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1 Remote sensing vs. field survey data in a post-earthquake context: 2 potentialities and limits of damaged building assessment datasets

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6
7 Keywords

8 Seismic risk, vulnerability, remote sensing, damage assessment

9 10 Abstract

11
12 Quick building damage assessment following disasters such as large earthquakes serves to establish a
13 preliminary estimation of losses and casualties. These datasets are completed by employing several
14 crowdsourcing initiatives, in which volunteers and collaborators map damaged buildings in a given area
15 at a qualitative damage scale based on a post-earthquake aerial or satellite image. Automating this
16 process is a temptation and a technical issue, but manual interpretation remains essential, with the
17 identification of moderate and lateral damage being the key and limiting factor. Following the Haiti
18 2010 earthquake, many studies were completed by crossing multilayer data gathered from different
19 sources (satellite, aerial, and field survey). These works created a building damage dataset that enabled
20 the construction of different sets of empirical vulnerability functions. In the present study, we proposed
21 to review the datasets used for the damage assessment again, investigate how they can be managed for
22 understanding urban damage patterns, and quantify the potentialities and limits of the sets.

23 A high-resolution map of damage in Port-au-Prince was used to obtain a deducted map of intensity and
24 was then compared to more detailed post-earthquake investigations such as the microzonation of the
25 city (Belvaux et al. 2018). These detailed post-earthquake investigations, in which array microtremor
26 measurements are performed for characterization of the subsurface soil, contribute to a better
27 understanding of local variations in intensity. Subsequently, a retro damage scenario was run,
28 considering the different sets of vulnerability functions (using the RISK-UE methodology vulnerability
29 indexes) fitted with empirical vulnerability functions. Using the characterization of the exposure on a
30 remote sensing basis, the results fit the heaviest damage well (building collapse), but they overestimated
31 moderate damage states compared to the observations. However, is an aerial image based dataset
32 sufficiently exhaustive for moderate damage, which is mostly visible from a lateral or internal point of
33 view? Finally, we suggested some range of adjustments that can be applied to a vulnerability assessment
34 originating from remote sensing data such that it can be used more accurately in the detection of urban
35 damage, even for moderate damage degrees.

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1. Introduction

41 Several rapid mapping initiatives utilized post-earthquake satellite and airborne imagery to produce
42 independent point feature sets marking the damage grade of affected buildings (such as the European
43 program Copernicus Emergency Management Service and HOT from the Open Street Map community).
44 Despite the obvious potential of satellite remote sensing technology in providing damage figures, the
45 scale and complexity of the urban structures caused the overall figures and patterns of the damage
46 assessments to yield a rather poor representation of the true damage extent.

47 The higher detail airborne imagery performs much better as confirmed by different validation studies
48 conducted during the last several years (Saito et al. 2010; Corbane et al. 2010; Ghosh et al. 2011;
49 Lemoine and Corbane 2013). (Lemoine and Corbane 2013) investigated the quality of damage
50 assessments derived from different activities such as, satellite-based damage assessments, aerial-based
51 damage assessments, field survey following a stratified random sampling, road track surveys from a
52 Low Cost Mobile Mapping System, and block-sampling using Pictometry data, through a simple
53 intercomparison and a validation using a complete building ground survey. The results showed that the
54 identification of building damage from aerial imagery provides a realistic estimate of the spatial pattern
55 and intensity of building damage, even if it still tends to underestimate several damage states that are
56 difficult to effectively identify from an aerial point of view. (Dong and Shan 2013) completed a review
57 work of pre- and post-earthquake damage assessment, and assessed what remote sensing techniques,
58 optical or not, are the most used in these cases: LIDAR, SAR, optical image, and ancillary data. Even if
59 techniques such as LIDAR have serious benefits (as for example to estimate debris volume), they found
60 that optical images, satellite or aerial, remain the most reliable and independent evaluation. More
61 recently, (Cooner, Shao, and Campbell 2016) presented a work testing three algorithms to automatically
62 map post-earthquake damage based on machine learning methods with great results. However, they
63 provided results in a binary form: damaged and undamaged, based on the most easily visible damage
64 (total collapse). (Romaniello et al. 2017) provides damage in terms of collapse ratio with automatic
65 image processing using Haiti 2010 Earthquake dataset. Remote-sensing-derived data is also a prevention
66 tool to estimate built-up areas and exposure to natural hazards such as earthquakes (Ehrlich et al. 2018).
67 Remote sensing can be used during all the phases of natural risk management (prevention, preparedness,
68 crisis management, recovery, and reconstruction).

69 The January 12, 2010, Port-au-Prince Earthquake in Haiti (M7-7.1) killed more than 200,000 people
70 (Calais et al. 2010). It was felt in all Hispaniola Island (Haiti and Dominican Republic) and in the East
71 part of Cuba. It was the first earthquake with an important work completed by several international
72 organizations generating a building damage dataset in the Port-au-Prince area. The goal of this work
73 was to estimate as soon as possible an order of magnitude of the damaged buildings and its economic
74 impact for international donors. Therefore, in more recent earthquakes such as Amatrice in Italy,
75 Ecuador, and Nepal in 2016, remote sensing has been used to aid damage assessment (Karimzadeh and
76 Mastuoka 2017; Piscini et al. 2017; Copernicus EMS 2016; Copernicus 2015).

77 However, other potential uses of these datasets exist, such as the establishment of empirical vulnerability
78 curves for Caribbean countries' building types. A very important work regarding the identification and
79 cartography of damaged buildings was attempted for the 2010 Haiti Earthquake using several techniques
80 for identification of the damaged areas and structures (remote sensing, aerial images, field inventory,
81 etc.). Based on these databases, some authors have proposed empirical fragility functions adapted to
82 current Haitian buildings (Hancilar, Taucer, and Corbane 2010; Hancilar, Taucer, and Corbane 2013;
83 Molina et al. 2014). In another context, South American countries, (Villar-Vega and Silva 2017) run
84 retro damage scenario for several past events and compared it with building damage datasets, in terms
85 of collapsed buildings. They used a set of fragility curves representative of these countries, but they did
86 not adapt a new set of curves. Among the main limitations they observed was the variation in the

87 portfolio when comparing models, based on recent census data, with past events 15 years old and the
88 quality and heterogeneities (in terms of damage states) among the building damage datasets.

89 The present work discusses these previous works in damage and vulnerability assessment completed
90 after the 2010 earthquake and proposes a high-resolution intensity map based on observed damage in
91 the Port-au-Prince area. This map was compared to the USGS ShakeMap (USGS 2017), which was
92 calculated during the hours/days after the earthquake, and some authors consider it as the reference in
93 terms of the intensity for this event. However, it should be considered that for this event, in reality,
94 there were very few observed or measured data considered in the ShakeMap calculation. Consequently,
95 ShakeMap for this event was mostly a model obtained using a ground motion prediction equation
96 (GMPE) calculation.

97 During the following years after the earthquake, important works have been completed in Haiti to better
98 understand this earthquake and its effects. (Rathje et al. 2011) compares building damage patterns with
99 available geological units, topographic units and identifies damage pockets. In terms of lithological site
100 affecting the seismic microzonation in Port-au-Prince, studies have been completed (Bertil et al. 2015;
101 Belvaux et al. 2018). The fault delimitation and its characterization (Calais et al. 2010) and the most
102 appropriate GMPE for a Haitian context have been proposed (Molina et al. 2014; Torres et al. 2016).
103 Considering all this information, the intensity of the 2010 earthquake can also be simulated.

104 Consequently, three intensity maps were compared in the present work: the USGS ShakeMap calculated
105 during the first hours/days, an intensity map derived from the observed damage database (JRC database),
106 and a simulated intensity map considering new investigations completed after the event: lithological site
107 effects, fault characteristics, and most adapted attenuation relation.

108 Finally, we ran several retro-damage scenarios, considering appropriate fragility functions for the typical
109 Haitian building stock and the aforementioned three intensity maps in the Port-au-Prince municipality.

110 2. Remote sensing and post-earthquake damage assessment

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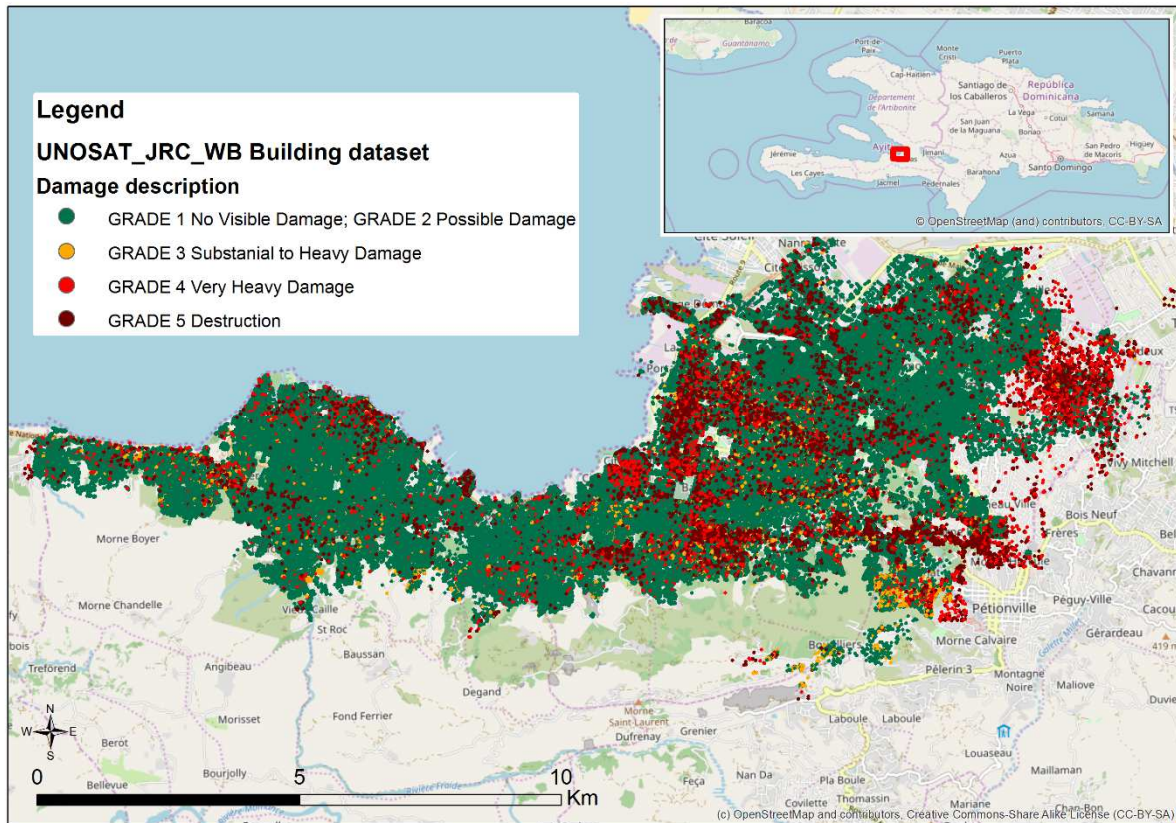
112 Following the Port-au-Prince earthquake, several actions and works were completed to assess the
113 damage and habitability in the area as soon as possible. Among them, the most important was a joint
114 collaboration between the United Nations Institute for Training and Research (UNITAR), the
115 Operational Satellite Applications Programme (UNOSAT), European Commission Joint Research
116 Centre (EC JRC) and the World Bank ((UNITAR/UNOSAT 2010), referred as UWJ hereafter. In fact,
117 many institutions and volunteers collaborated during the weeks following the earthquake to produce a
118 final global building damage assessment for the Port-au-Prince area (11 municipalities). Given its huge
119 volume of data in the most impacted area, this dataset is the reference in terms of damage assessment
120 for the 2010 earthquake.

121 Based on this work, several UWJ authors (Corbane et al. 2010; Ghosh et al. 2011; Lemoine and Corbane
122 2013;) compared damage building datasets after the Port-au-Prince Earthquake. Ghosh et al. (2011)
123 presented a work completed by the GEO-CAN¹ damage assessment, in the framework of joint
124 collaboration, which produced a damage building dataset combining satellite images, aerial images,
125 fieldtrip validations in some zones and even some data estimated by models. The EMS98 damage scale
126 was used as shown on Figure 1. The authors have validated this data by field trip in several districts.
127 They have worked with pre-earthquake images, noting each pre-existing building. They compared it to
128 the Open Street Map (OSM) and Chinese Academy of Sciences (CAS) quick damage assessment using
129 satellite images, in which only collapsed buildings were identified. As occurred in other recent

¹ Global Earth Observation Catastrophe Assessment Network

130 earthquakes, crossing aerial estimation with field trip observations, they found that the main difficulty
131 was identifying the partial collapses and intermediate-moderate damage states.

132 Another important dataset of damages is the MTPTC dataset (Haitian Ministry of Public Works and
133 Telecommunications) created by Miyamoto et al. (2011), which contains household habitability
134 (classified using a color code: green, yellow, or red) and % of loss. It is based on fieldtrip work, using
135 the USA ATC-20 method to assess habitability. Their work was completed building by building.



136
137 Figure 1: UNOSAT-JRC-WB damage dataset of Port-au-Prince and surroundings area. Basemap
138 OSM.

139 Globally, the MTPTC and UWJ datasets are quite coherent in total sum. However, great differences can
140 be found in several areas, as is noted by Lemoine and Corbane (2013); in completely destroyed areas,
141 the MTPTC could underestimate the number of initial buildings. The MTPTC survey's main goal was
142 to assess damage in remaining buildings. In addition to the complexity in assessing damage degree,
143 another difficulty is comparing habitability surveys, which mix structural and functional points of view
144 (such as the MTPTC survey) with damage degree surveys (such as UWJ) which are mostly structural.
145 (Douglas et al. 2015) found the same type of difficulties in the L'Aquila earthquake datasets.

146 (Saito et al. 2010) using the Pictometry methodology, assessed 1300 buildings in the Port-au-Prince
147 area. Pictometry® is the name of a patented aerial image capturing process that produces imagery
148 showing the fronts and sides of buildings and locations on the ground (EagleView, n.d.). They have
149 compared observed damage to an intensity MMI map (ShakeMap) completed by the US Geological
150 Survey (USGS) but they did not identify a clear relation. In their opinion the whole area of Port-au-
151 Prince should be classed as MMI=IX. They analyzed the reasons for the great differences between the
152 damage assessment completed using GEO-CAN (using satellite imagery) and that using Pictometry.
153 GEO-CAN is not exhaustive in delimiting pre-existing buildings and cannot correctly identify
154 intermediate damage, mostly the identification of the D4 EMS98 damage state (partial collapse). They

155 also compared their results to a field survey damage assessment of only 124 buildings; even with a better
 156 view of lateral damage obtained using Pictometry (soft story, moderate damage), damage was still
 157 underestimated using Pictometry. Looking at some of the individual buildings, the principal causes of
 158 these discrepancies were lower-story collapses, which were not visible in Pictometry, and cases where
 159 the Pictometry image was obscured by either trees or adjacent buildings. The main limit of this
 160 comparison is the reduced number of buildings assessed in the field.

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163 Table 1: Synthesis of damage observations in the Port-au-Prince area completed by different authors.

Data source	Method	Area /specifications	Assessed buildings	% buildings D4 and D5
UWJ dataset	Aerial images + fieldwork validation in several areas	Shanty zones, Port-au-Prince municipality	40,270	23.6
		Residential low-medium-high density, Port-au-Prince municipality	50,100	25.15%
GEO-CAN	Hybrid methodology: Satellite images, field surveys, and modelled data	Whole Port-au-Prince area, 11 municipalities	298,739	19.6%
		Port-au-Prince municipality	106,902	23.5%
MTPTC (Miyamoto et al. 2011)	Fieldwork Habitability using ATC-20 assessment	Single-family	290,381	21% (red color tag)
		Multifamily	70,175	16% (red color tag)
(Cambridge Architectural Research Ltd 2010; Saito et al. 2010)	Pictometry	Downtown	199	28.2%
		Residential	308	19.15%
		Shanty	354	21.75%
EEFIT (Saito et al. 2010)	Fieldwork	8 different locations	142	46%

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165 3. Data interpretation

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167 3.1. Deducted intensity maps of Port-au-Prince following the 2010 earthquake

168 Seismic intensity for the 2010 earthquake has been characterized using very poor data. (Hough,
 169 Taniguchi, and Altidor 2012) and (Gould et al. 2011) proposed PGA and intensity values at several
 170 points in Port-au-Prince based on damage assessment of very specific structure and electrical equipment.
 171 As a consequence of this poor data, the construction of empirical vulnerability functions has to address
 172 semi-modelled intensity data, as was completed by (Ufuk Hancilar, Taucer, and Corbane 2013) who
 173 proposed empirical vulnerability functions (in PGA, PGV, and intensity) based on the USGS ShakeMap

174 for this event. ShakeMap is a calculation combining observed (seismic stations and intensities) and
 175 modelled data (ground motion prediction equation). However, the first versions of the 2010 earthquake's
 176 ShakeMap were simply a model of ground motion via attenuation relations, fitted only by several Do
 177 you feel it (DYFIT) points from web intensity forms from the USGS website. More recently, the USGS
 178 has produced a new version of the intensity and PGA ShakeMap of the 2010 Earthquake, integrating
 179 more DYFIT points than previous versions. In both cases, the intensity in the Port-au-Prince
 180 municipality was approximately VIII MMI.

181 However, as previously discussed, the damage assessment is very comprehensive and exhaustive
 182 (locating every building) in urban areas combining field surveys, aerial images and satellite information.
 183 Instead of using models to estimate macroseismic intensity such as ShakeMap fitted with several sparse
 184 observations (DYFIT), in this work we propos to obtain a high-resolution macroseismic intensity map
 185 of Port-au-Prince based on damage assessment.

186 The EMS98 scale was used in this work (Conseil de l'Europe 1998). The Port-au-Prince area (covered
 187 by the UWJ damage assessment) was divided into grid cells 500 m in length. For each cell, an intensity
 188 value was estimated based on the damaged building, the total number of buildings was counted, and
 189 their damage distribution was calculated (buildings in damage states D5, D4, D3, and no visible-slight
 190 structural damages). To be as representative as possible, cells with less than 10 buildings and cells with
 191 only completely destroyed buildings were not considered.

192 A work has been completed to clearly identify the areas where the UWJ dataset is exhaustive or not
 193 using slightly damaged buildings. In some areas, only buildings in the D4 and D5 state exist on the UWJ
 194 dataset while many more buildings occur; this means that in these areas UWJ only identified heavily
 195 damaged buildings. Regardless, this situation is quite rare within the Port-au-Prince municipality.

196 The EMS98 scale considers six vulnerability classes of buildings. Globally, all of the buildings in the
 197 area are considered as vulnerability class B (Grunthal and Levret 1998). This means that all of the
 198 buildings correspond to reinforced concrete (RC) structures with no seismic design or unreinforced
 199 masonry buildings. The most vulnerable class in EMS98 (A) does not represent the whole building
 200 typology in Haiti (no adobe or stone masonry buildings occur in Haiti). This choice has a major impact
 201 in the intensity evaluation. Consequently, the intensity was deducted as in Table 2 (Giovinazzi 2005;
 202 Milutinovic and Trendafiloski 2003). Following this table, for each regular cell, three estimations of
 203 intensity values were done, according to the three damage degrees. It is possible that two different
 204 intensities (or three) are deducted for each damage state. Intermediate values (such as 9.5) are attributed
 205 in this case.

206

207 Table 2 : Relation between damaged percentage in one cell and EMS98 intensity for buildings in
 208 vulnerability class B (Milutinovic and Trendafiloski 2003; Giovinazzi 2005)

EMS98 intensity in cell i	% of buildings in cell in D5	D4	D3
XI	>50%		
X	10-50%		
IX	0-10%	>10%	
VIII		0-10%	10-50%
VII			0-10%

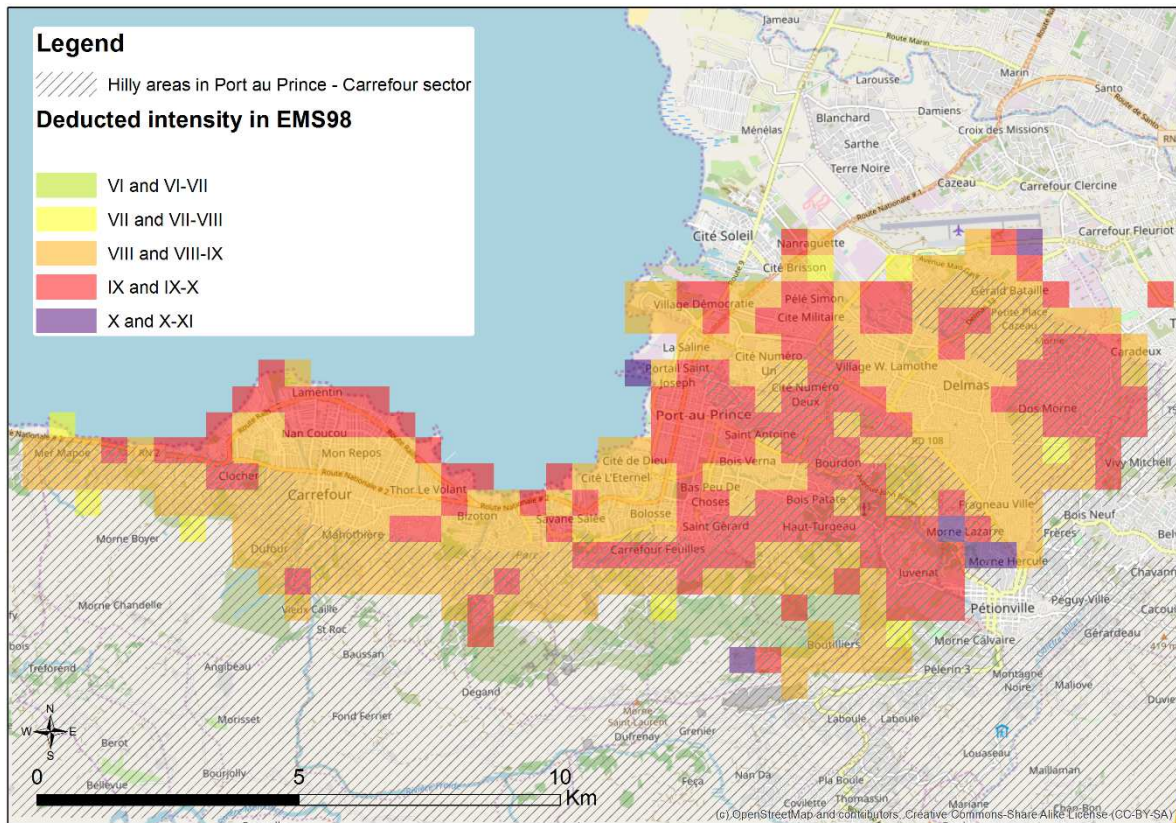
215 Figure 2 shows a close-up image of an area in Port-au-Prince, showing the damage assessment (color
 216 dots) and the estimated intensity. Regular cells where the red and garnet dots are more frequent appear

217 in intensity IX, cells where buildings in the D4 and D5 states are more scattered in intensity VIII. It is
 218 clear that for local differences in terms of damage, the distinction of one degree of intensity at this scale
 219 can be justified. The heaviest damage is more concentrated in the southern area.



220
 221 Figure 2: Close-up image of one district of Port-au-Prince. The back color represents the deduced
 222 intensity. The dots represent the damaged buildings from the UWJ dataset.

223 The obtained intensity in Carrefour, Port-au-Prince, Pétienville, and the Delmas area varies between
 224 VIII and X (Figure 3). These intensities are of the same order of magnitude of the values proposed by
 225 (Cambridge Architectural Research Ltd 2010) for Port-au-Prince (VIII-IX). The intensity evaluation
 226 completed by the USGS with the Internet forms “Do you feel it?” shows VIII at several points in the
 227 Port-au-Prince municipality and locally IX in Pétienville.



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Figure 3: Deducted intensity map, based on the building damage dataset from UWJ in the Port-au-Prince area.

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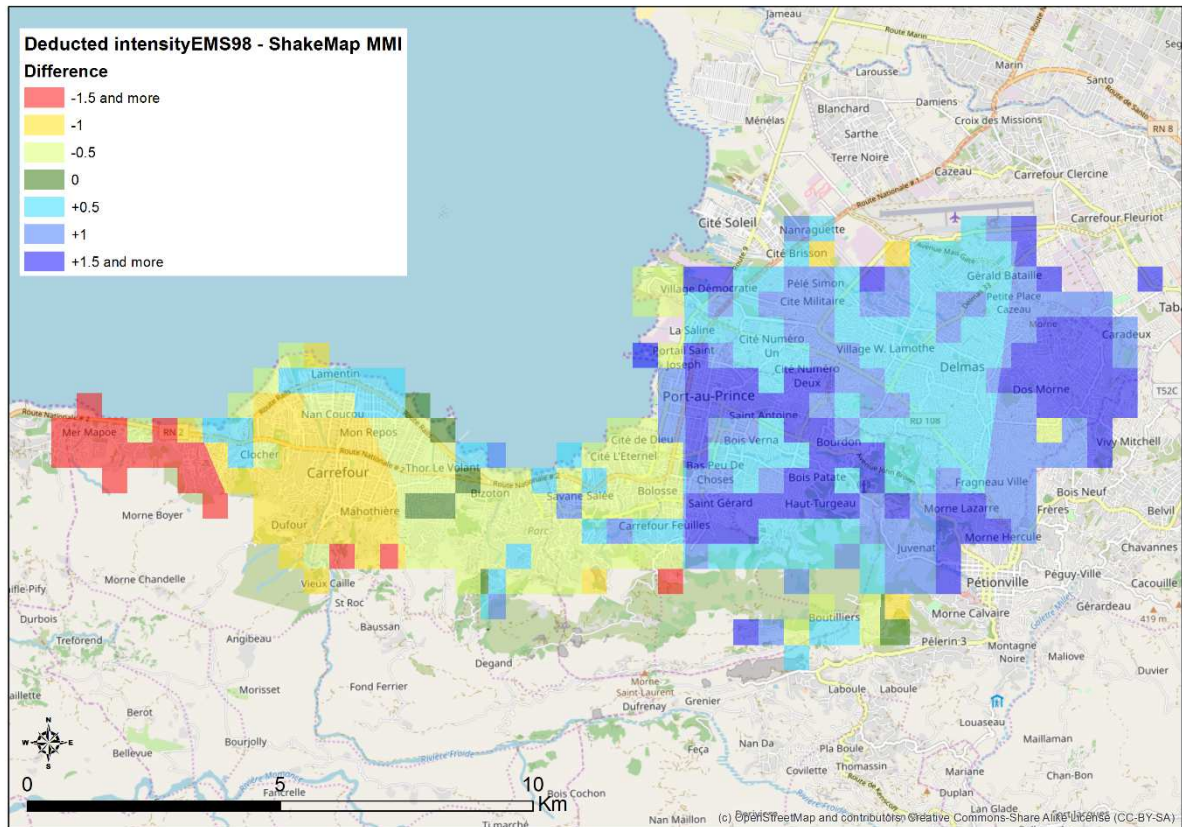
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Figure 4 shows a comparison of the obtained intensity map to the USGS ShakeMap, which is the intensity reference map for this event as discussed. Comparing the two intensity maps, the ShakeMap intensities are lower. This is because ShakeMap calculated for several hours after the mainshock for this event considering mostly ground motion attenuation (there are few seismic stations in the area) and the lithological site effects are very summarily considered. Several persons provided punctual damage observations (DYFIT) but the ShakeMap intensity map remains a map with very few/poor data in the Port-au-Prince area. The Eastern part of the studied area (Delmas, Petionville) has intensity values near VIII in ShakeMap but the damage pattern in these areas corresponds to intensity IX or more. To the West (Carrefour), closest to the epicenter, the intensity values in ShakeMap are greater than those obtained using damage. Differences could also be because of the two intensity scales, MMI and EMS98, even if several authors consider that they are equivalent (Musson, Grünthal, and Stucchi 2010). Considering a single vulnerability class, EMS98 and MMI should be close.

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Figure 4: Differences between deduced intensity and the intensity map from the USGS ShakeMap.

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3.2. Modelling the intensity using post-earthquake investigations

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USGS ShakeMap calculated the intensity map for the Port-au-Prince earthquake during the first hour and then it was updated during the following days after the main shock, integrating the very poor local observed or measured data. Many research works completed during the years after the disaster in Haiti have more knowledge in terms of characterization of the source and the site effects. Therefore, it was important to investigate what the 2010 Earthquake ShakeMap would reveal after being integrated with this new data.

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In the present work, we proposed to calculate the 2010 earthquake's intensity map integrating several investigations completed after the earthquake. The steps were as follows: i) estimation of the bedrock PGA choosing the most adequate GMPE for the Port-au-Prince earthquake, the fault location, and the most appropriate magnitude; ii) estimation of the local PGA considering the lithological site effect (microzonation, (Bertil et al. 2015)); and iii) conversion of PGA into macroseismic intensity using empirical relationships. Table 3 summarizes all these parameters.

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(Molina et al. 2014) and Torres et al. (2015) proposed the most appropriate GMPE for the Port-au-Prince earthquake (Chiou and Youngs 2008) used for rock conditions. The fault dimension and characteristics were taken from (Calais et al. 2010). Following the earthquake in Haiti, a large seismic microzonation (MZ) project was completed in in the Port-au-Prince area (Bertil et al. 2015; Belvaux et al. 2018). This project characterized and mapped the main geotechnical units in Port-au-Prince (for example, in terms of NEHRP soil classes) (BSSC 2003) as shown in Figure 5. An amplification factor NEHRP was associated with each geotechnical unit as shown in the figure. The Figure 6 presents the intensity map obtained with CY2008 MZ simulation.

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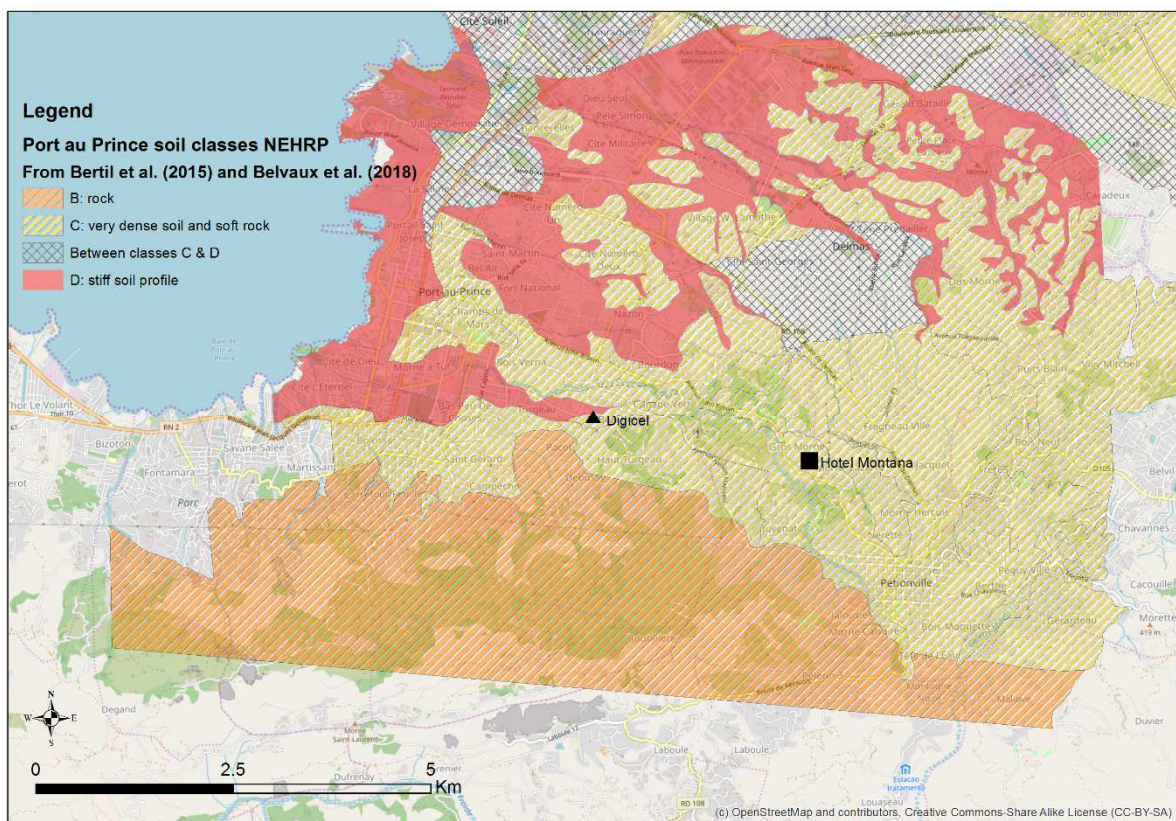
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GMPE and earthquake parameters	(Chiou and Youngs 2008) for strike slip
	Mw 7.0–7.1 (Calais et al. 2010)
	Top rupture depth 3 km
	Fault delimitation from (Calais et al. 2010)
Soil amplification map and coefficients	(Bertil et al. 2015; Belvaux et al. 2018)
PGA-intensity conversion	(Atkinson and Sonley 2000)

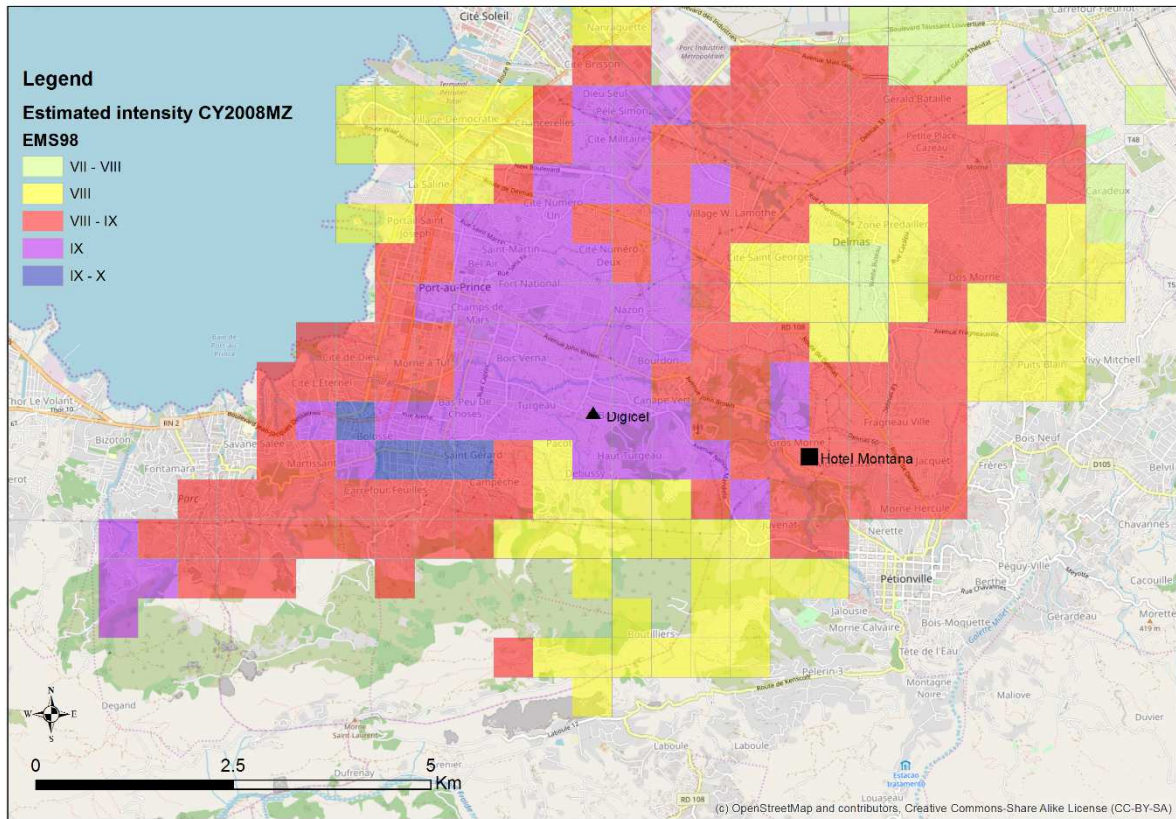
270 Table 3 : Main characteristics of the simulation termed CY2008 MZ.

271 Figure 7 shows the differences between the deduced intensity and estimated intensity (CY2008 MZ)
 272 and Figure 8 shows it in a map. In the majority of the cells the two values of intensity are equivalent,
 273 which is a positive result. In other cases, the intensity is overestimated or underestimated by ½ intensity
 274 level, which can be considered acceptable when addressing macroseismic intensity uncertainty. The
 275 CY2008 MZ simulation seems to considerably underestimate the intensity (1 intensity level or more) in
 276 several cells, mostly in the eastern part of the area. This can be explained by other phenomena not
 277 considered here, such as landslides or topographical amplification, and by the ground movement
 278 attenuation calculated by the GMPE. (Hough, Taniguchi, and Altidor 2012) showed how overestimated
 279 damage areas corresponded with topographical amplification as, for example, in the Petionville area.



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281 Figure 5: Map of lithological classification for the Port-au-Prince from microzonation (taken from
282 Bertil et al. (2015).

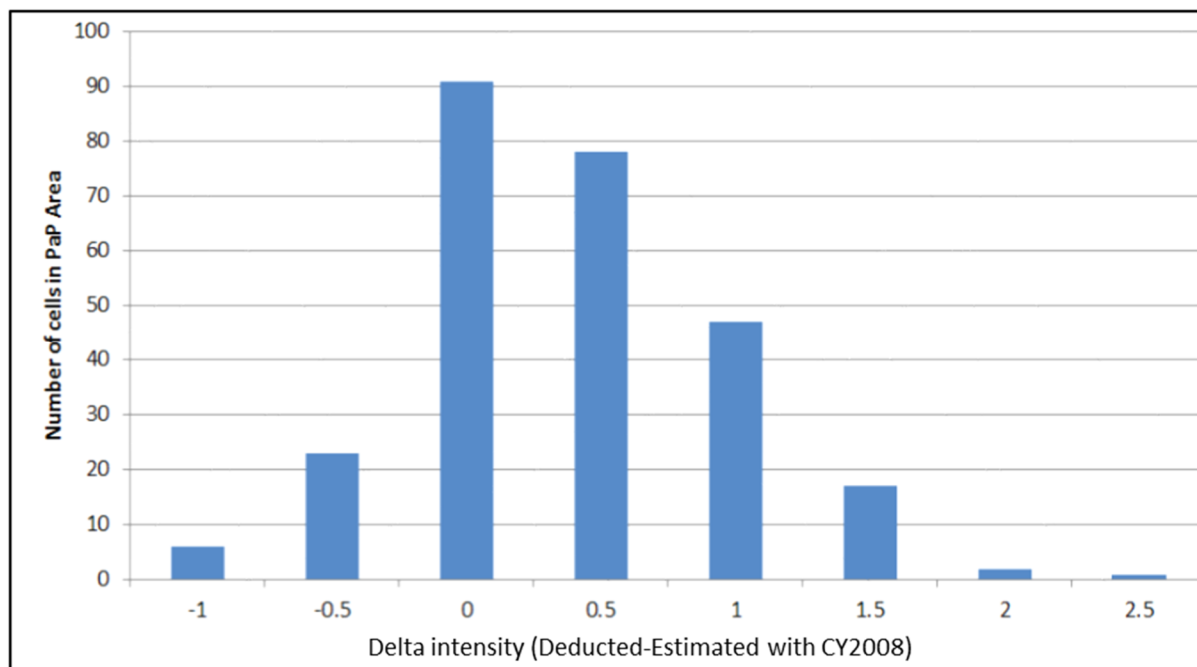


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Figure 6: Map of estimated intensity in the Port-au-Prince area using the CY2008 MZ simulation.

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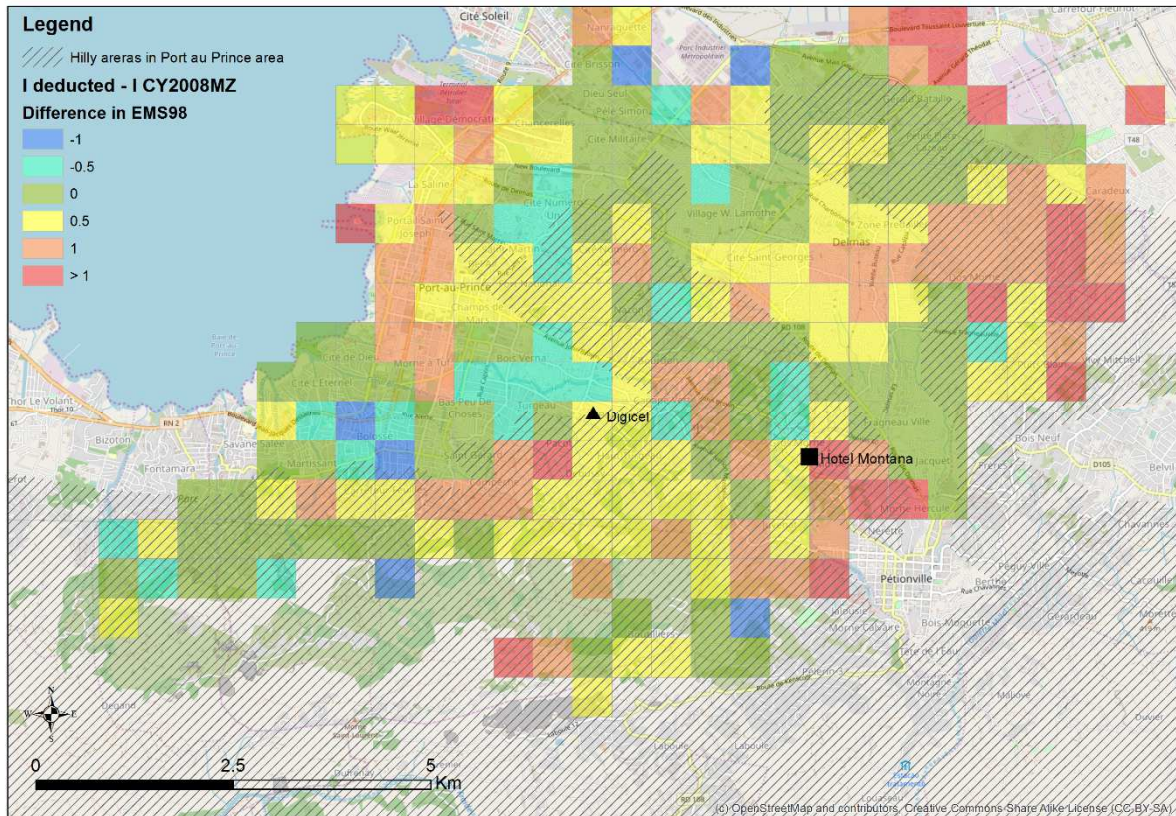


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Figure 7: Comparison between our deducted intensity and estimated with CY2008 intensity in the Port-au-Prince area.



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290 Figure 8: Map of differences (at 0.5 intensity levels) between the deduced intensity and estimated
 291 (CY2008MZ) by cell grid of 500 m in the Port-au-Prince area. Green cells correspond to equivalent
 292 values; positive values correspond to underestimation using the CY2008 MZ simulation and negative
 293 values to overestimation.

294 We attempted to compare these estimations to instrumental data, but it does not exist in the Port-au-
 295 Prince area for the 2010 mainshock. Table 4 compares our estimations to several works that attempted
 296 to deduct PGA values in the Port-au-Prince area, based on damage assessment of electrical facilities
 297 (Gould et al. 2011) or estimation from horizontal solid rigid movement (Hough, Taniguchi, and Altidor
 298 2012). At Digicel and Hotel Montana our PGA estimations seems to be consistent with their value.
 299 However, very high discrepancies appeared when looking at intensities, which may be explained by
 300 different interpretations using the MMI or EMS98 scale. In any case, the determination of intensity
 301 evaluating damage to individual structures does not seem appropriate.

302 Looking at the Hotel Montana point in more detail, (Hough et al. 2010) measured a topographical
 303 amplification factor varying between 2.3 and 2.5 with an aftershock signal. Taking this value of the
 304 topographic amplification factor, we estimated the total amplified PGA at the Hotel Montana site as the
 305 following product: PGA of bedrock * lithological amplification factor * topographical amplification
 306 factor. Then, we converted it into macroseismic intensity. We estimated a high intensity X, which fits
 307 quite well with the observed damage in the area (deducted intensity varies between IX and X). In our
 308 work, we did not characterize the topographic factor in the whole area; thus, underestimation was
 309 possible in zones with steeper slopes and hills. (Rathje et al. 2011) observes in several districts with
 310 shapes with ridges and steep valleys (Hotel Montana, Bois Patate, St Gerard) an over-damage ratio with
 311 a collapse ratio varying from 40 to 74%. Recently, (Green 2018) compares building damage dataset with
 312 a simulation of PGD amplification due to landslides and topographic factor in Port au Prince area, but
 313 he did not find a clear correlation between damages density and PGD. Unsurprisingly damages in fact
 314 are a combination of local soil factors (local site effects and landslides), topographic amplification and

315 local variations in building vulnerability. Moreover, we find “social-economic” correlations like the fact
 316 that shanty areas tends to be located in high slope zones.

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Point ID	Long/Lat	Deducted PGA (in cm/s ²)	Other source intensity	Present work		
				Deducted intensity	Calculated CY2008 PGA (cm/s ²)	Calculated CY2008 Intensity
Hotel Montana sector (hill)	-72.297/ 18.527	440 ¹	VIII ¹	IX-X	400 (1000 with topographical factor)	VIII-IX (X considering topographical factor)
Digicel (foothill)	-72.3232/ 18.5327	300-470 ^{2,3}	VIII ²	IX-X	470	IX
HVCV – Canapé Vert (foothill)		300-700 ³	VIII ³	IX-X	425	VIII-IX
HBME – Delmas (South airport), (flat sector)		150-350 ³	VIII ¹ , V-VI ³	VIII-IX	370	VIII-IX
HCEA-Laboule (South Port-au-Prince), reference aftershock station		80-190 ³	VIII ¹	VIII	300	VIII

318 Table 4: Comparison of deducted PGA and intensity at several points in Port-au-Prince with deducted
 319 and calculated PGA and intensity in the present work. Data sources include 1) USGS ShakeMaps
 320 (<http://earthquake.usgs.gov/earthquakes/ShakeMap/global/shake/2010rja6/download/stationlist.xml>), 2) Goodno et al.
 321 (2011), and 3) Hough et al. (2012).

322

323 3.3. Data interpretation - Empirical vulnerability curves

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325 The UWJ dataset has only damaged buildings in areas exposed to higher levels of seismic
 326 intensity (>VII-VIII) after the 2010 event. In this work, we attempted to find additional building
 327 damage in other earthquakes in the same regional context. The previous largest earthquake on
 328 La Hispaniola Island was in 2003, in the north-central part of La Hispaniola near Puerto Plata
 329 (Dominican Republic), a Mw 6.5 earthquake, killing 2 persons and injuring 98. USGS
 330 Shakemaps estimates its intensity around VI-VII in Puerto Plata city and V-VI in Santiago de
 331 los Caballeros city. The Dominican authorities (seismic vulnerability reduction agency,
 332 ONESVIE) provided us the location of the heaviest damage and the characteristics of the
 333 damaged buildings (8 in D5, 14 in D4, 24 in D3), in addition to the observations in situ from
 334 (Lopez Rodriguez and Martinez Cruzado 2003). The total number of buildings in the impacted
 335 area, and the total number of undamaged buildings, is unknown; however, the Dominican Stat
 336 Data office (ONE) for the 2010 census estimated more than 200,000 dwellings in the impacted
 337 area (municipalities near Puerto Plata in addition to Santiago de los Caballeros). Consequently,

338 we imagined that many buildings were undamaged or had no reported damage (D0-D1), even
 339 D2. Heavy damages were not enough significant in number. It is difficult to estimate a damage
 340 assessment for this event with this partial dataset.

341 With UWJ catalog, using the equation 1, we calculate the mean damage grade “ μ_d ” for
 342 ShakeMap intensity intervals. Equation 2 is used for calculating the standard deviation, which
 343 added or subtracted form mean damage grade. The results are shown on Table 5.

$$344 \quad \mu_D = \sum_{k=0}^5 p_k * k \quad 0 < \mu_D < 5 \quad (1)$$

$$345 \quad \sigma_D = \sqrt{\mu_D \left(1 - \frac{\mu_D}{5}\right)} \quad (2)$$

346 Once the mean damage grades are calculated using the above equation, we are fitting a set of
 347 curves in which beside the intensity and the mean damage grade we are adding the vulnerability
 348 index parameter, as presented in equation 3. This equation was developed and used in the
 349 framework of FP5 RISK-UE project ((Milutinovic and Trendafiloski 2003) and considers the
 350 vulnerability index as follows:

$$351 \quad \mu_D = 2.5 \left[1 + \tanh\left(\frac{I + 6.25V - 12.8}{2.1}\right) \right] \quad (3)$$

352

Intensity (ShakeMaps)	UWJ Damage building distribution (in ratio)					μ_d	σ	$\mu_d + \sigma$	$\mu_d - \sigma$
	D1	D2	D3	D4	D5				
8	0.55	0.21	0.05	0.07	0.12	2.01	1.10	3.11	0.92
8.5	0.73	0.00	0.05	0.11	0.11	1.88	1.08	2.97	0.80
9	0.71	0.12	0.05	0.06	0.06	1.65	1.05	2.70	0.60
9.5	0.49	0.26	0.10	0.07	0.08	2.00	1.10	3.10	0.91

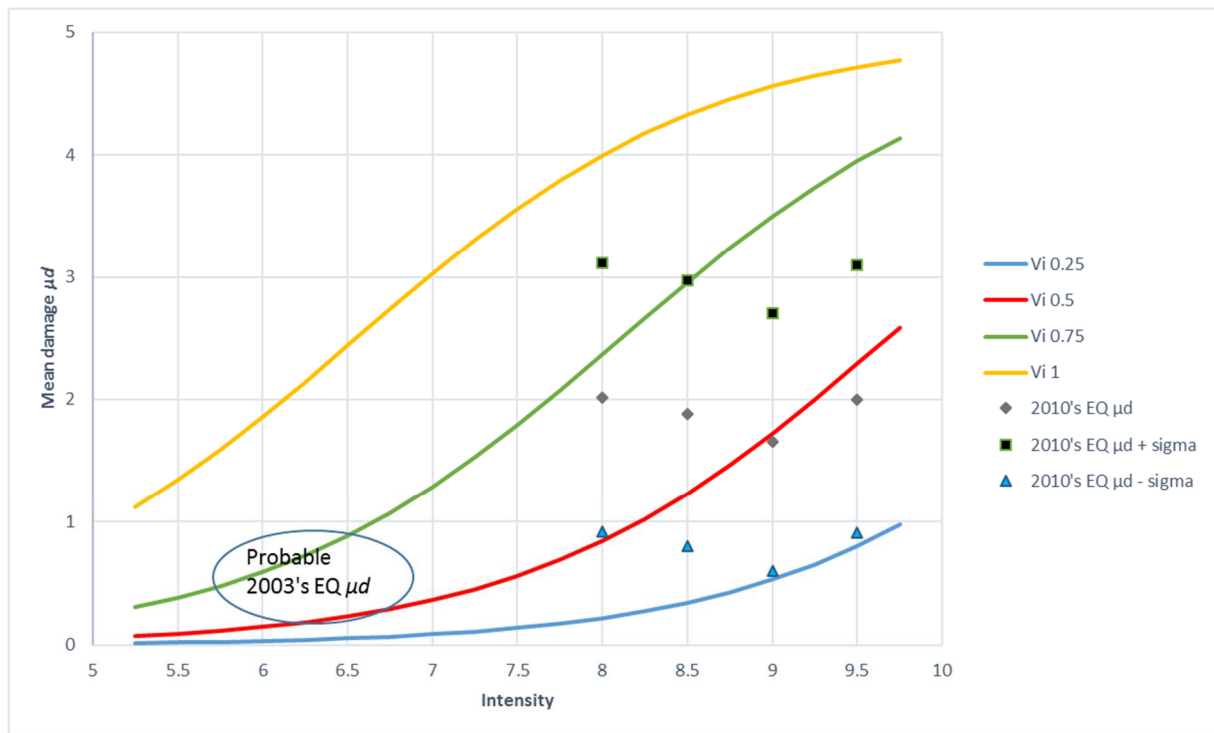
353

354 Table 5: Field investigation data coming from UWJ catalog combined with ShakeMap intensity values
 355 for January 12, 2010 Haiti earthquake. Calculation of mean damage grades and standard deviation.

356 The fragility curves based on 4 values of vulnerability index following the RISK-UE
 357 methodology are compared with mean damage from 2010’s (Table 5) and 2003’s earthquakes
 358 in Figure 9. Surprisingly mean damage μ_d do not increases when ShakeMap intensity increases.
 359 As discussed in the previous sections, this can be due to accuracy of ShakeMap intensity at this
 360 scale of work. It seems that there is no a clear spatial correlation between damages and intensity
 361 from ShakeMap.

362

363



364

365 Figure 9: fragility curves based on RISK-UE indexes and mean damage for 2010's Earthquake. The
 366 probable, but not calculated, mean damage for 2003's earthquake is shown.

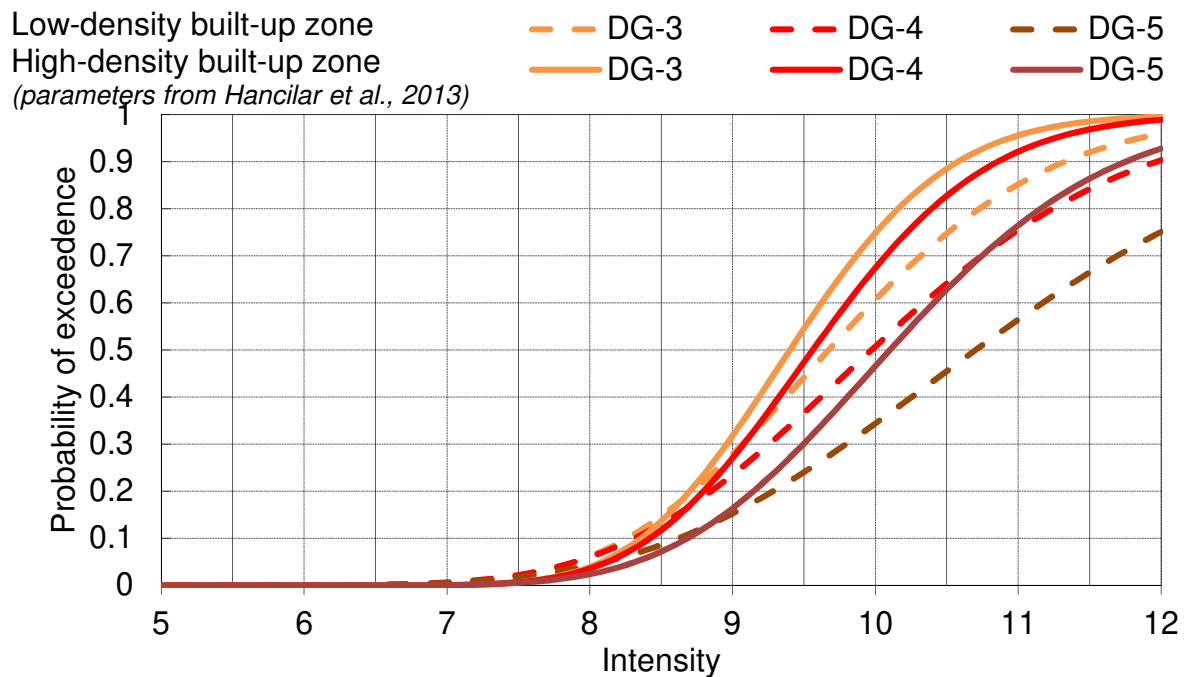
367 Discrepancies can also come from UWJ catalog. UWJ dataset were obtained using remote
 368 sensing techniques and present an inventory of a large number of buildings (299,257) which is,
 369 generally, very useful for statistical analysis. The downside of these types of methods is that
 370 the detection of the damage degree is difficult. Indeed, the damage degree that represents large
 371 deformation of the structure is well identified (D4 and D5), but the intermediary damage
 372 degrees that represent small deformation structural damage (D3) and/or non-structural damage
 373 (D1 and D2) are quite difficult to observe. For the intensity equal or exceeding VII-VIII more
 374 than 60% of buildings showed no visual damage D1 (Table 5). This value surely cannot
 375 represent the reality.

376 (Ufuk Hancilar, Taucer, and Corbane 2013) works with the UWJ dataset and combines it with
 377 ShakeMap intensity in order to produce vulnerability functions. The first family of curves were
 378 given by built areas density (Figure 10). As it can be seen, they had to manage with a catalog
 379 poor damage data in low-moderate intensities (\leq VII). If this task of the completeness of the
 380 data for the small intensity values is not performed, the fragility curves obtained show poor
 381 results, as for example only 5% damaged structures (D3) for an intensity equal to VIII (Figure
 382 10). In this case, for construction of reliable fragility curves, the observational data should be
 383 numerically completed, for the lower intensity values.

384 The remote sensing observational data of damages after an earthquake do not discriminate the
 385 structural type, but they are considering the level of density of considered area (e.g. Low-
 386 density built-up zone, Medium-density built-up zone ...). Therefore, in order to have
 387 information about the structural type, the huge amount of remote sensing data has to be coupled
 388 with others type of data, like field observations. (Ufuk Hancilar, Taucer, and Corbane 2013)
 389 have done an important work in which the main purpose of the targeted field campaign was to
 390 validate the remote sensing based damage assessment. Using the parameters (median and

391 lognormal standard deviation) from the study of (Ufuk Hancilar, Taucer, and Corbane 2013),
 392 Figure 10 presents the comparative fragility curves derived by the sub-sets of remote sensing
 393 for low-density built-up zone and for high-density built-up zone. Only the damages degrees
 394 D3, D4 and D5 were considered and the aggregation of D2 and D1, as well as no damage (D0),
 395 into one category was considered, since that for these classes, there is no visible damage in
 396 remote sensing based assessment. As observed in the Figure 10, the ground motion intensities
 397 for buildings in the remote sensing dataset range between 7.4–9.8

398



399

400 Figure 10: Fragility curves based on remote sensing observations for high-density and low-density
 401 built-up zone (median and standard deviation parameters form Hancilar et al., 2013)

402

403 For a damage scenario, we need to complete these range of intensities with the intensities
 404 inferior to 7.4. In the next step, we are trying to calibrate these curves to the manner of
 405 description of the fragility curves proposed by the RISK-UE methodology. To take advantage
 406 of the remote sensing observations for the extensive damage degrees and to improve or calibrate
 407 them for a lower damage degree we plotted these data and literature-equivalent data against
 408 intensity value (Figure 11 to Figure 14).

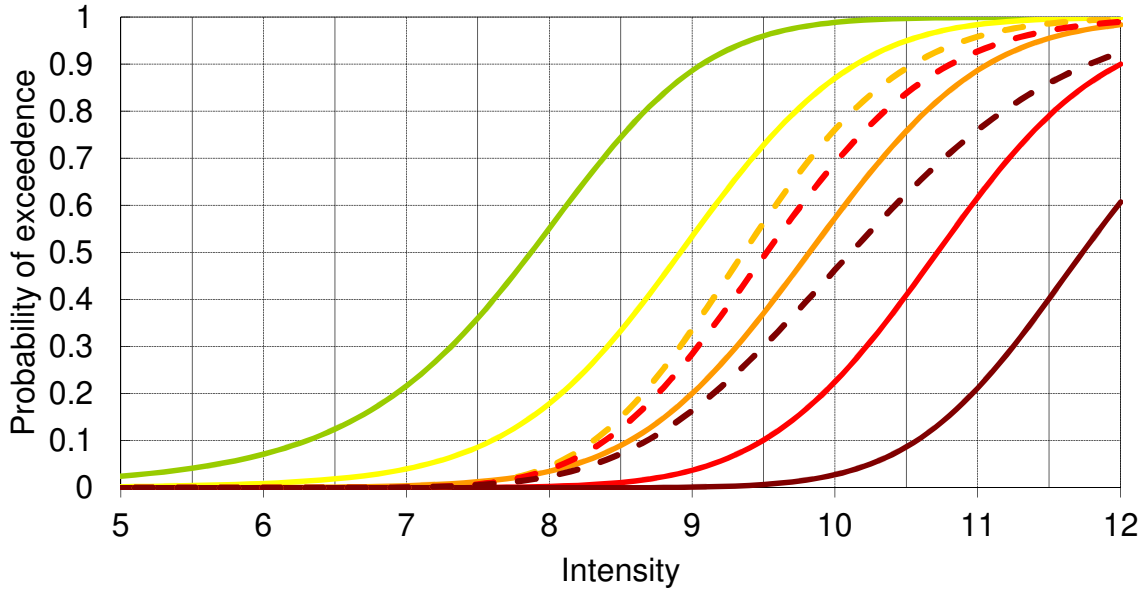
409

410 Figure 11 shows the curves based on the Haiti observed data (dashed lines) for high-density
 411 built-up zone and the curves calculated based on the RISK-UE methodology for a vulnerability
 412 index of $V_i=0.522$, which corresponded to the most vulnerable Concrete Moment Frame
 413 typology. Figure 12 uses a vulnerability index of $V_i=0.672$ considering the previous value and
 414 a supplementary vulnerability factor because of the pre- or low-code construction period
 415 (+0.16) as described in the RISK-UE methodology.

416

Previous data, $V_i=0.522$:
 Haiti observations (broken line):

— D1 — D2 — D3 — D4
 — D5 - - DG-3 - - DG-4 - - DG-5



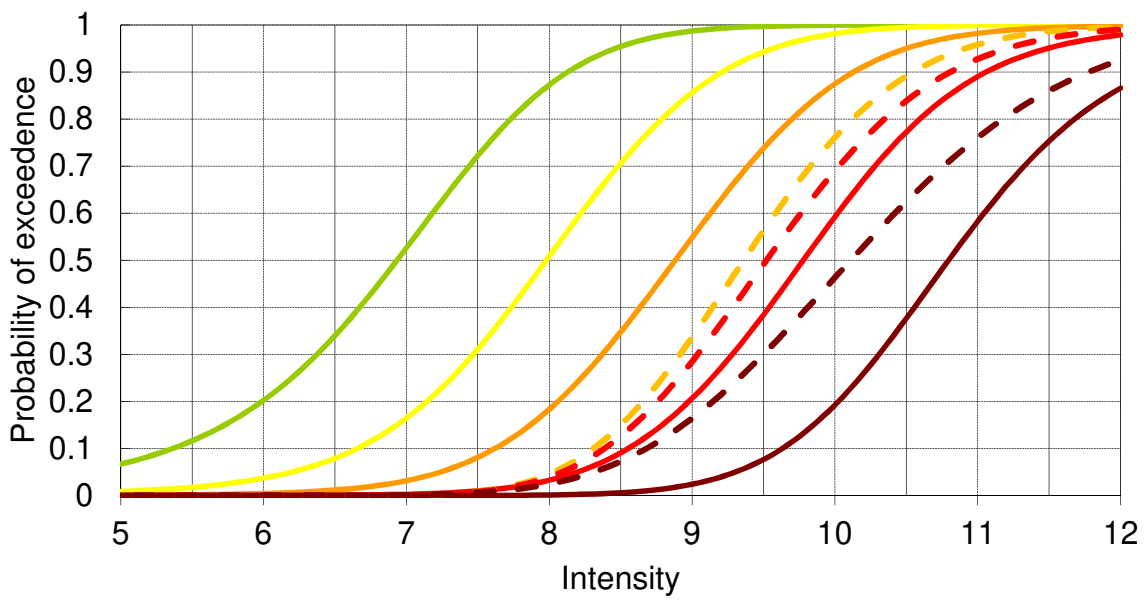
417
 418
 419
 420

Figure 11: Fragility curves based on damage observations and comparison to the RISK-UE ($V_i=0.522$).

421 It is apparent that the difference between the D4 and D5 curves is not as important, particularly
 422 for $V_i=0.672$. This seems realistic because it can be considered without much error, that the
 423 same typology of structure is more vulnerable in Haiti than in Europe from a construction
 424 practice point of view. Therefore, the higher probability of having D4 and D5 using the remote
 425 sensing data is useful to adapt the fragility curves to regional construction.

Previous data, $V_i=0.672$:
 Haiti observations (broken line):

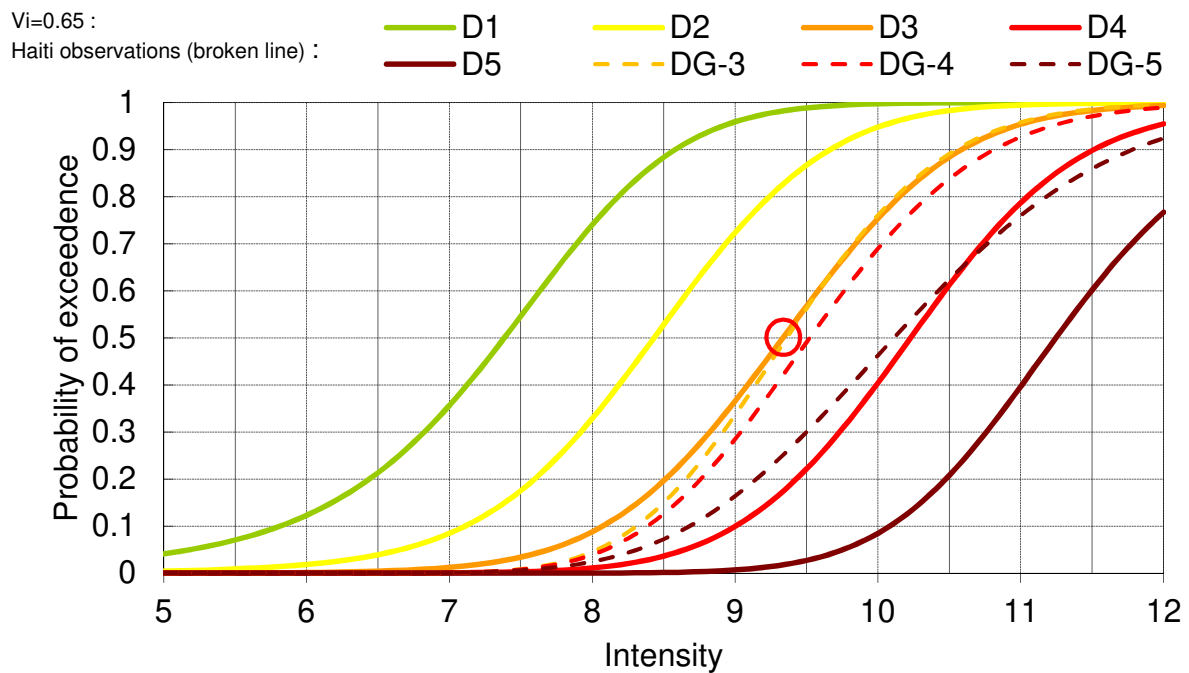
— D1 — D2 — D3 — D4
 — D5 - - DG-3 - - DG-4 - - DG-5



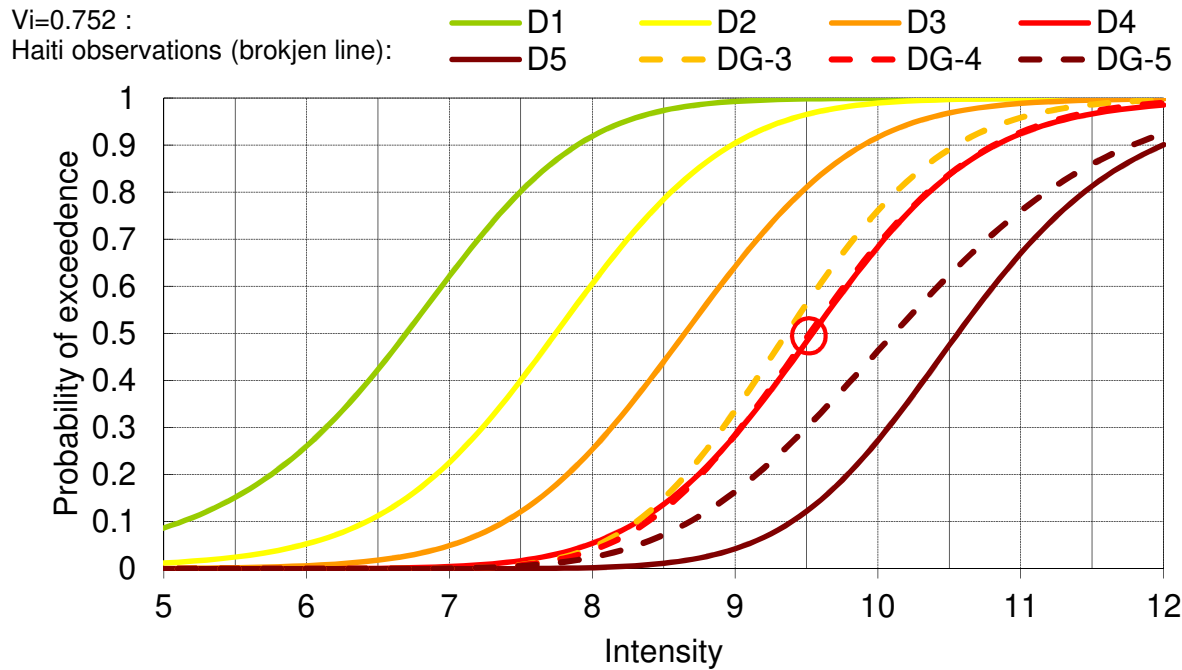
426
 427
 428

Figure 12: Fragility curves based on damage observations and comparison to the RISK-UE ($V_i=0.672$).

429 Figure 13 and Figure 14 show the coefficient that can be used if we want to "calibrate" the
 430 existing empirical fragility curves to those obtained using the remote sensing observation after
 431 the earthquake event. This "shift/calibration" is necessary for areas in which the regional
 432 context for building is unknown, and hence we are obliged to adapt exiting curves derived from
 433 other regional areas, but also for the data coming only from the remote sensing services. (Ufuk
 434 Hancilar, Taucer, and Corbane 2013) said that the omission errors (e.g. number of buildings
 435 omitted from a damage state by remote sensing assessment as a percentage of the total number
 436 of buildings assigned to that damage state by field observations) for damage grades DG-0-1-2,
 437 DG-3, DG-4, and DG-5 were 26%, 94%, 70%, and 53%, respectively. This suggests that there
 438 is high discrepancy between field and remote sensing data, particularly for DG-3 and DG-4,
 439 and even for DG-5. Hence, Figure 13 propose a "calibration factor" relative to the damage
 440 degree D3 and Figure 14 relative to the damage degree D4. In order to calculate the value of
 441 the "calibration factor", we try to superpose the respective fragility curve (D3 or D4) coming
 442 from the remote sensing with the one coming from the RISK-UE methodology, by considering
 443 that the 50% of probability of exceedance is the same for both curve (red round in Figure 13
 444 and 14). That "calibration factor" shifts all the set of the fragility curves to the right or to the
 445 left, which mean that only the fragility curves of the targeted damage degree (D3 or D4) will
 446 be superposed, and the other fragility curves will cover all the range of the intensities.
 447
 448



449
 450 Figure 12: Fragility curves based on remote sensing observations and comparison to the RISK-UE
 451 fragility curves (vulnerability index $V_i=0.522$ and correction factor of 0.128) for calibration of the
 452 median value of the D3 damage degree.
 453



454

455 Figure 13: Fragility curves based on remote sensing observations and comparison to the RISK-UE
 456 (vulnerability index $V_i=0.522$ and correction factor of 0.23) for calibration on the median value of the
 457 D4 damage degree.

458

459

460 4. Damage scenario

461

462 Several post-earthquake damage scenarios have been completed using the Armagedom software (Sedan
 463 et al. 2013). This software computes damage using the RISK-UE methodology of level 1 (Milutinovic
 464 and Trendafiloski 2003; Lagomarsino and Giovinazzi 2006) and vulnerability indexes and macroseismic
 465 intensity as input.

466 We only calculated post-earthquake damage scenarios for the Port-au-Prince municipality. The
 467 distribution of buildings types in the 36 districts in Port-au-Prince was provided by (Benito et al. 2012)
 468 (Figure 15). They distinguished all residential buildings of six building types, which were associated
 469 with the building types from (Lagomarsino and Giovinazzi 2006) termed L&G. The most frequent
 470 building type was RCCB, which has reinforced concrete frames with masonry infill walls. Nearly 60%
 471 of the buildings in each district were in this category. The most important differences in terms of building
 472 types among the districts appears in the presence or absence of reinforced concrete shear-walls (RCSW),
 473 unreinforced masonry (URM), and confined masonry (RLBM).

474 Some authors have worked on capacity curves and fit them to Haitian building stock (Molina et al. 2014;
 475 Torres et al. 2016); in the present work, addressing deducted or observed intensities, we proposed to
 476 calculate damage scenarios based on vulnerability indexes.

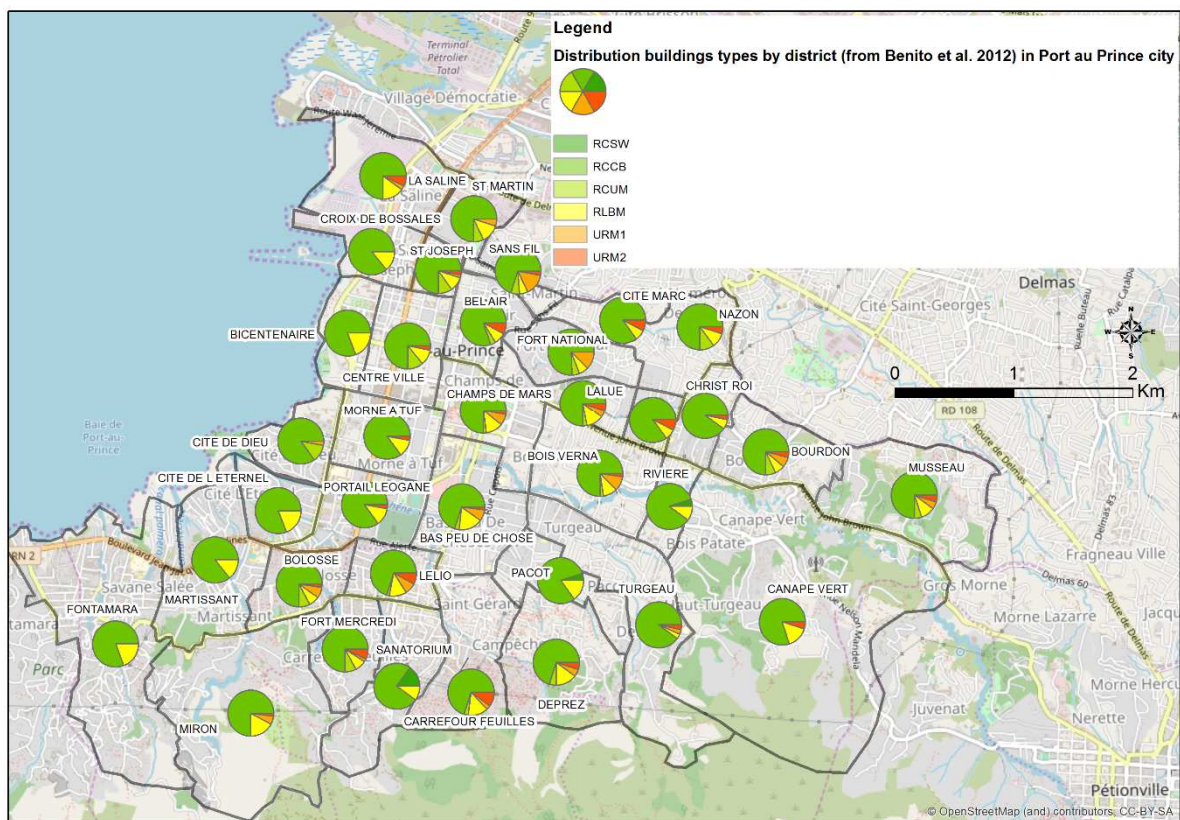
477 Based on the aforementioned relation between the Haitian building types and L&G types, we proposed
 478 to use two sets of L&G vulnerability indexes. The first set considers vulnerability indexes from L&G
 479 and adds +0.08 as an aggravation factor for no seismic code cases. The second set adds +0.16, as a
 480 “regional correction.” These correction values are those proposed usually when using RISK-UE

481 methodology to assess current building vulnerability ((Lagomarsino and Giovinazzi 2006; Milutinovic
 482 and Trendafiloski 2003)

483 As previously shown in Figures 11 to 13 vulnerability indexes between 0.6 and 0.75 fit quite well with
 484 empirical functions if looking only at very heavy damage (D4) and to the intermediate damage degree
 485 if a shift-correction factor to the D3 damage degree is applied.

486 Table 7 presents the six scenarios' main characteristics. Two parameters change, the two sets of
 487 vulnerability indexes and three seismic intensity maps: the USGS ShakeMap, intensity CY2008, and
 488 deducted intensity map obtained using the interpretation of damage of the UWJ dataset. The flowchart
 489 in the Figure 16 shows the relation between the different datasets and data sources used, calculated or
 490 estimated in the present work.

491
 492
 493



494
 495 Figure 15: Distribution of building types by district in the Port-au-Prince municipality. Taken from
 496 Benito et al. (2012).

497

Building type (Torres et al. 2016)	Type L&G	Description	Vi L&G + 0.08 (no code)	Vi L&G + 0.08 (no code) + 0.08 (regional correction)

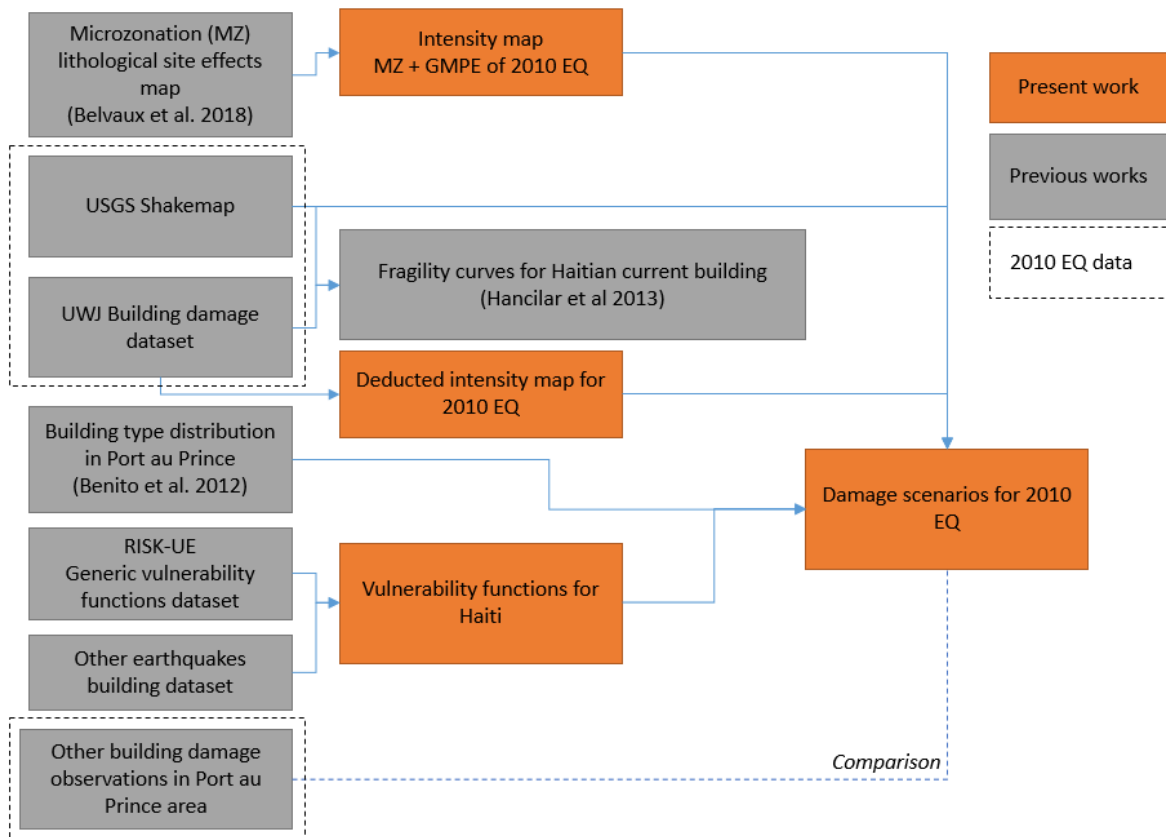
RCSW	RC2-1	Reinforced concrete shear walls, without code and poor maintenance	0.62	0.7
RCCB	RC1-1	Reinforced concrete frames – masonry infill walls, without code and poor maintenance	0.72	0.8
RCUM	RC1-1	Reinforced concrete frames – masonry infill walls, without code and poor maintenance	0.72	0.8
RLBM	M7 precode	Confined/reinforced masonry, poor maintenance, poor connection roof/walls	0.53	0.61
URM1	M6 precode	Unreinforced masonry concrete slabs, poor maintenance, poor connection roof/walls	0.696	0.776
URM2	M5 precode	Unreinforced masonry – wooden frames, poor maintenance, poor connection roof/walls	0.82	0.9

498 Table 6: RISK-UE vulnerability indexes for the main building types in Port-au-Prince.

499

Scenario	Seismic intensity input	Vulnerability distribution
SC1	CY2008	Benito et al. 2012 building types distribution
SC2	USGS ShakeMap	
SC3	Local intensity deducted from JRC catalog	Lagomarsino and Giovinazzi (2006) V_i + aggravant factor 0.08
SC4	CY2008	Benito et al. 2012 building types distribution
SC5	USGS ShakeMap	
SC6	Local intensity deducted from JRC catalog	Lagomarsino and Giovinazzi (2006) V_i + aggravant factor 0.16

500 Table 7 : Main characteristics of damage scenarios in terms of seismic intensity input and vulnerability
501 distribution.



502

503 Figure 16: flowchart showing the relation between the different data sources used in the present work.

504 5. Discussion

505

506 Table 8 show the results of the six damage scenarios, in terms of % and number of buildings in the D3,
 507 D4 and D5 damage states, in addition to the values of the UWJ dataset in the Port-au-Prince
 508 municipality. Results show the great influence of vulnerability functions and confirms that the global
 509 building stock in Port-au-Prince was very vulnerable. The damage scenarios' estimated number of
 510 buildings in the D3 damage state is very high when compared to that of the UWJ dataset. Moderate
 511 damage states are difficult to evaluate using only aerial images. Some authors (Saito et al. 2010), with
 512 a very limited field survey dataset, have estimated that heavy damage reached 46% in Port-au-Prince,
 513 whereas the Pictometry or aerial image estimates between 20 and 30%. We can interpret this as many
 514 buildings tagged as D3 in the UWJ dataset are in reality D4 or D5. More pessimistic vulnerability values
 515 (SC4 to SC6) gives strong damage ratios, only comparable with (Saito et al. 2010) observations. Results
 516 from SC1 to SC3 vulnerability values corresponds quite well with other observations datasets (GEO-
 517 CAN, Pictometry, MTPTC). Maybe these values are those the most appropriated for Haiti building
 518 stock.

519 Results obtained using the initial ShakeMaps (SC2 and SC5) underestimated heavy damage because
 520 ShakeMaps estimates mainly an intensity VIII in Port-au-Prince, which is, in our opinion, an
 521 underestimation of the intensity by one level as discussed previously. Increasing the intensity respect
 522 ShakeMaps, the important damages (the sum of D3, D4 and D5) are greater, differing heavily with UWJ
 523 dataset. We cannot reproduce the low value of buildings in D3. This kind of situation could correspond
 524 to a situation with two families of buildings in Port au Prince, very vulnerable and very low vulnerable,
 525 but field reports did not notice the existence of an important group of low vulnerable buildings, so we
 526 do not consider this option.

Scenario	% D3	% D4	% D5	ND3	ND4	ND5
SC1	29.4%	17.8%	3.6%	27516	16610	3349
SC2	27.5%	12.0%	1.3%	25718	11166	1238
SC3	30.0%	22.4%	6.4%	28001	20895	5947
SC4	30.9%	27.3%	9.4%	28901	25531	8808
SC5	32.8%	22.2%	4.4%	30656	20719	4153
SC6	28.9%	30.4%	14.6%	27001	28431	13685
Observed UWJ (buildings tagged “Port- au-Prince” municipality in dataset)	5.6%	11.67%	12.58%	5230	10801	11633
GEO-CAN		23.5%				
MTPTC		16-21%				
EEFIT		46%				
Pictometry		19-28%				

528

Table 8: Results of post-earthquake damage scenarios.

529

6. Conclusions

530

531 The seismic intensity is extremely important when constructing empirical fragility functions for
532 buildings. In the Port-au-Prince earthquake, instrumental data was so poor or nonexistent that seismic
533 intensity considered in empirical damage functions was mostly from simulations and models. For
534 earthquakes in developing countries with a very low density of seismological stations, tools such as
535 USGS ShakeMaps are of great importance in the minutes, hours, and days after the earthquake.
536 However, in these cases, ShakeMaps is not the definitive version of “what happened,” because it heavily
537 depends on first parameter estimation. It is also important to consider the representativeness of less
538 damaged areas and complete the building damage dataset in these areas (intensities VI or VII, for
539 example). If nothing else, empirical damage functions could appear too “vertical,” passing very quickly
540 from no-damage to strong-damage.

541 Exhaustive building damage datasets are a tool and set of data suitable for many applications. In the
542 case of Haiti, several datasets exist, collected by a multitude of actors and organizations that collaborated
543 to build them. Even though the damage datasets such as UWJ are incomplete, they are still the most
544 exhaustive, but do not describe the reality, mostly in terms of moderate state damage, which is very
545 difficult or impossible to identify using aerial/satellite imagery. Even with field survey controls, many
546 authors have highlighted this risk of underestimation. However, this dataset remains a reference.

547 A huge building damage database permits one to map damage and consequently macroseismic intensity
548 at a very small scale (in our work 500-m cells) based on EMS98 damage-intensity conversion criteria.
549 The basis of this work was to consider the intensity statistically representative of an area, and not based
550 on only punctual observations. This intensity map, called “deducted intensity,” corresponds quite well
551 with the perceived intensity (MMI=IX (Cambridge Architectural Research Ltd 2010)). In any case, in
552 the Port-au-Prince area, one can see strong damage variations, which induces strong intensity
553 differences. In our opinion, global building vulnerability is quite constant (without strong spatial
554 disparities) and consequently intensity variation should be to the result of other factors: lithological or
555 topographical site effects, landslides, and attenuation of ground motion at a Port-au-Prince scale. Based
556 on the seismic microzonation completed in Port-au-Prince (Bertil et al. 2015; Belvaux et al. 2018) we

557 attempted to match the deducted intensity map with a classical approach to estimate intensity
558 (calculation of PGA by GMPE, consideration of microzonation and lithological amplification, and
559 conversion in intensity). In a large number of cells, the estimated intensity fits the deducted. In another
560 important number of cells, the deducted intensity is higher than that estimated (perhaps because of
561 topographic effects).

562 Finally, we calculated seismic damage scenarios for the Port-au-Prince municipality using the RISK-
563 UE method of vulnerability indexes, adapting the indexes to the Haitian context and previous works in
564 terms of vulnerability assessment of the current Haitian buildings. First, the results of the damage
565 scenarios show the great influence of vulnerability functions and confirms that the global building stock
566 in Port-au-Prince was very vulnerable. Second, intensity maps also have a strong influence; during the
567 first hours ShakeMap, for example, underestimated the damage. Post-earthquake investigations obtain
568 elements to understand the high damage level in Port-au-Prince. In addition, damage scenarios cannot
569 reproduce the situation of many buildings with heavy damage (D4 and D5), only a few buildings with
570 moderate damage (D3), and many buildings with minor/no damage. Is the building damage dataset
571 exhaustive for moderate damage? We do not believe so. Even if the damage scenarios are not at all the
572 damage reality, some damage scenario results are nearer to those of several observers, aerial/satellite
573 datasets that still underestimate moderate/heavy damage. Remote sensing images combined with aerial
574 or semi aerial images (such as Pictometry) are a precious tool for the first trends of damage and in prior
575 damaged areas, but field survey control is necessary for moderately damaged buildings. In the case of
576 Haiti, but probably in many other cases, it would be better to combine in the same dataset the UWJ data
577 (mostly from satellite-aerial assessment) with the habitability assessment from the MTPC dataset.

578

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588

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