A first approach to earthquake damage estimation in Haiti. Advices to minimize the seismic risk.

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Abstract

This study is in the frame of the cooperative line that several Spanish Universities and other foreign partners started with the Haitian government in 2010. According to our studies (Benito et al. 2012) and recent scientific literature, the earthquake hazard in Haiti remains high (Calais et al. 2010). In view of this, we wonder whether the country is currently ready to face another earthquake. In this sense, we estimated several damage scenarios in Port-au-Prince and Cap-Haitien associated to realistic possible major earthquakes. Our findings show that almost 50% of the building stock of both cities would result uninhabitable due to structural damage. Around 80% of the buildings in both cities have reinforced concrete structure with concrete block infill; however, the presence of masonry buildings becomes significant (between 25% and 45% of the reinforced concrete buildings) in rural areas and informal settlements on the outskirts, where the estimated damage is higher. The influence of the soil effect on the damage spatial distribution is evident in both cities. We have found that the percentage of uninhabitable buildings in soft soil areas may be double the percentage obtained in nearby districts located in hard soil. These results reveal that a new seismic catastrophe of similar or even greater consequences than the 2010 Haiti earthquake might happen if the earthquake resilience is not improved in the country. Nowadays, the design of prevention actions and mitigation policies is the best instrument the society has to face seismic risk. In this sense, the results of this research might contribute to define measures oriented to earthquake risk reduction in Haiti, which should be a real priority for national and international institutions.

Keywords:

Seismic risk, earthquake damage, vulnerability, resilience, Haiti.

1. Introduction.

The historical seismicity of Haiti, as well as the current fault activity, has been widely studied in the past decade (e.g. Bakun et al. 2012; McCann 2006; Prentice et al. 2003; Manaker et al. 2008). According to the literature, the country has suffered significant, damaging earthquakes in the past two centuries associated to both the Enriquillo fault system (EFS, to the south) and the Septentrional fault (to the north). Manaker et al. (2008) even concluded that the Enriquillo fault had enough strain accumulated to cause a Mw 7.2 earthquake at that moment. Thus, the scientific community and local institutions were meant to know the seismic hazard and the possibility of occurrence of significant events. However, the population was not ready for the 2010 Haiti earthquake. As a consequence, the impact was devastating. Numbers on physical damage and human losses have been given in several sources (e.g. United Nations Stabilization Mission in Haiti - MINUSTAH), labelling the Haiti earthquake as one the major catastrophes in history.

After the earthquake, according to the United Nations Office of the Special Envoy for Haiti, public international cooperation agencies pledged $13.34 billion in the New York Donors Conference co-hosted by the USA and the United Nations in March 2010 (additionally, private funding raised $3.06 billion). The budget was meant to be used in the recovery process from 2010 to 2020 to rebuild cities and to relief the devastation caused by the 2010 earthquake. By the end of 2012, $6.43 billion (more than half of the budget) had already been disbursed. Many scientific institutions and researchers, as well as NGOs and other development cooperation actors, have worked day by day in the country since the earthquake occurrence. They have executed projects with funding from foreign governments oriented to rebuild the damaged cities and to improve the quality of life of the people. Five years have passed; however, no significant progress has been materialized yet, such as the implementation of a seismic code specifically for Haiti or the elaboration of an earthquake risk emergency plan. The most efficient way to prevent disasters like that in Haiti is through creating built environment and societies that are resilient to earthquake risk, which is the ultimate goal of seismic risk studies. Furthermore, apart from external consulting projects, the capacitation of local technicians to face the seismic phenomenon should be a priority for the international community.

As an example, we can mention the case of the Spanish cooperation in seismology and earthquake engineering. On the one hand, the Spanish Seismic Network (SSN) trained local engineers in seismic network design and implementation. Moreover, the SSN contributed to the installation of seismic stations with the aim of implementing a local satellite seismic network, which, at the moment of writing this paper, was not operative as it was designed. On the other hand, the Technical University of Madrid (UPM) and other partners designed and executed several cooperative projects from 2010 to 2014 in collaboration with a local counterpart from the Ministry of the Environment of Haiti. As a result of such projects, local engineers have been trained and valuable results on earthquake hazard and risk have been provided and made public (e.g. Pierristal et al. 2013; Dorfeuille 2013; Benito et al. 2012). However, all these results are unused by national and international institutions with competence in the subject, slowing down the implementation of mitigation measures that are common in countries of high seismic risk.

With the intention of continuing our collaboration with Haiti, in this paper we present damage estimates obtained for Port-au-Prince and Cap-Haitien after simulating several scenario earthquakes (probable earthquake and the largest possible earthquake, respectively). Our main objective is to remark the need for earthquake risk mitigation policies and emergency preparedness actions in the country in order to manage the seismic risk. Furthermore, this study provides other cooperative initiatives, such as the United Nations Development Programme (PNUD 2015), with a quantitative framework in which to base future studies.

2. Earthquake damage study

In general, risk is defined as the expected physical damage and the connected losses that are computed from the convolution of probability of occurrence of hazardous events and the vulnerability of the exposed elements to a certain hazard (United Nations Disaster Relief Organization). According to McGuire (2004), seismic risk entails a set of events (earthquakes likely to happen), the associated consequences (damage and loss in the broadest sense), and the associated probabilities of occurrence (or exceedance) over a defined time period.

For a deterministic analysis, seismic hazard - the first component - refers to the shaking effects at a certain site caused by a scenario earthquake. While the term exposure represents the availability and inventory of buildings, infrastructure facilities and people in the respective study area subjected to a certain seismic event. Structural (i.e., physical) vulnerability stands for the susceptibility of each individual element (building, infrastructure, etc.) to suffer damage given the level of earthquake shaking. This results in structural (and non-structural) damages, which directly implicate economic losses as well as casualties.

The inputs needed to estimate these damages are described in the following paragraphs, namely: earthquake source, ground motion prediction equations, local geology in the site -which is responsible for site amplification-, building inventory and associated structural vulnerability, and the corresponding epistemic uncertainties related to that information.

In order to compute the damage probability, the analytical risk and loss assessment tool SELENA was used (Molina et al. 2010). In SELENA, three user-selectable methods are incorporated to compute the damage estimates: the traditional capacity spectrum method as proposed by ATC-40 (ATC 1996), a recent modification called the Modified Acceleration Displacement Response Spectra (MADRS) method, and the improved displacement coefficient method I-DCM (ATC 2005). All these methods use damage functions (that is, capacity curves and fragility functions) to estimate the damage probability. In our previous work (Molina et al., 2014), we designed a procedure for earthquake damage assessment in Haiti, which we calibrated with damage data collected after the 2010 earthquake. The procedure considered the use of the MADRS method in SELENA; therefore, in order to apply the same procedure in the present study, we have used the MADRS method for damage estimation.

2.1. Scenario earthquakes that might hit Haiti in a near future

In figure 1 we show the epicentres of the seismic catalogue of Haiti elaborated in the SISMO-HAITI project (2012). As can be seen in the map, Haiti has been hit by widely damaging earthquakes in the past (Scherer 1912; Kelleher et al. 1973; Bakun et al. 2012). According to Bakun et al. (2012) three earthquakes of magnitude Mw ranging from 6.6 to 7.5 hit he south of Haiti in the XVIII century. The first one happened in 1701 and destroyed the city of Léogane. Other earthquakes happened in 1751 and 1770; their location indicates that they might be associated to the EFS and their date of occurrence suggests a trigger effect for the second one. Although small earthquakes have been felt in recent years, there is no evidence of large damaging earthquake activity on the EFS in the last 240 years (from 1770 to 2010); except for the magnitude 6.7 event in 1830 and the magnitude 6.3 earthquake on the 8th April 1860. The latter probably occurred offshore on a secondary structure. Hence, a new period of large earthquakes in the EFS might have started with the 2010 earthquake after 240 years of seismic quiescence. Considering the significant seismic potential of the entire EFS, Haiti and Dominican Republic should be prepared for future devastating earthquakes (Bakun et al. 2012).

Additionally, to the north, the Septentrional fault caused two events (in 1842 and 1887) that hit severely the cities of Cap-Haitien and Port-de-Paix. The estimated magnitudes of these two events are 8.0 and 7.8 respectively, according to McCann (2006). There are several events that could be also related to the activity of this fault (1784, 1903 and 1956 earthquakes), although their connection to this structure is unclear.

To define realistic scenario earthquakes which are useful for deterministic hazard assessment, we analysed the historical seismicity but also the following information: (1) the nature of the active faults all over the region, (2) the structural characteristics -geometry and kinematics- of the fault zones, and (3) all the data available about slip modelling of the 2010 earthquake, which provides valuable information about the thickness of the seismogenic crust in La Hispaniola. We selected and defined four major geological seismic sources that could affect the two cities under study. To this end, we conducted a combined analysis of the faults with probable Quaternary activity –identified from the digital elevation model- and the spatial distribution of the seismicity. Figure 2 represents the main geological sources we selected, which are: a) the Septentrional fault zone (green); b) the Enriquillo fault system (blue); c) the NW-SW reverse faults of the central folded region of La Hispaniola (yellow) ; and d) the seismic source of the 2010 earthquake (violet). For these sources we proposed 10 scenario earthquakes, which are described in detail in the SISMO-HAITI project report (2012).

For the Septentrional fault, due to the lack of information about the detailed structure and its segmentation, we defined two scenarios: a conservative scenario with a rupture length of 150 km (the one represented in green in figure 2) and a more probable scenario considering one third of the length (50 km). For the EFS we have used the segmentation proposed by Prentice et al (2010). Regarding the reverse faults of the folded belt, we defined two scenarios based on two faults mapped on a digital elevation model, which are located at different distances from Port-au-Prince. Finally, other scenario could be the repetition of an event similar to the 2010 earthquake.

The magnitude of each scenario was calculated from the geometry, kinematics and size of the source using scale relationships (figure 2). Recently Stirling et al. (2013) have made an intensive compilation and analyses of more than 40 scale relationships for the GEM (Global Earthquake Model). We selected the relationship proposed by Stirling et al. (2008) to be used in reverse and strike-slip tectonic regimes. The introduction of the well constrained geometrical data of the source of the 2010 earthquake into this relationship provided a Mw 7.23. This value is very close to the magnitude calculated from seismological data (Mw 7.0, according to USGS), proving that the relationship we used in this research is highly reliability.

Taking into account the previous analyses, we selected two seismic scenarios to be simulated in the present study. The scenarios correspond to the major possible earthquakes likely to occur within the next decades in the Septentrional fault (estimated Mw 7.9) and the Dumay segment of the EFS (estimated Mw 7.0). The magnitudes were estimated using the fault size (length and width) showed in Table 1 and the empirical relationship of Stirling et al (2008); the coordinates (latitude and longitude) correspond to the location of the scenarios named Sept3 and Dum3, respectively (figure 2).

For each scenario, we simulated not only one earthquake, but five events along the fault segment by varying the coordinates of the epicentre (red points in figure 2). The rest of the parameters given in table 1 remained constant. The goal of defining different locations was to take into account the epistemic uncertainty inherent to this input. This allowed us, on the one hand, to check the influence of the source-to-site distance on the damage scenario for both cities; and on the other hand, to obtain a range of values for the number of expected damaged buildings, instead of one single estimate.

2.2. GMPEs and local site conditions.

Currently there is still not enough ground motion data to estimate specific ground motion prediction equations (GMPE) for Haiti. In order to reproduce the ground shaking caused by the earthquake, in Molina et al. (2014) we combined the New Generation Attenuation (NGA) models proposed by Boore and Atkinson (B&A, 2011) and Chiou and Youngs (C&Y, 2008) with the V_S^{30} and V_S^{30} plus one standard deviation values obtained from Cox et al. (2011). We calibrated these V_S^{30} values with the results we obtained from our field work; moreover, the values are coherent with those obtained by Gilles et al. (2013). The ground shaking estimation yielded by these GMPEs takes into consideration the soil effect, given the inclusion of the V_S^{30}.

According to our results, that ground shaking estimation in combination with the vulnerability model we proposed for Port-au-Prince, yielded the lowest residuals in the calibration process. Thus, in the present paper we used the above mentioned GMPEs and V_S^{30} values for Port-au-Prince, as in Molina et al. (2014). The V_S^{30} values for Port-au-Prince vary from 278 m/s to 577 m/s.

For Cap-Haitien, we assumed the V_S^{30} values proposed by Bertil et al. (2014). They define 6 soil classes for the city and provide V_S^{30} values for each soil class. The V_S^{30} values for Cap-Haitien present higher variability than those in Port-au-Prince, ranging from 140 m/s at central alluvial plain to 800 m/s at bedrock.

Figure 3 shows the working geographical units (hereafter referred to as geounits) delineated for each city of study, which coincide with the districts, and the V_S^{30} spatial distribution. In both cities, the presence of soft soils is observed along the bay, whereas the hardest soil is mainly found in mountainous areas (from northeast to southwest in Cap-Haitien; in the southern and north-eastern areas of Port-au-Prince). It is important to note that we have used the specific Vs^{30} value of each geounit in the GMPEs to compute the ground motion at each site, instead of a given interval, mean value, or soil-specific amplification factor.

2.3. Building stock classification

With the aim of simplifying the seismic risk assessment, the building stock exposed to earthquakes in the cities under study has to be classified into Model Building Types (MBT). Each MBT represents a group of buildings with similar behaviour under earthquake shaking. The classification has to be detailed, to guarantee realistic outcomes; as well as generic, to allow the classification of buildings into categories.

In this study, we took the exposure and vulnerability of Port-au-Prince from our previous work (Molina et al., 2014). In July 2011 the SISMO-HAITI working group carried out a field campaign in Port-au-Prince, guided by local civil engineers, in order to examine the exposure and the local construction techniques. Additionally, the Ministry of Public Works of Haiti (MTPTC— *Ministère des Travaux Publics, Transports et Communications*) provided a building database compiled after the 2010 earthquake, containing structural information, damage state and use of 86,822 buildings in Port-au-Prince. Based on both sources of information, we classified the exposure into six MBT according to the material of their structure and walls, and the number of stories. A detailed description of every building typology is included in Molina et al., 2014.

In order to estimate the exposure of Cap-Haitien, in this study we used the Haitian census of 2003 provided by the Institute of Statistics and Informatics of Haiti (IHSI). Nevertheless, this exposure estimation should be considered as an approximation since the census is outdated. During our field campaign in 2011, we found that the building typologies of Cap-Haitien and Port-au-Prince are quite similar, hence we applied in Cap-Haitien same criteria as those used for Port-au-Prince regarding MBT classification and vulnerability allocation.

Table 2 shows the number of buildings of every building typology in both cities. RC-CB is the predominant MBT (76 % in Port-au-Prince and 81% in Cap-Haitien), which describes reinforced concrete frame buildings, consisting on reinforced concrete columns, beams and slabs, with unreinforced concrete block infill. No mechanical connection is made between the wall panel and the columns, floor or roof slabs. Each MBT was further classified as low rise (1-3 stories) and high rise (3-6 stories), except for W-UM, which was only low rise.

2.4. Vulnerability allocation

After the 2010 Haiti earthquake, many authors published papers and reports analysing the damage and losses in the country due to the earthquake (e.g. Holliday and Grant 2011; Marshall et al. 2011; Lang and Marshall 2011). A summary of the main points of these papers can be found in Molina et al. (2014). The overall conclusion is that the physical damage was greater than expected for a 7.0 Mw earthquake; and it was due mainly to the low quality of construction materials and the poor building design, what was also confirmed after our field visit in 2011. In the case of RC-CB buildings, for instance, they had very thin columns and were often reinforced with deformed -and sometimes even smoothed- bars, which are not adequate. Column reinforcement was minimal and ties were insufficient. Concrete and mortar quality was generally low. In other words, the vulnerability of the building stock was (and still is) very high; hence, the seismic risk remains also high.

We represented a vulnerability scale in both cities -Port-au-Prince and Cap-Haitien-, based on the MBT assigned to each building. We calculated the ratio (M/R Ratio) between the number of masonry and wood buildings (RL-BM, CM-UM and W-UM typologies, more vulnerable) with respect to the number of buildings with reinforce concrete structure (RC-SW, RC-CB and RC-UM typologies, less vulnerable) in each geounit. The M/R Ratio ranges between 0.20 and 0.45. A value of 0.20, for instance, means 20 masonry or wood buildings out of every 100 reinforced concrete buildings. In order to facilitate the interpretation of the result, we elaborated a vulnerability map (figure 4) for each city showing the spatial distribution of the M/R Ratio classified into three intervals. In case of future earthquakes, for the same level of ground motion, districts with lower M/R Ratio (yellow geounits) are expected to register less damaged buildings than those with higher M/R Ratio (red geounits).

As can be interpreted from figure 4, the vulnerability of the building stock of Cap-Haitien is related to the city urban structure. The M/R Ratio is higher to the north and south, where rural areas with mostly poor-quality buildings are found. Districts in yellow (M/R Ratio of 0.20 to 0.25) are characterized by a regular street network and robust buildings, mostly colonial-period houses. On the contrary, districts in orange present irregular urban pattern, as well as unpaved streets and weak houses.

In Port-au-Prince, figure 4 reveals the high M/R Ratio obtained for districts in the southern mountains and surrounding the Fort National Hill (geounit 19). Both are hilly areas where small, weak buildings are stuck to each other. According to the M/R Ratio, almost half of them are poor-quality masonry or wooden houses. In fact, those areas were severely damaged by the 2010 earthquake. In the rest of the districts, the proportion of such kind of buildings is about 25% in relation to reinforce concrete structures.

The damage functions (capacity and fragility functions) used in this study were taken from our previous work (Molina et al., 2014). In Molina et al. (2014), we obtained damage functions starting from the parameters assigned by Lagomarsino and Giovinazzi (2006) and Hazus (FEMA 2003) to the MBT described in table 2. Then we calibrated these initial damage functions using the damage data from the 2010 earthquake. The final parameters (calibrated) of the capacity curves (yield and ultimate displacement and acceleration, and ductility) are in table 3, along with the designation of the initial curves. From these parameters, the fragility functions were derived using the lognormal cumulative probability function given in FEMA (2008). The damage limit states, Sd, and the normalised standard deviation, β, needed to build these fragility functions were obtained as indicated in Lagomarsino and Giovinazzi (2006), and are presented in table 4.

2.5. Structural damage scenarios and associated economic losses

Taking into consideration the epistemic uncertainties related to the scenario earthquake location and the GMPE selection, a logic tree has been developed using the five scenario earthquakes and the two GMPEs described in section 2.1 (figure 2) and section 2.2, respectively. Therefore, ten structural damage scenarios were obtained for each geounit in each city. The structural damage is represented in terms of the number of buildings reaching every degree of damage, i.e. slight, moderate, extensive and complete, as well as no damage (Lagomarsino and Giovinazzi, 2006).

In figure 5 we show the maps of the expected number of uninhabitable buildings estimated for both, Cap-Haitien and Port-au-Prince. As uninhabitable buildings we considered all buildings reaching complete damage plus 90% of those reaching extensive damage. The represented damage corresponds to the expected value of the results given by the two GMPEs and the scenario earthquakes Sept3 and Dum3 (figure 2), whose locations are presented in table 1.

In the case of Cap-Haitien, Sept3 corresponds to a Mw 7.9 and 20km deep earthquake, located 10km from the city. If such an event occurs, more than 13,500 buildings are expected to suffer extensive or complete damage, what is 47% of the total number of buildings in Cap-Haitien. The spatial distribution of the damages is related mainly to the type of soil, what points out the importance for risk analysts to consider the soil effect in seismic risk studies. All the geounits located on softer soil (centre and west) would register higher damage than the rest, with a percentage of uninhabitable buildings ranging between 45% and 60%. In eastern geounits (located on harder soil), the percentage presents higher variation, with values from 15% to 60%, in concordance to the heterogeneity of the soil type distribution.

In Port-au-Prince, Dum3 accounts for a Mw 7.0 and 15km deep earthquake, located 10km to the southwest of the city. Results show that we can expect almost 30,000 buildings reaching at least extensive damage, what makes 45% of the total number of buildings of Port-au-Prince. The damage spatial distribution shows that the source-to-site distance and the soil effect have dominated the damage estimation. The southern geounits are expected to suffer severe damage due mainly to the proximity to the epicentre, where over 50% of the buildings would be uninhabitable. Even heavier damage is expected in some central districts, especially in those located by the Port-au-Prince Bay, where the softer soil amplifies the ground motion. Special attention is to be paid to geounit 19 (the Fort National Hill) and surroundings, where according to the damage scenario, only 15-to-30 percent of the buildings are expected to end up uninhabitable. The presence of hard soil and the relatively large distance to the epicentre have led to low damage estimates. However, this hilly area suffered extreme damage in the 2010 earthquake due to the particular characteristics of the buildings located there. In the Fort National district the urban network is irregular, dense and not planned; and small, brittle houses are forced to be stuck to each other due to the steep terrain morphology. The combination of these urban factors increases the seismic vulnerability in the area. The same happens in the southern mountainous region, where also severe damage was observed after the 2010 earthquake.

The maps of figure 5 are essentially showing the spatial distribution of the expected heaviest structural damage in both cities. This information is especially useful for risk managers, since it enables the identification of those districts in which to develop building reinforcement and prevention measures with top priority. These maps also provide a picture of the city situation after the next major earthquake, what allows for designing an informed emergency plan, as well as an optimal resources allocation beforehand.

The logic tree allowed us to carry out a sensitivity analysis aimed at studying the influence of the input parameters on the damage results obtained for the five scenario earthquakes. Table 5 shows the results for RC-CB buildings (the predominant MBT in both cities), for extensive and complete degrees of damage, and for two nearby geounits with different type of soil. The number of damaged buildings is given for the ten branches of the logic tree, along with the expected value and corresponding uncertainty. The three following parameters were analysed:

- Source-to-site distance: Depending on the GMPE, the calculated distances are Joyner-Boore (d_{JB}) -when the B&A NGA model is used- or Joyner-Boore and rupture distance (d_{JB} and d_{rup}) -for the C&Y NGA model. In table 5 we observe that the influence of this input is negligible for

Cap-Haitien. The magnitude associated to the scenario earthquake of Cap-Haitien (7.9 Mw) corresponds to a large rupture; therefore, moving the hypocentre along the fault segment does not imply a significant source-to-site distance difference (d_{JB} is 7.26 km for Sc1 and 7.12 km for Sc3). On the contrary, the differences are important for Port-au-Prince (d_{JB} is 4.66 km for Sc1 and 3.55 km for Sc4). Consequently, the number of complete damaged buildings in geounit 3 ranges from 729 to 928 when the B&A GMPE (Gm1) is used and from 801 to 865 when using the C&Y GMPE (Gm2). Analogous variation is observed in geounit 14.

- GMPE: In table 5 we see that the number of damaged buildings is generally higher when using the C&Y GMPE (Gm2) with respect to the B&A GMPE (Gm1); this being particularly noticeable in the case of Cap-Haitien. This result is consistent with the higher ground motion obtained when using the C&Y GMPE in comparison with the acceleration values yielded by the B&A GMPE.
- Soil type: Table 5 also shows the influence of the soil effect on the damage results. For example, according to the damage scenario Sc1-Gm1, in Port-au-Prince there are 729 buildings reaching complete damage in geounit 3 (33% of the RC-CB total number of buildings); while in geounit 14 this number is reduced to 350 (19% of the RC-CB total number of buildings). Similarly, in Cap-Haitien, 74 buildings in geounit 38 might have complete damage (22% of the total); while the number is 31 (6% of the total) in geounit 40. In both cities the source-to-site distance is similar for the pair of geounits; hence the responsible for the damage reduction seems to be the increment of V_s^{30} (from 278 m/s to 577 m/s in Port-au-Prince, and from 140 m/s to 800m/s in Cap-Haitien).

In this paper, we have equally weighted each branch of the mentioned logic tree. For future earthquake loss estimation, a detailed sensitivity study of the input parameters should be carried out in order to correctly decide on the weights of the logic tree (Atkinson et al., 2014; Bommer, 2012); however, this is out of the scope of our paper.

In order to describe the damage distribution for each MBT, figure 6 shows the damage probability corresponding to the most and less unfavourable damage scenarios for both cities. In Cap-Haitien, Sept1 is the furthest event to the city, while Sept3 is the closets; and as we have mentioned, the damage estimates for each scenario are not very different. Buildings with reinforced concrete structure (RC-CB and RC-UM) and reinforced masonry buildings (RL-BM) show practically the same damage pattern, with almost the same number of buildings reaching every degree of damage. Considering the estimation of extensive and complete damage for these buildings, it is deduced that approximately 50% of them would result uninhabitable. As expected, confined masonry (CM-UM) and wood (W-UM) buildings present higher moderate damage and lower none and slight damage degrees than the others; in any case, the rate of uninhabitable buildings remains about 50%.

In Port-au-Prince, Dum1 is the furthest event to the city, while Dum4 is the closets. Hence, Dum1 causes less damage than Dum4, as can be seen in figure 6 where severe degrees of damage (moderate, extensive and complete) increase in Dum4 for all the MBT. If we focus on RC-CB typology, which is representative of about 75% of the total number of buildings in Port-au-Prince, we see that about 50% of the buildings would have slight or no damage in case of Dum1 scenario, being reduced to 40% in case of Dum4. Moderate damage would be observed in slightly more than 10% of the buildings in both scenarios; whereas around 40% of the buildings would undergo extensive and complete damage if Dum1 scenario happens, being increased to 50% in case of Dum4. Thus, if an earthquake happens in the Dumay segment of the EFS, regardless of the rupture starting point location along the segment, about half of the RC-CB buildings in the city would result uninhabitable. As for other MBT, RC-SW provides the best performance, since the complete damage percentage is the lowest and the slight damage is the highest. The opposite pattern is observed for W-UM buildings. Again, RC-UM and RL-BM present similar performance as RC-CB, as well as CM-UM; although the latter shows slightly lower complete damage percentage than the others.

Although it is difficult to establish a reliable economic loss model for the country, we attempted to give an approximation of the economic losses connected to the scenario earthquakes simulated in this research. Based on the damage results previously described, we estimated that the reconstruction would cost about USD 700 million to the city of Cap-Haitien and USD 2,100 million to Port-au-Prince. For the estimation we assumed an average built area of 100 m2 and a construction price of 700 USD/m^2 (according to the current construction techniques in the country for concrete block buildings).

3. Advices to minimize the seismic risk in Haiti

The results obtained in the present study reveal the high seismic risk existing in Haiti, and point out the need for specific mitigation measures in order to avoid these negative predictions. Our study provides the national authorities and the scientific community with knowledge and a quantitative basis to define such policies. In this regard, we propose the following measures:

- For seismicity monitoring: a broad coverage seismic network might be implemented in Haiti including the instruments installed by different foreign agencies, such as the Spanish Seismic Network and Natural Resources Canada. Additionally, Haitian experts have been trained in Spain to be the seed of a seismology and earthquake engineering team in Haiti (Pierristal et al. 2013; Dorfeuille 2013). Their experience might be used in order to improve the seismic knowledge in the country and to implement risk mitigation measures with local capacities.
- For the establishment of minimum requirements to provide building safety: as the first Haitian seismic code is being defined (Bertil et al. 2014), we recommend to take into consideration the guidelines given in Pierristal et al. (2013), as well as the seismic hazard map elaborated by Benito et al. (2012).
- For reinforcement of the current building stock: the maps of M/R Ratio plotted in this paper identify the geounits where the presence of masonry and wood buildings is high with respect to reinforced concrete structures. Additionally, the maps of uninhabitable buildings highlight the areas of the city where the heaviest damage is expected in case of earthquake. All these maps could be used to select those districts where priority actions oriented to building reinforcement are needed.
- For emergency preparedness: in Cap-Haitien, more than half of the districts would result seriously affected and probably unable to act in case of earthquake. Such a chaotic situation would be difficult

to manage by emergency agents. In Port-au-Prince, heavy damage is expected in mountainous and hilly areas, where the building density is very high and access is problematic. This could complicate the evacuation and/or rescue tasks after an earthquake occurrence; hence urban planning should be revised and modified in such areas. To this respect, it is worth mentioning that despite the relevance of the urban context regarding earthquake vulnerability (unplanned urban areas generally present higher vulnerability), this aspect is still not considered in the current seismic risk estimation approaches. Thus, the scientific community should increase efforts in the improvement of the risk assessment models.

4. Conclusions

Considering the high seismic hazard of Haiti (Benito et al. 2012; Calais et al. 2010), we estimated several damage scenarios in the main cities – Port-au-Prince and Cap-Haitien – associated to two earthquakes likely to occur in the future. It should be noted that the census in which the exposure assessment of Cap-Haitien is based dates from 2003, thus that part of the study should be updated.

Our findings enable stating the following conclusions:

- The damage scenarios estimated for Port-au-Prince and Cap-Haitien indicate that future possible earthquakes would leave almost 30,000 and 14,000 uninhabitable buildings, respectively. This represents about 50% of the building stock of both cities, meaning that half of the families would lose their homes. Such a situation would cause a great impact in the Haitian society again, seriously affecting the people, the institutions, and the economy.
- Regarding this aspect, we roughly estimated that a future major earthquake would cost USD 700 million to the city of Cap-Haitien, while in Port-au-Prince the amount might reach USD 2,100 million.
- With respect to the damage spatial distribution, in Cap-Haitien severe damage is predicted all across the centre and the western part of the city. In Port-au-Prince, the heaviest damage is expected in the southern mountains and by the bay. Despite the vulnerability of the buildings is somewhat correlated to the damage distribution, it is worth to notice the significant influence of the soil effect.
- Finally, based on these results, we have also provided several prevention measures oriented to mitigate the high seismic risk of the country, which are common in other countries with similar level of risk. These measures are: (1) implementation of a broad coverage seismic network; (2) definition of a specific seismic code for Haiti; (3) building reinforcement; and (4) emergency planning.

Therefore, despite the fact that more than USD 15 billion were collected from all over the world to help Haiti recover from the 2010 earthquake and the lessons learned from such a tragedy, we can sadly conclude that Haitian cities have not been prepared yet to face future large events. After five years working in Haiti, we have only seen rather small improvements that are merely generating little change at a slow pace. That is not enough. There exists a fragile connection between the scientific cooperative work and the country decision makers, which is preventing the projects to have a real impact in Haiti. All agents involved in the process –national authorities, scientists, international cooperation agencies- are in charge of changing this situation in order to guarantee the continuity of the projects and the application of useful results.

Cooperation with Haiti must continue with the aim of increasing the national resilience to earthquakes.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest.

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Figure 1

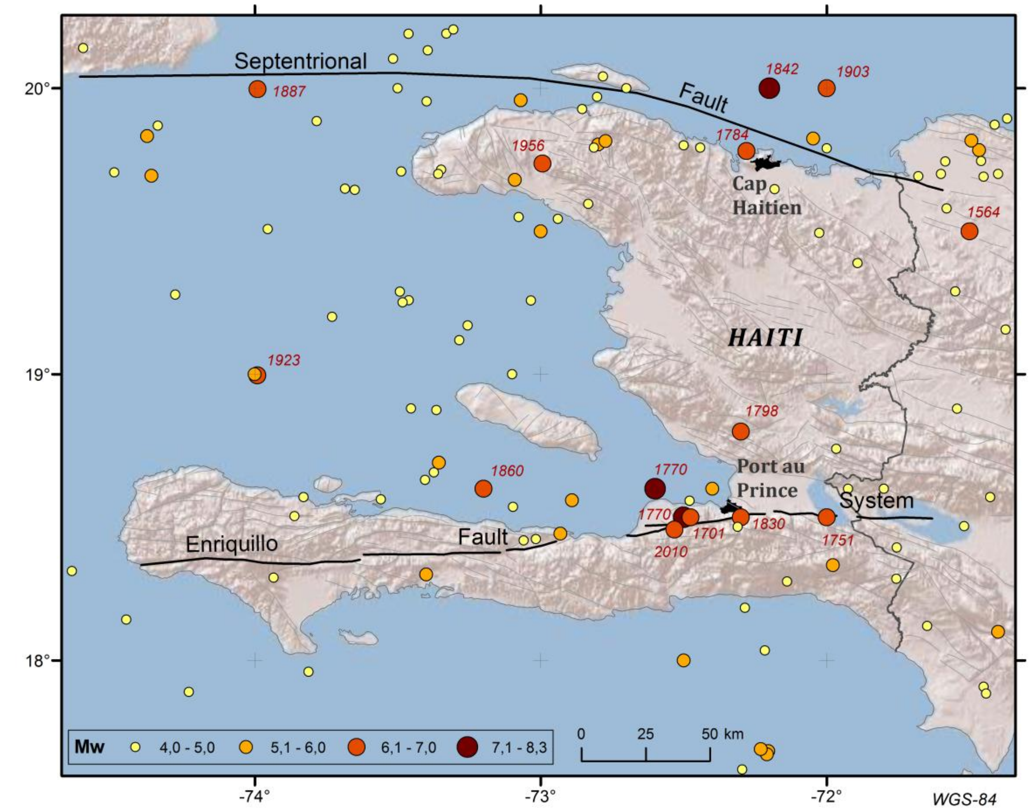

Figure 1. Seismicity of Haiti updated to 2010. Seismic data taken from the Sismo-Haiti project (2012). The main faults are also plotted.

Figure 2

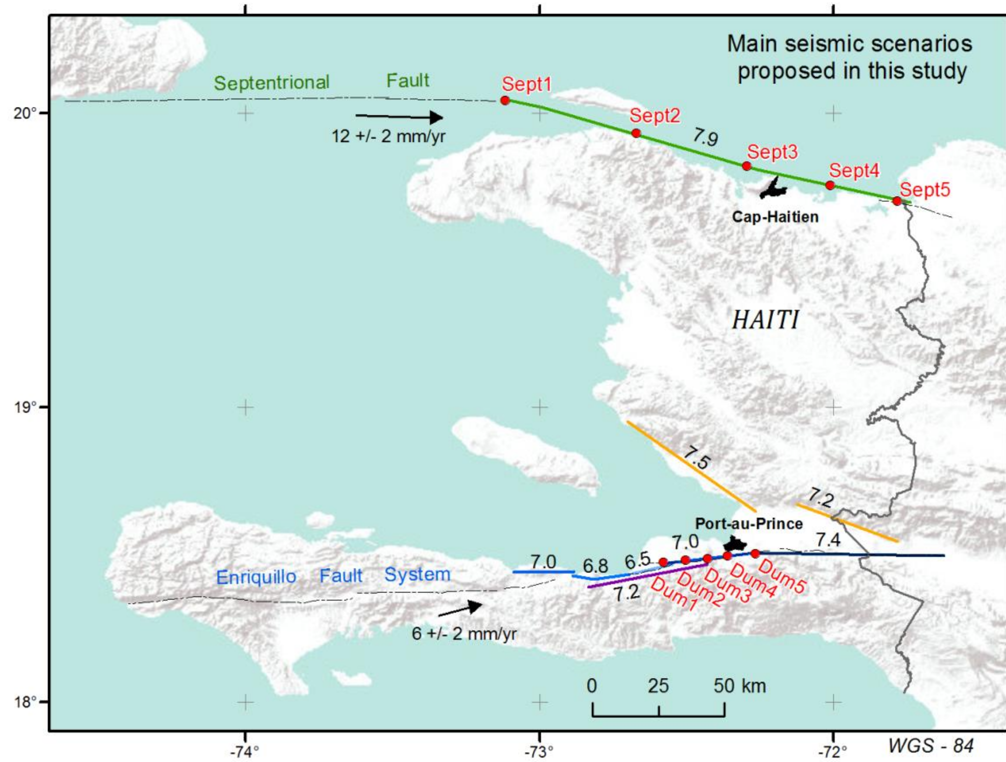

Figure 2. Main scenario earthquakes proposed in this study from the analysis of different fault segments in the active faults of Haiti. Numbers on the segments indicate the Mw obtained using the relationship of Stirling et al. (2008). Red points represent the scenario earthquakes simulated in this study in the Septentrional fault and the Enriquillo Fault System. The arrows show the slip-rate associated to the main faults, taken from Calais et al. (2010).

Figure 3

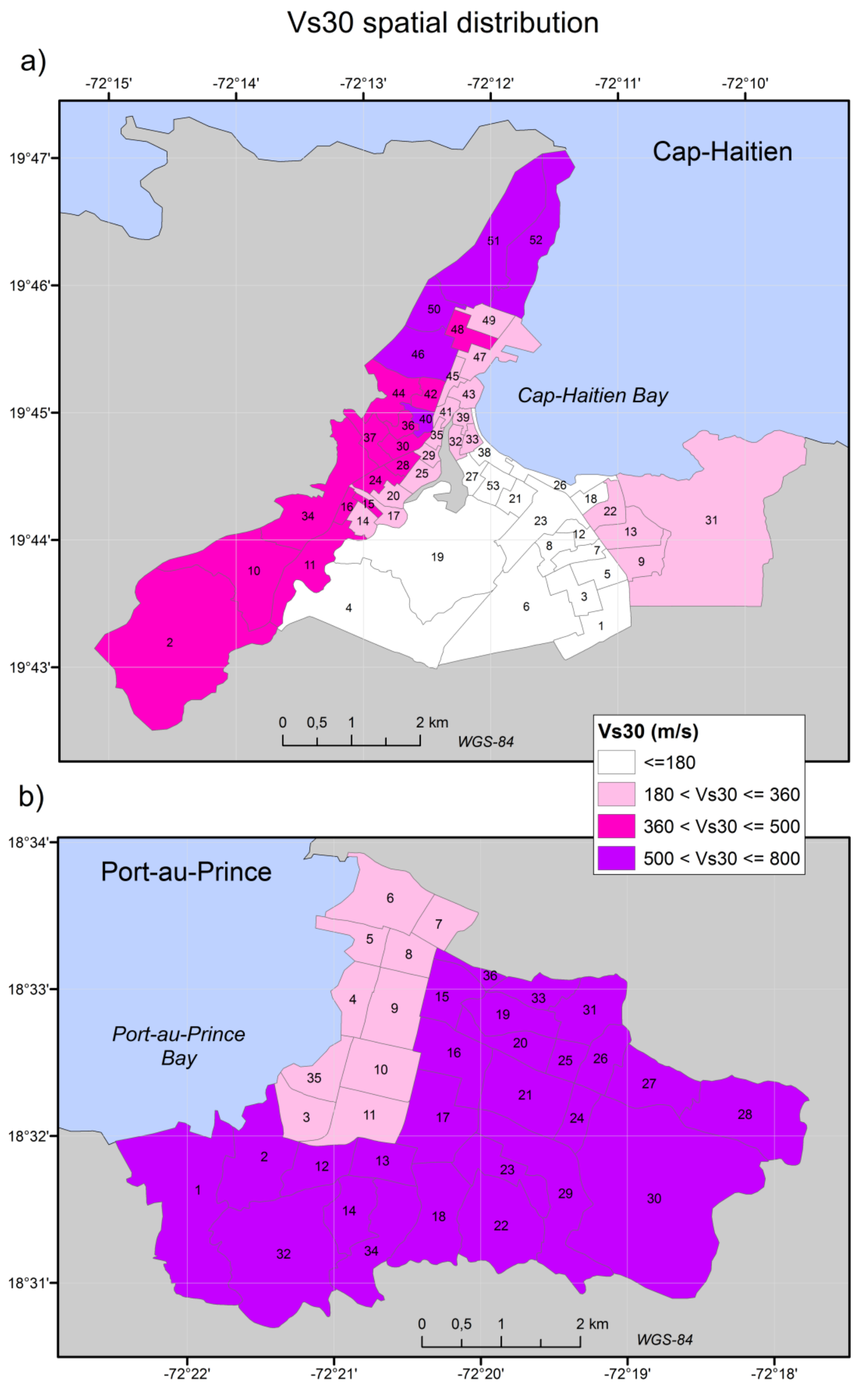

Figure 3. Geounits and V_S^{30} values considered for a) Cap-Haitien and b) Port-au-Prince. Numbers inside the geounits are identifiers.

Figure 4

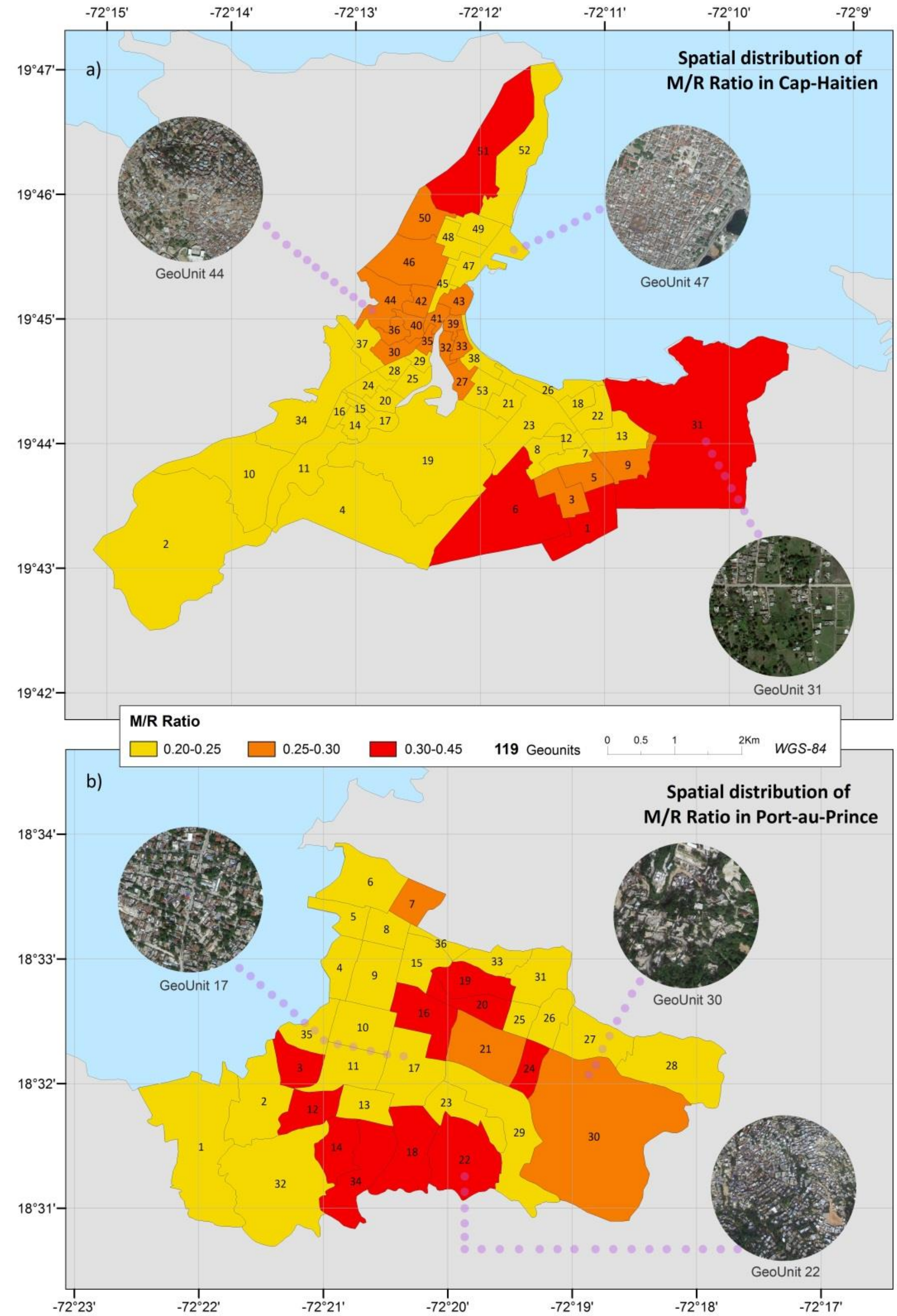

Figure 4. M/R ratio distribution in (a) Cap-Haitien and (b) Port-au-Prince. Numbers account for the geounit identifiers. Circular images are from Google Earth.

Figure 5

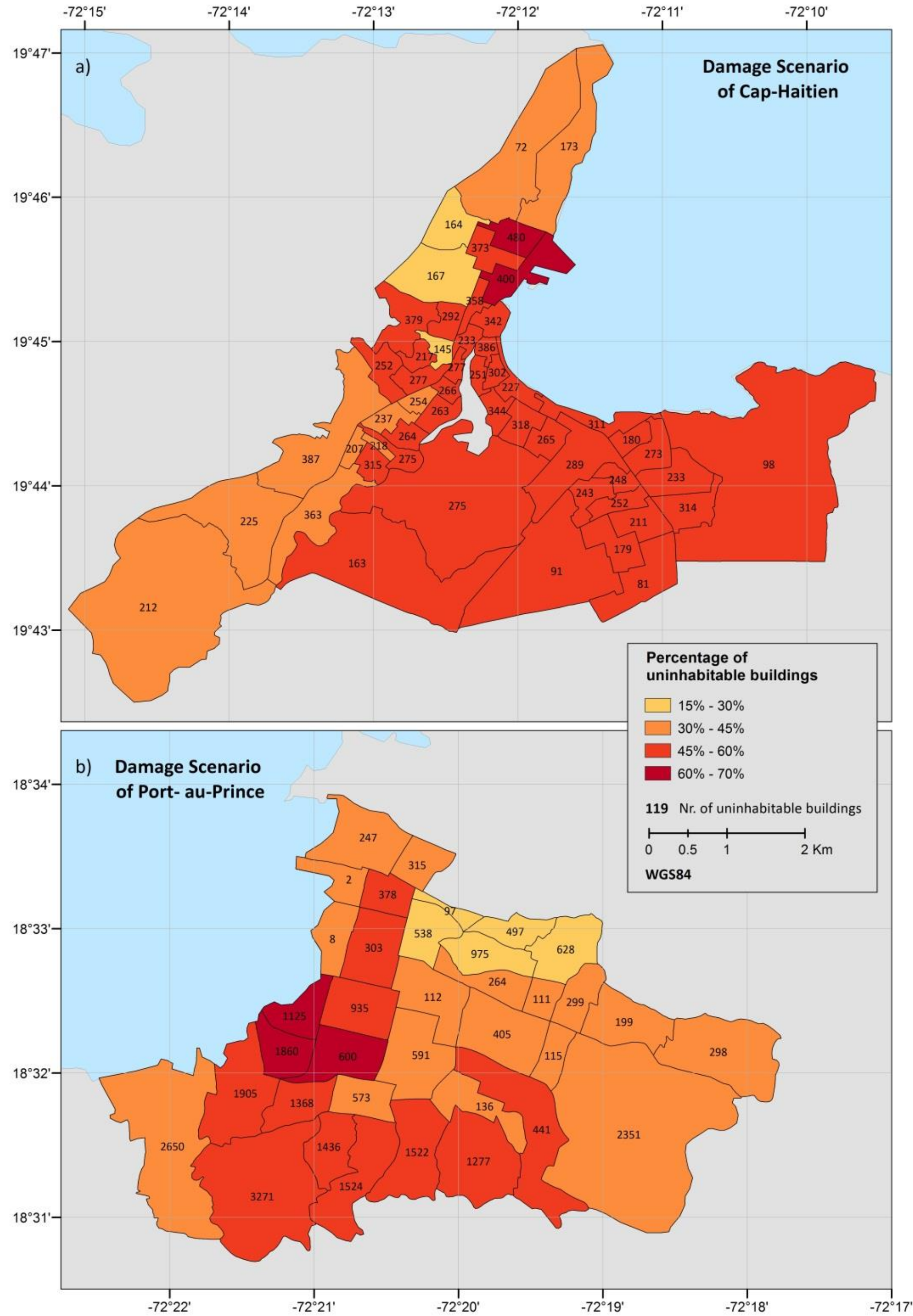

Figure 5. Damage scenarios in terms of percentage and number of expected uninhabitable buildings. a) In Cap-Haitien for a Mw 7.9 earthquake associated to the Septentrional fault. b) In Port-au-Prince for a Mw 7.0 earthquake associated to the Dumay fault. The earthquake parameters are in Table 2.

Figure 6

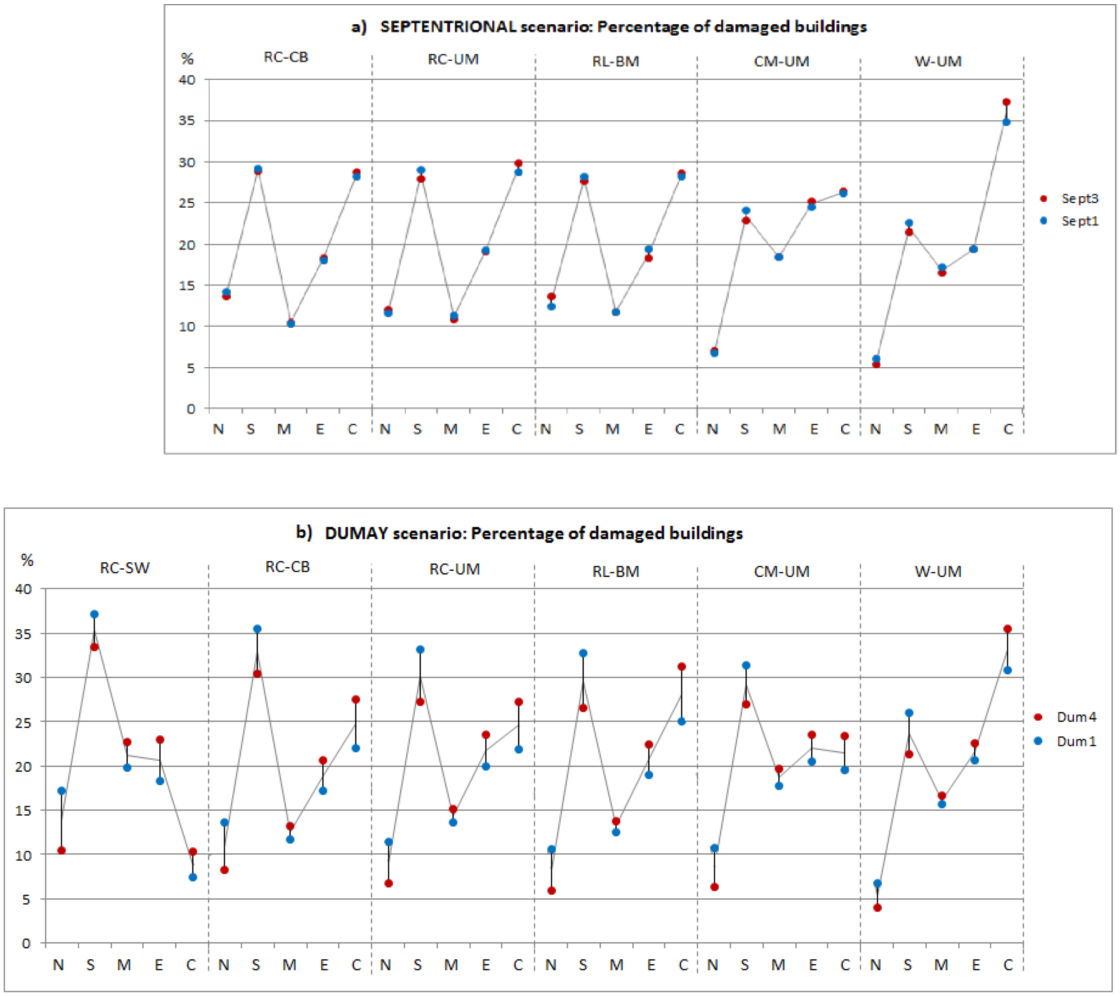

Figure 6. a) Damage distribution in Cap-Haitien associated to Sept3 (most unfavourable) and Sept1 (less unfavourable) scenario earthquakes. b) Damage distribution in Port-au-Prince associated to Dum4 (most unfavourable) and Dum1 (less unfavourable) scenario earthquakes. Letters in the horizontal axis indicate the five degrees of damage: None, Slight, Moderate, Extensive, and Complete.

Table 1

Table 1. Parameters of the scenario earthquakes selected in this study. The coordinates correspond to the centre of the fault plane. Dumay is a fault segment of the EFS.

Fault	**Latitude**	**Longitude**	**Azimuth**	**H (km)**	**Dip**	**Focal Mec.**	**LxW[(a)] (km)**	**Mw**
Septentrional	19.830°	-72.270°	285º	20	90º	Strike-Slip	150x15	7.9
Dumay (EFS)	18.502°	-72.438°	270º	15	90º	Strike-Slip	68x15	7.0

(a) LxW stands for "Length by Width" of the fault's rupture plane

Table 2

Table 2. Classification of the building stock in Port-au-Prince (PAP) and Cap-Haitien (CH) into different model building types.

MBT[(a)]	Materials		Number of Buildings	
	Structure	**Walls**	**PAP**	**CH**
RC-SW	Reinforced Concrete	Reinforced Concrete	941	0
RC-CB	Reinforced Concrete	Unreinforced Concrete Blocks	48547	22951
RC-UM	Reinforced Concrete	Unreinforced Masonry	2036	415
RL-BM	Reinforced Masonry	Unreinforced Concrete Blocks	9150	4590
CM-UM	Confined Masonry	Unreinforced Masonry	1909	363
W-UM	Wood Frame	Unreinforced Masonry	1875	401

(a) The name of each MBT is composed by two abbreviations, which describe the structure and the wall composition, respectively. The abbreviation meanings are the following: RC - Reinforced Concrete; SW - Shear Wall; CB – Concrete Blocks; UM – Unreinforced Masonry; RL – Reinforced Masonry; BM – Block Masonry; CM – Confined Masonry; W – Wood.

Table 3

Table 3. Final parameters of the capacity spectra used in this study (taken from Molina et al., 2014). Dy (m) and Ay (m/s2) represent the yield point spectral displacement and acceleration, respectively. Du (m) is the spectral displacement of the ultimate point.

MBT	Dy (m)	Ay (m/s^2)	Du (m)	μ	Initial Curve[(a)]
RC-SW	0.0450	6.2021	0.0900	2	RC2-I, L&G
RC-CB	0.0500	5.7000	0.0750	2	RC1-I, L&G
RC-UM	0.0350	5.6000	0.0550	2	C3-Pre code, H
RL-BM	0.0400	5.4000	0.0600	2	M7-Pre code, L&G
CM-UM	0.0600	3.8000	0.1200	2	M6-Med. Code, L&G
W-UM	0.0520	3.8500	0.0900	3	M6-Pre code, L&G

(a) Designation of the initial curves that were assigned to each MBT and calibrated afterwards in Molina et al., 2014.L&G stand for Lagomarsino and Giovinazzi (2006) and H for Hazus (FEMA, 2008)

Table 4

Table 4. Final parameters of the fragility functions used in this study (taken from Molina et al., 2014): Damage limit states, Sd,i and normalised standard deviation, β, for slight (i= 1), moderate (i = 2), extensive (i = 3) and complete (i = 4) damage states

MBT	**Sd,1**	**β**	**Sd,2**	**β**	**Sd,3**	**β**	**Sd,4**	**β**
RC-SW	0.0315	0.30	0.045	0.32	0.0563	0.38	0.090	0.50
RC-CB	0.0350	0.30	0.050	0.32	0.0563	0.38	0.075	0.50
RC-UM	0.0245	0.30	0.035	0.32	0.0400	0.38	0.055	0.50
RL-BM	0.0280	0.30	0.040	0.32	0.0450	0.38	0.060	0.50
CM-UM	0.0420	0.33	0.060	0.40	0.0750	0.54	0.120	0.70
W-UM	0.0364	0.33	0.052	0.40	0.0615	0.54	0.090	0.70

Table 5

Table 5. Number of RC-CB buildings reaching extensive or complete damage for each branch of the logic tree. Sc1 to Sc5 corresponds to the scenario earthquakes described in Section 2.1. for each city; Gm1 corresponds to Boore and Atkison NGA model and Gm2 corresponds to Chiou and Youngs NGA model. Expected value and uncertainty are also provided at the end of the table. Results are given for two nearby geounits per city that are located on soft (geounits 3 and 38) and hard (geounits 14 and 40) soil.

City	**Port-au-Prince**				**Cap-Haitien**			
Geounit	**Geounit 3 V_s^{30} =278 m/s # RC-CB bldg.[(a)] = 2168**		**Geounit 14 V_s^{30} =577 m/s # RC-CB bldg. = 1889**		**Geounit 38 V_s^{30} =140 m/s # RC-CB bldg. = 333**		**Geounit 40 V_s^{30} =800 m/s # RC-CB bldg. = 544**	
Degree of damage	**Extensive**	**Complete**	**Extensive**	**Complete**	**Extensive**	**Complete**	**Extensive**	**Complete**
Sc1-Gm1	528	729	286	350	60	74	20	31
Sc1-Gm2	554	801	393	503	91	183	92	114
Sc2-Gm1	555	804	327	403	60	75	20	32
Sc2-Gm2	562	828	404	522	91	183	93	114
Sc3-Gm1	577	885	374	471	61	75	21	32
Sc3-Gm2	569	853	414	540	90	184	93	115
Sc4-Gm1	585	928	396	508	60	74	20	32
Sc4-Gm2	572	865	418	548	91	183	92	114
Sc5-Gm1	585	928	396	508	60	74	20	32
Sc5-Gm2	572	865	418	548	91	183	92	114
EV ± unc[(b)]	566±6	848±20	383±14	490±22	76±5	129±19	56±13	73±14

(a) Total number of buildings with reinforced concrete structure and concrete block walls in the geounit.
(b) Expected value plus/minus corresponding uncertainty