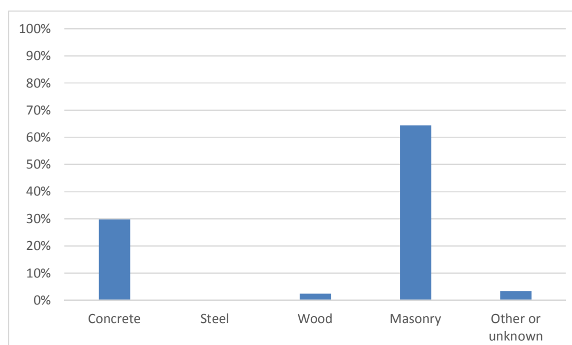

Figure 8. Primary construction material

SEISMIC VULNERABILITY FOR BUILDING TOPOLOGIES

Overview. In the aftermath of the 2010 Haiti Earthquake, an extensive damage assessment program was undertaken to catalog the observed damage Miyamoto et al. (2011). In total, approximately 400,000 building sites were investigated. The collected data included building GPS coordinates, occupancy, and number of stories, assigned evaluation tag, and an estimate of the level of damage. As part of the project, these data were evaluated. Approximately 93% of buildings in the database comprise residential occupancy which is similar to Northern Haiti

Although no strong motion recordings of the 2010 Earthquake are available, Hough et al. (2012) used the aftershock data and measurement of rigid body motions to develop estimates of the peak ground accelerations for the 2010 event. A PGA of order 0.2 to 0.4 g was estimated.

Fragility functions for Concrete buildings. FEMA HAZUS (FEMA, 2003) lists the fragility parameters based on building type, number of stories, building code vintage, and damage state. The relevant FEMA HAZUS building types for the current study are C3, denoting concrete frame buildings with unreinforced infill. FEMA HAZUS defines four code vintages: high-, moderate-, low-, and pre-code. The high vintage corresponds to the newer buildings constructed in regions of high seismicity. By contrast, the pre-code class denotes locations for which no seismic action was (is) expected and thus no seismic design requirements were used. The pre-code class is the most suitable for the large majority of surveyed buildings and structures in Northern Haiti.

For C3 buildings, FEMA HAZUS defines the following structural damage states: a) Slight (hairline cracks on most infill walls, cracks at frame-infill interfaces); b) Moderate (larger cracks of infill falls; some walls exhibit crushing of brick around beam-column connections; Diagonal shear cracks concrete beams or columns); c) Extensive (Large cracks fall of infill walls, some infill walls may bulge out-of-plane; few walls may fall partially or fully; few concrete columns or beams may fail in shear, Structure may exhibit permanent lateral deformation); and d) Complete (Structure has collapsed or is in imminent danger of collapse). FEMA HAZUS fragility medians are based on PGA values for C3 building type. The default values need to be adjusted to account for the spectral shape, soil type and epicentral distance. In addition, FEMA HAZUS fragility parameters for pre-code are equal to 80% of values of low-code. To account for the quality of construction in Haiti, an additional 0.8 reduction factor is applied here to distinguish Haiti and U.S. construction practices. The default and adjusted median values are listed in Table 1.

Table 1. PGA-based median of fragility values, pre-code construction

	Slight	Moderate	Extensive	Complete
Default values	0.10	0.14	0.21	0.35
Adjusted values	0.18	0.26	0.39	0.65

There are several independent sources of uncertainty in analysis described in this report. These include uncertainty in seismic hazard data, in damage assessment data collection, in building data, and in damage state Assuming that the uncertainties are independently distributed, the total uncertainty can then be computed from the square root of sum of squares of all components. A total uncertainty of 0.75 was computed for this study. For PGA-based analysis, FEMA HAZUS, lists a value of 0.64g as the suncertainty for all dmaage states of C3 buildings. Given the design and construction practices in Haiti, the higher value of uncertainty is reasonable.

Using the median values and variations developed earlier, the fragility (vulnerability) functions for the concrete buildings are computed and plotted in Figure 9. Also shown in the figure are the percentage of yellow + red tagged and red-tagged buildings at PGA of 0.3 g, a value corresponding to approximate average of PGA estimates for the surveyed sites. There is good correlation between observed damage and assumed fragility functions. The red-tagged (extensive or greater damage) is correlated to the expected number of fatalities. The combination of yellow- and red-tagged (moderate or greater damage) is key variable in determining the number of displaced people that would be in need of temporary housing.

Fragility functions for unreinforced masonry buildings. For unreinforced walls, there are a wide range of fragility data available. The fragility parameters vary significantly depending on the wall construction. For example, while in the U.S., the fragility data are based on brick or concrete blocks constructed with good mortar, the walls in Haiti typically use stones, rubbles, and poor mortar and thus have lower quality and higher vulnerability. It is expected that non-standard URM bearing walls will experience damage factors that are much larger than nonductile RCMF construction. Therefore, the expected performance of Haiti unreinforced bearing wall buildings is significantly worse than the non-ductile (pre-code) concrete buildings that were discussed earlier.

The FEMA HAZUS mean fragility values are similar to RCMF buildings with infill. However, it is noted that FEMA HAZUS is based on U.S. construction and assumes a ductility value of 5 in developing capacity curve. The default values of means for fragility functions are modified to represent the Haiti construction more closely.

As part of a comprehensive effort in assessing the seismic hazard with particular emphasis on European construction, Lagomarsino and Cattari (2014) developed a complete taxonomy for URM construction. Of interest is the following taxonomy which is similar to Haiti construction: *BW-IP\URM-HS-RU-LM\R\R\x\LQD-WoT-WoRB\F-T\P-T\L\PC: Bearing wall In-plane, URM-hard stone rubble wall with lime mortar, regular in plan and elevation, no tie rods no ring beams, flexible wood floor, pitched wood roof, low rise building, pre code construction.*

Rota et al. (2010) developed a new analytical approach for masonry structures using nonlinear analysis. For their prototype building, they considered a three-story masonry building in Southern Italy with reinforced concrete floors and tie beams. This is superior construction to what is anticipated in Haiti. The authors computed the fragility parameters from incremental dynamic analysis

Karantoni et al (2012) developed fragility parameters for stone masonry buildings using nonlinear analysis. They studies buildings with various wall height to length (h/l) ratio, flooring (flexible or rigid), and masonry compressive strength.

In this report, the average of mean values is used for each damage state. The uncertainty is set at 0.75 consistent with earlier discussion of concrete buildings; see Table 2. Figure 10 presents the proposed fragility relations for unreinforced masonry buildings for this study.

Table 2. Summary PGA based fragility values

Source	DS1		DS2		DS3		DS4	
	σ	μ	σ	μ	σ	μ	σ	μ
FEMA HAZUS modified	0.07	0.64	0.08	0.64	0.14	0.64	0.22	0.64
Lagomarsino and Cattari	0.04	0.65	0.07	0.61	0.13	0.53	0.16	0.47
Rota database	0.13	0.36	0.19	0.27	0.26	0.22	0.31	0.18
Karantoni database	0.04	0.65	0.08	0.72	0.12	0.78	0.19	0.70
Fragility parameters	0.07	0.75	0.10	0.75	0.16	0.75	0.22	0.75

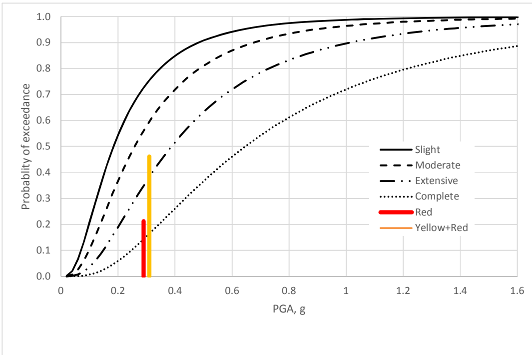

Figure 9. RC Fragility functions

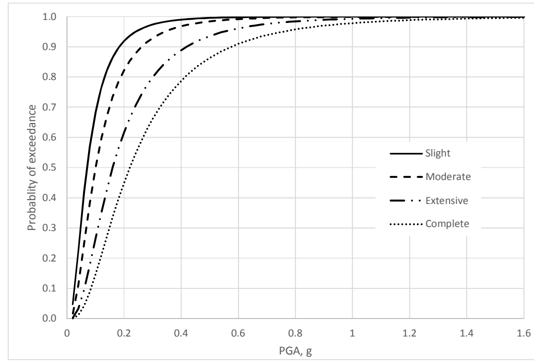

Figure 10. URM Fragility functions

RISK ASSESSMENT METHODOLOGY

The seismic loss estimation due to a scenario-based (design level) earthquake intensity in Northern Haiti was probabilistically evaluated in terms of the building damage and casualties. Figure 11 summarizes the analysis procedure.

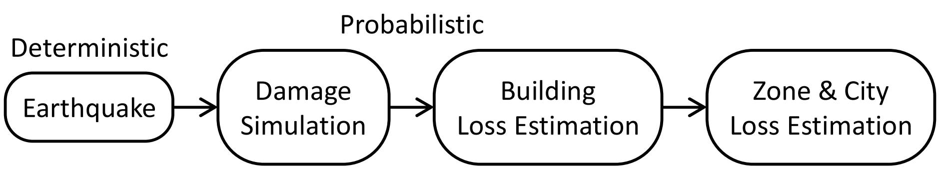

Figure 11. Assessment sequence

For both the building loss rate and the occupant casualty rate corresponding to a given building damage state, the FEMA HAZUS consequence functions were adjusted to account for the regional modification factor to translate the FEMA HAZUS values to that of Haiti. The modification factors were based on the work by the USGS researches (USGS, 2009; USGS, 2011). The structural damage rates are distributed between 40% and 90% at areas in Port-au-Prince in the aftermath of the 2010 Earthquake (DesRoches et al., 2011). The destroyed structure rate can be averagely presumed as 50% in the areas suffered larger than MMI 8. The expected earthquake intensity at Northern Haiti is comparable with the 2010 Earthquake. Thus the physical loss rate at Extensive damage state was set as 0.55 for concrete and 0.75 for URM buildings. The FEMA HAZUS rates for other damage states were adjusted in proportion for other damage states. The number of confirmed fatalities announced by the Government of Haiti is 316,000 (DesRoches et al., 2011) in the affected area. Other estimates place casualties as low as in the 70,000s. In this report, a casualty rate of approximately 0.15 in the most affected area and an average casualty rate of approximately 10% are anticipated. A similar casualty rate can be anticipated in Northern Haiti. In this report, the casualty rate of URM at Complete damage state is set at 28% and the rates at other damage states are proportionally adjusted. Table 3 presents the adjusted factors used in this project.

Table 3. Physical damage and causality rates for Northern Haiti

Parameter	**Building type**	**Damage state**			
		Slight	**Moderate**	**Extensive**	**Complete**
Physical damage	Concrete	0.022	0.11	0.55	1.00

	Masonry	0.03	0.15	0.75	1.00
Causality	Concrete	0.00	0.00	0.000222	0.23
	Masonry	0.00	0.000222	0.000443	0.28

The building physical damage and casualties were estimated based on the consequence functions using the damaged building area and the occupants as independent variables. The seismic losses mentioned above are evaluated for all surveyed (1,458) buildings. For each building, the results comprises a single set of results. Next, Monte Carlo simulation (MCS) was applied and the results for individual simulations were analyzed. Of particular interest is determining the minimum number of MCS that needs to be carried out to obtain stable results. This number is defined at the MSC value at which the expected value (mean) of building damage area and casualties converge. As shown in Figure 12, when the number of MCS equals 5,000, convergence is obtained. Thus, in this report, the MCS value of 5,000 was used. Figure 13 presents the MCS outcomes for a sample building selected for the database of surveyed buildings. For this particular building, approximately 24%, 16%, 22%, 22%, and 16% outcomes fall into the no damage, slight, moderate, extensive, and complete damage, respectively. The distributions would vary from building to building depending on the site seismicity and building construction.

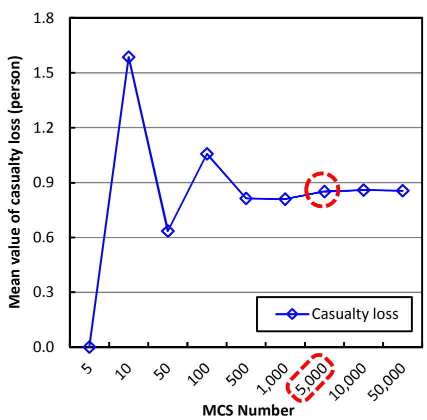

Figure 12. Selection of the required minimum number of MCS

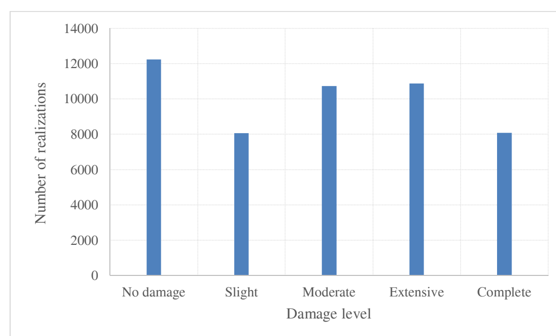

Figure 13. Distribution of outcomes for a selected building

RISK ASSESSMENT RESULTS

Overview. For each building, the estimated loss (structural damage and casualty) was computed based on the expected value (mean) from 5,000 Monte Carlo simulations. The analysis results were expressed in relative values (percentages). These figures were then multiplied by the building footprint to obtain damaged area and by the number of occupants to obtain the casualties. Then, these were aggregated within to each zone and summed over zones to obtain citywide values. In addition, the different damage states were categorized into three categories corresponding to the expected level of post-earthquake damage (green, yellow, and red- tagged). The graphical distribution of findings from probabilistic risk analyses are presented in Figure 14 and Figure 15 for physical damage and causalities, respectively, for Cap Haitien. In the figures, the color distribution indicates the intensity of expected structural damage or casualties. The data from these maps can be used to identify the zones that are most susceptible to earthquake losses and thus can be prioritized for allocation of resources for seismic retrofit and earthquake preparedness.

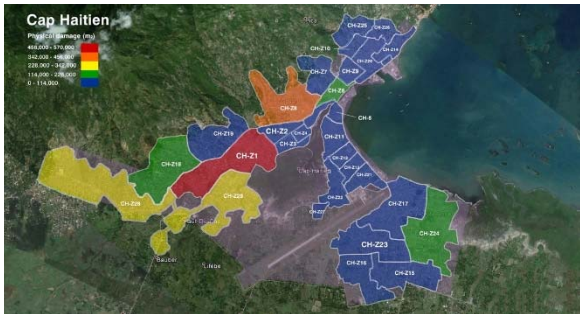

Figure 14. Distribution of physical damage, Cap Haitien

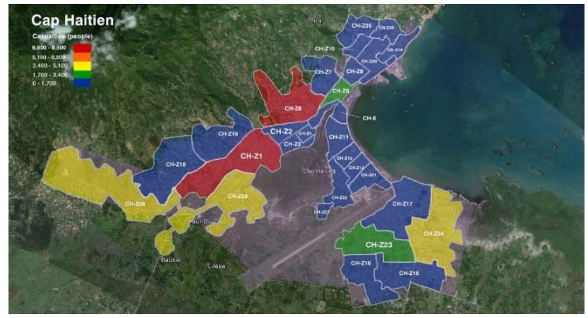

Figure 15. Distribution of casualities, Cap Haitien

Aggregated findings. Table 4 and Table 5 list the rate and total values for the quantities of interest. As shown, it is expected that over 50% of built area would sustain noticeable damage. Furthermore, more than 52,000 buildings are expected to be assigned either a yellow or red tag. This is approximately 55% of building stock. Temporary housing (shelter) would be required for internally displaced people (IDP) as the result of the building physical damage after an earthquake. It is anticipated, that immediately after the earthquake. The number of IDP will be close to 350,000. This translates to the need for temporary housing for the IDP. The data from the 2010 Earthquake can be used as a guideline to assess the number of shelters. In 2010, there were approximately 1,500,000 IDP, comprised of nearly 300,000 households (HH). Approximately 1,500 camps were required at the time for temporary housing. However, the number of IDPs decrease with time. The key for depopulating the temporary camps is a rapid assessment program that would allow the safe buildings to be identified and for people to return home. This would then need to be followed by rapid retrofit/reconstruction of damaged buildings that can be salvaged based on the damage survey. It is anticipated that these four cities would experience approximately 75,000 causalities.

Table 4. Aggregated ratios

City	Damage ratio	Building tag			IDP rate	Casualty rate
		G	Y	R		
Fort Liberte	61%	38%	29%	33%	52%	12%
Ouanaminthe	47%	50%	26%	24%	41%	8%
Port-au-Paix	64%	35%	30%	35%	55%	13%
Cap Haitien	50%	47%	28%	25%	44%	9%
Sum	54%	45%	28%	27%	46%	10%

Table 5. Aggregated quantifies

City	Damage area, m2	Building tag			IDP	Casualties
		G	Y	R		

Fort Liberte	190,700	1,900	1,400	1,600	14,000	3,300
Ouanaminthe	517,800	8,000	4,100	3,700	46,000	9,400
Port-au-Paix	1,415,100	5,200	4,500	5,300	67,000	16,000
Cap Haitien	2,505,000	27,100	16,600	15,100	221,000	45,800
Sum	4,628,600	42,200	26,700	25,700	348,000	74,700

CONCLUSIONS

Probabilistic risk analysis was carried out for four major cities in Northern Haiti. These cities have a population of approximately 760,000 people in an area of 20 km^2 and with nearly 95,000 buildings. Analysis showed the following for a design level earthquake:

- Level of overall (from minor to complete collapse) physical damage is approximately 50% of building area
- Approximately 28% and 27% of the buildings will be yellow and red tagged.
- More than 25,000 buildings will be collapsed or severely damaged. These buildings would likely need to be then demolished. More than 26,000 buildings would have major damage. These units would then need to be repaired.
- The casualty rate for the area is close to 10% resulting in loss of life of about 75,000 people.
- Using probabilistic distributions, the standard deviation and confidence levels were computed. It was seen that there was 68% probability that the causalities would be between approximately 48,000 and 101,000. Furthermore, there was 84% confidence that the casualties would not exceed 101,000.
- The initial number of IDP is anticipated to be close to 350,000. Temporary housing for the IDP should be planned for.

These values are much larger than what can be expected for buildings that meet the modern code seismic requirements. Therefore, it is recommended that as a follow-up to this study, a Haiti-based seismic retrofit program, similar to the one underway in Port-Au-Prince, be investigated to address the most vulnerable sites identified in this report.

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