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PROJECTING CATASTROPHIC LOSSES IN A MULTI-HAZARD ENVIRONMENT

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Abstract. Event-based scenarios present a valuable tool in calibrating and refining all elements of loss estimation and visualization. The visualization concept is especially important to the decision makers, affording them an understanding of inventory, hazard, and vulnerability functions. Using the city of Mayaguez in the western part of Puerto Rico as a test bed, building inventories are developed to represent some 33 urbanizations and more than 60 years of construction. Assimilating the outcome from the analysis tools, retrofitting measures, and uncertainty modeling, seismic and hurricane wind fragilities are quantified. Long term projections based on the maximum probable loss analysis are also reported. The changes in existing vulnerability functions are examined to reflect differences in the building types and construction practice.

1 INTRODUCTION

Although the Mayaguez earthquake of 1918 was the last major earthquake in Puerto Rico, geologists have warned for years that potentially devastating earthquakes are just around the corner. In fact, there have been no less than thirteen major earthquakes in the recorded history of the Island. Calculated probabilities for an earthquake of strong intensity (Intensity VII or more in the Modified Mercalli scale) over a period of 50 years stand at 33 to 50 percent (McCann 1985). On the other hand, since the second half of the nineteenth century, the Puerto Rico has been hit by a total of 15 hurricanes and 14 tropical storms. This will amount to approximately one every 5.5 years. Of these, five have been category III or higher hurricanes. The most expensive hurricane in the history of Puerto Rico was Hurricane Georges of September 22, 1998. The total losses are estimated at over 4 billion US dollars.

While most of the risk assessments are focused on selected single hazards, this work presents an integrated multi-hazard risk assessment of the city of Mayagüez. This approach has several benefits because different hazards affect different building types and different geographic zones.

Multi-hazard loss estimation studies serve several purposes, prominent amongst which is the design of insurance policies and reinsurance decisions. In traditional insurance models, losses are predicted using recent past experience and limited data. This is ineffective in dealing with low frequency, high severity catastrophic losses and produce sharp periodic jumps in premiums. Catastrophe models take a long term view using scientific models and can potentially result in relatively stable premiums. Loss estimation is also of vital importance to municipal and national authorities in order to prepare emergency response and disaster recovery plans and natural hazard risk mitigation strategies. Such strategies include the development of design codes and systematic retrofit to the existing building stock.

2 OVERVIEW OF THE RISK ASSESSMENT METHODOLOGY

The framework of the methodology used in this work includes the four major modules shown (Figure 1): Hazard module, Exposure module (or input module), Vulnerability module and Loss estimation module. This scheme is suitable to fit the two hazards considered here without modifications.

The exposure is the group of the insured systems and structures. This module is the base for the data collection to develop city inventories, and it feeds to the other three modules that represent the engine of the catastrophe model. These three engine modules are interdependent to each other with the output of a module acting as input of the other one.

The Hazard module determines the hazard of each event at each location. The hazard is the consequence of the event that causes damage (for a hurricane it is the wind at ground level, for an earthquake the ground shaking).

Vulnerability is the fragility or the damageability of the buildings. This module provides the damage estimates to a particular system or structure resulting from exposure to a given hazard.

Finally, in the Loss Estimation module the damages obtained from the vulnerability module are associated to the repair cost and the risk is presented.

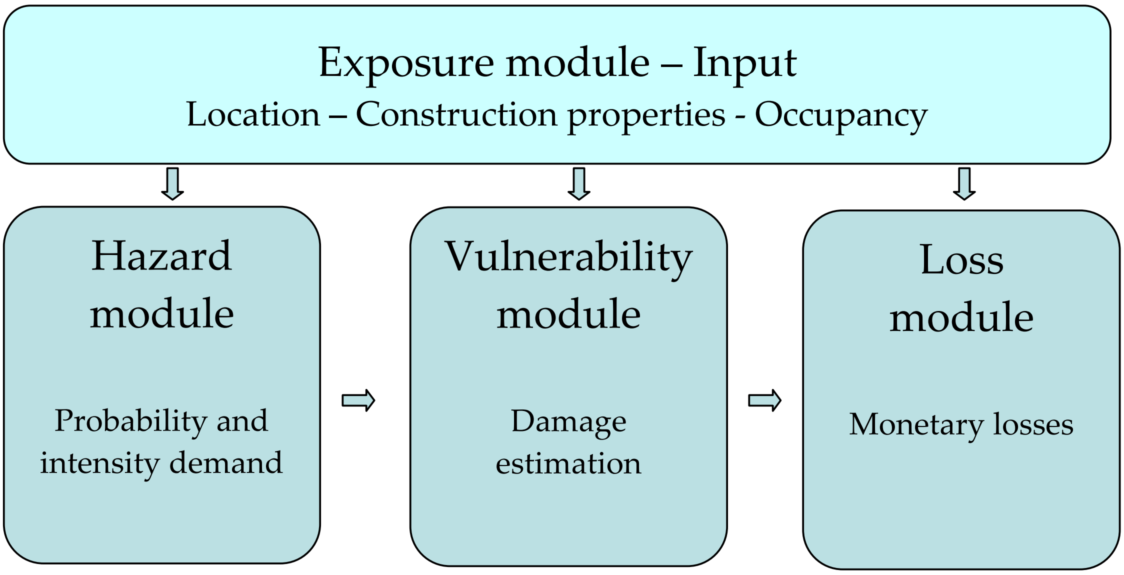

Figure 1: Catastrophe model modules

3 EXPOSURE

The exposure is the group of the insured systems and structures. Basic input includes location, age, occupancy, and construction type. A building inventory for the city of Mayagüez in the western part of Puerto Rico was created based on the interpretation of satellite images and aerial photos stored in a Geographic Information System by the Center for Collection of Municipal Taxes (CRIM, as per its acronym in Spanish). The census track units shown in Figure 2 are used as the basic mapping units for the building survey.

Figure 2: Census track of the city of Mayagüez

For each census track, the following data is extracted:

- The number and size of the buildings are collected using the CRIM database.
- The number of buildings with metal roof is counted using the satellite images. Industrial buildings are differentiating of the rest.
- Soil types are obtained from the soil maps developed as part of the Insurance Commissionaire initiative funding this research. These maps are based on standardized site geology classification proposed in the NEHRP (National Earthquake Hazard Reduction Program) provisions (Building Seismic Safety Council 2001).
- Wind exposure and topographic effects are assigned, based on the maps developed in the project by means of satellite photos and topographic maps. Exposure categories should be assigned to all likely wind directions that properly reflect the characteristics of ruggedness of the land and irregularities of the surface. Additionally, wind speed-up effects at isolated hills, ridges, and escarpments constitute abrupt changes in the general topography and shall be included in the force analysis.
- The zoning classifications are noted.

3.1 Building Inventory classification for earthquakes

In the case of earthquake hazard, the basic construction classes considered are: concrete moment resistant frames (CMRF), concrete shear walls (SW), steel moment resistant frames (SMRF) and Wood. Commercial steel buildings and Industrial buildings are considered in individual categories due to their special characteristics.

Combining the information of each census track with the default assumptions described in (Gerbaudo 2007), it is possible to approximate the percentage of each construction class in the census. The procedure for the inventory classification is as follows:

1. Industrial buildings are easily distinguished from the satellite images. Summing the areas of the industrial buildings from the CRIM database and dividing it by the total building areas from the sector, the results are expressed as a percentage of the total building areas.
2. The percentage of one story buildings multiplied by the percentage of metal roof buildings is assumed to be wood-zinc house types.
3. The percentage of one story buildings minus the percentage of wood-zinc house types are assumed shear wall for urbanizations and concrete moment resisting frame for the owner built.
4. Two story buildings are assumed shear wall for urbanizations and concrete moment resisting frame for the owner built.
5. The 90 percent of buildings between three and seven stories are assumed concrete multistory type and the other 10 percent are assumed steel frame.
6. Buildings of more than seven stories are assumed high-rise steel.

3.2 Building inventory classification for hurricanes

For the hurricane loss estimation the buildings are classified as: concrete, wood-zinc, mixed, small institutional, large institutional and mixed institutional.

The procedure for the inventory classification for hurricanes is as follows:

1. The area percentage of Industrial buildings is calculated.
2. The area percentage of institutional buildings is identified and divided into small and large institutional buildings according to their square footage.

3. The percentage of one story buildings multiplied by the percentage of metal roof buildings is assumed wood-zinc type.

4. The percentage of two story buildings times the percentage of metal roof buildings is assumed two stories mixed buildings.

5. The percentage of three story buildings times the percentage of metal roof buildings is assumed three stories mixed buildings.

6. The buildings without metal roof are assumed concrete and are divided according to their heights.

4 HAZARD

4.1 Probabilistic Hazard

One can use a deterministic scenario event or an event based on a probabilistic model to define the hurricane and earthquake hazards. The probabilistic approach will lead to the annual frequency with which different losses are expected to occur, or alternatively, the annual expected loss at a given location for a defined value of exposed buildings. The uncertainty in the natural event demand can be therefore approximately described in terms of a random variable (S) of an adequate intensity measure, such as the peak ground acceleration for earthquake or 3-second peak gust for hurricanes, over a given period of time (t). The mean annual probability of exceedance (λ) of such a random variable is generally referred to as the hazard curve:

$$\lambda(s) = P_{annual}(S \geq s) \tag{1}$$

The probabilistic seismic hazard is defined according to the latest version of U.S. Geological Survey (USGS) seismic hazard curves for Puerto Rico and the Virgin Island (Mueller et al. 2003). These hazard curves relate the seismic hazard measured by peak ground acceleration (PGA) and the annual frequency of exceeding this PGA. The earthquake hazard curve for the city of Mayagüez is shown in Figure 3.

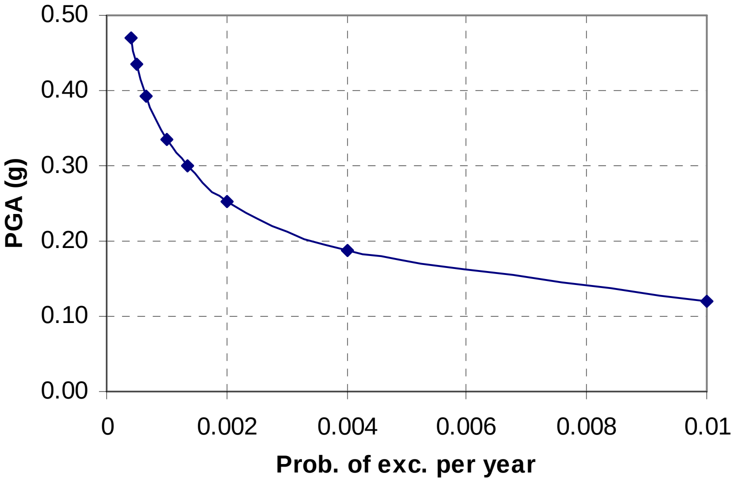

Figure 3: Earthquake hazard curve for the city of Mayagüez (Mueller et al. 2003)

A probabilistic hurricane hazard model considers many hurricanes at a given location and assigns a probability of occurrence to each hurricane. The first step of wind field simulation is to establish hurricane recurrence model for the target site. A recent study estimates the hurricane frequency using data from 1870 to 2003 (Landsea et al. 2004). Charts giving return periods of tropical cyclones, having winds of least specified value near storm center, and passing within specified distances from site were developed for the principal cities of Puerto Rico. Figure 4 show the chart corresponding to the city of Mayagüez. The wind speeds in the Figure 4 are not necessarily at the building site, so this chart does not address expected wind return periods at site itself. A simple meteorological model HURRECON (Boose et al. 1994; Boose and Chamberlin 1997; Boose et al. 2001; Boose et al. 2004), based on published empirical studies of many hurricanes, was used to estimate the wind speed at site. HURRECON uses information on the track, size, and intensity of a hurricane, as well as the cover type, to estimate surface wind speed. Then for each category of hurricane, a Monte Carlo simulation is run to get a set of probable wind speeds at the site.

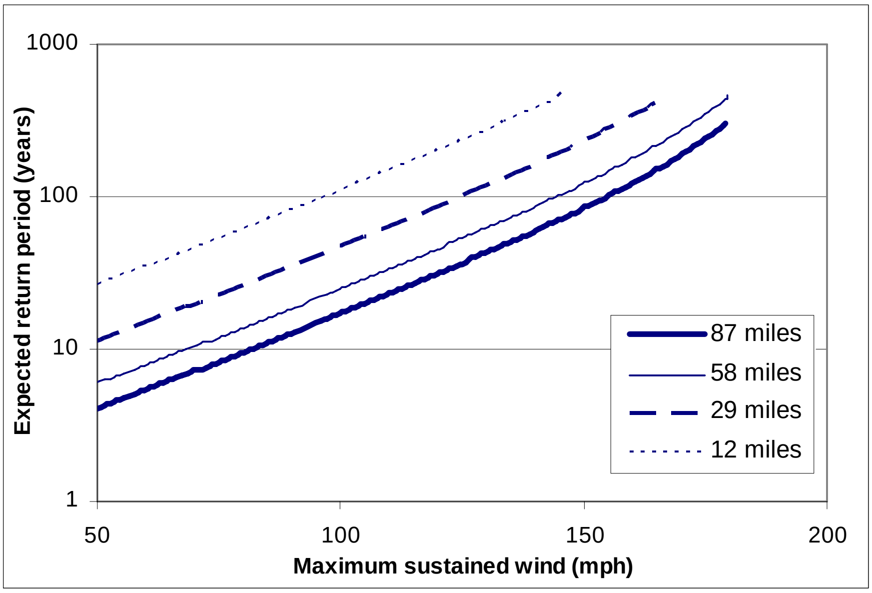

Figure 4: Hurricane hazard curves for the city of Mayagüez

4.2 Deterministic hazard

In deterministic hazard analysis, a single event is used to arrive at a scenario-like description. The scenario events are described by mean of the spatial distribution of the demand intensity s for a particular event j:

$$S_{Event:j}(x,y)=s \tag{2}$$

Earthquake Scenarios take the expected ground motions and effects of a specific hypothetical large earthquake (ShakeMap Working Group 2001). The ground shaking produced by an earthquake is represented by means of SakeMaps. For an earthquake magnitude and epicenter, ShakeMaps show the range of ground shaking levels at sites throughout the region depending on the distance from the earthquake, the rock and soil conditions at sites, and variations in the propagation of seismic waves from the earthquake due to complexities in the structure of the Earth's crust. The methodology to generate scenarios assumes that a particular fault or fault segment will rupture over a certain length relying on consensus-based information about the potential behavior of the fault.

Three different earthquake scenarios developed by the Puerto Rico Seismic Network (Huerfano et al. 2006) are used (Table 1). The first earthquake scenario simulates the historic 1918 Mona Passage earthquake (M= 7.3) with an average PGA of 0.33 g in the city. The second scenario corresponds to an earthquake event of magnitude 7.0 and epicenter in the Lajas valley. The third and last scenario reproduces a magnitude 7.3 earthquake from 1867 with its epicenter located in the Virgin Islands and an average PGA of 0.35 g in the city.

Earthquake scenario	**Fault Location**	**Magnitude**	**Values at Mayagüez**	
			PGA	**MM Intensity**
1918 Mayagüez	N18.44 W67.50: Mona Passage	7.3	0.33	VIII
Lajas M7	N18.01 W66.95: Lajas Valley	7.0	0.35	VIII
1867 Mayagüez	N18.00 W65.66: Virgin Islands	7.5	0.15	VIII

Table 1: Earthquake scenario events.

As for earthquakes, one may consider a single past hurricane with a known wind field distribution, to subject a predetermined zone to this field, and then compute the resulting losses ("scenario" hurricane). In general the variation of wind intensity over the zone of interest will depend upon the size and meteorological characteristics of the hurricane and certain physical characteristics of the zone.

Using a meteorological model, it is possible to demonstrate that the variations in wind speeds over the limits of a city in Puerto Rico is small compared with the level of precision inherent to the overall loss estimates. Then, for each hurricane scenario considered, a constant wind speed may be assigned to a city. Table 2 lists the scenarios for the city of Mayagüez, including the historical date, wind speed, closest point of approach, and direction.

Hurricane	Date	Sustained wind speed [mph]	Closest point approach [miles]	Direction
San Ciriaco	1899, August 7-8	138	15	ESE to WNW
San Felipe II	1928, September 13	161	19	SE to NW
Georges	1998, September 22	109	15	E to W

Table 2: Hurricane scenarios for Mayagüez (Caribbean Hurricane Network 2007).

5 VUNERABILITY

Vulnerability is the propensity of things to be damaged by a hazard. Each type of hazard puts a somewhat different set of elements at risk. For a full definition of vulnerability, the expected levels of damage at all hazard severities must be known. Vulnerability for a range of events of different severities can be given by means of a continuous function mapping values of damage to values of hazard severity.

The vulnerability module estimates the damage level of the building using fragility curves that relate the demands generated in the hazard module with the damage in the building. The fragility curves are defined based on the building construction class and in some cases are sensitive to additional material and geometric properties.

For a specific damage state, DS, a fragility curve is a plot, as function of a demand, S, of the conditional probability of the building being or exceeding the damage state. Commonly, a fragility curve is taken to be lognormal, in which case it can be expressed algebraically in terms of the standard cumulative Normal distribution Φ by:

$$P\left(d \geq DS \middle| S\right) = \Phi\left[\frac{\ln\left(S\right) - \mu_{LN}}{\sigma_{LN}}\right] \tag{3}$$

where σ_{LN} is the lognormal standard deviation which takes into account the sources of uncertainty and μ_{LN} is the mean value of lognormal of S at which the building reaches the threshold of the damage state DS.

Design fragility curves for the construction classes most common to Puerto Rico were derived by our groups of specialists in earthquake, hurricane and flood hazards. A variety of analytical procedures have been followed, ranging from static elastic analysis to nonlinear time history analyses of 3D models to laboratory testing. The choices made for the analysis method, structural idealization, hazard definition and damage models strongly influence the derived curves. Table 3 and Table 4 list the parameters defining the earthquake and hurricane fragility curves respectively. For a detailed discussion, the reader is referred to the thesis works by Avilés (2006), Cortés (2006), García González (2007) and Mieses (2007) and Gerbaudo (2007).

Building type	Number of Stories	PGA (g)								Source
		Slight		Moderate		Extensive		Complete		
		μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}	
Concrete Shear Wall	**1**	-2.55	1.10	-1.85	0.97	-1.61	0.95	-1.46	0.94	(Mieses 2007)
	2	-2.05	0.72	-1.69	0.70	-1.43	0.68	-1.29	0.66	
	>2	-0.18	0.98	0.13	0.90	0.29	0.89	0.38	0.80	
Concrete MRF	**1**	-1.81	1.03	-1.37	0.87	-1.18	0.82	-1.04	0.78	
	2	-1.83	0.55	-1.44	0.56	-1.21	0.51	-1.03	0.49	
Steel MRF	**1-3**	-1.55	0.37	-1.11	0.38	-0.49	0.33	-0.024	0.30	(Cortés-Areizaga 2006)
	4-7	-1.07	0.22	-0.67	0.26	-0.13	0.25	0.15	0.19	
	>7	1.2	0.41	-0.77	0.42	-0.28	0.32	-0.057	0.25	
Commercial Steel	**2**	-1.46	0.33	-0.98	0.38	-0.4	0.31	0.044	0.23	
	3	-1.46	0.25	-1	0.27	-0.33	0.27	0.029	0.21	
	4	-1.11	0.19	-0.67	0.19	-0.11	0.17	0.32	0.28	
Industrial	**1**	-1.66	0.33	-1.12	0.33	-0.59	0.38	0.015	0.35	
	2	-1.5	0.36	-1.05	0.33	-0.48	0.24	-0.05	0.28	
Wood	**1-2**	-1.81	0.64	-1.28	0.64	-0.70	0.64	-0.26	0.64	(FEMA 2003)

Table 3: Earthquake fragility curves parameters.

Building type	Nº of Stories	Gust Wind Speed [mph]							
		Slight		Moderate		Extensive		Complete	
		μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}	μ_{ln}	σ_{ln}
Concrete	**1**	4.920	0.150	5.110	0.190	7.000	0.100	7.000	0.100
	2	4.920	0.140	5.200	0.220	7.000	0.100	7.000	0.100
	3	4.900	0.130	5.180	0.220	5.640	0.080	5.740	0.100
Multistory	**2-4**	4.775	0.090	5.120	0.140	7.000	0.100	7.000	0.100
	5-7	4.775	0.090	5.090	0.130	5.750	0.120	5.750	0.120
	8-10	4.775	0.090	5.090	0.130	5.510	0.145	5.530	0.145
	11-13	4.775	0.090	5.050	0.110	5.360	0.135	5.380	0.130
	14-16	4.775	0.090	5.000	0.100	5.240	0.140	5.260	0.140
Wood	**1**	4.840	0.110	4.910	0.160	5.100	0.170	5.160	0.180
	2	4.840	0.110	4.910	0.160	5.050	0.170	5.100	0.180
Mixed	**2**	4.840	0.110	4.910	0.160	5.100	0.170	5.150	0.180
	3	0.500	0.200	0.068	0.000	0.000	0.000	0.000	0.000
Small Institutional	**1**	4.880	0.100	5.020	0.120	5.325	0.070	5.385	0.090
	2	4.880	0.100	5.020	0.120	5.280	0.070	5.350	0.095
Mixed Institutional	**1**	4.880	0.100	5.020	0.120	5.310	0.070	5.390	0.100
Large Institutional	**1**	4.880	0.140	5.050	0.140	5.180	0.130	5.230	0.150

Table 4: Hurricane fragility curves parameters (García González 2007).

6 LOSS ESTIMATION

The general equation for the probable loss with an annual probability of exceedance P_e can be given by:

$$PL_{P_e}^{m,n} = \sum_{i=2}^{5} RC_i^n P_m \left[DS = d_i \left| S_{P_e} \right. \right] \tag{4}$$

The term $P_m \left[DS = d_i \middle| S \right]$ is the discrete probability for one structure type *m*, defined as the conditional probability of reach a damage state $DS=d_i$ given the occurrence of the specific hazard intensity *S* among the spectrum of hazards. The damages states d_i correspond to slight (i = 2), moderate (i = 3), extensive (i = 4) and complete (i = 5).

The discrete probabilities are obtained as difference between the fragility curves described in the previous section:

$$P_m \left[DS = d_i \middle| S = s_{P_e} \right] = \begin{cases} P\left(DS \geq d_i \middle| S = s_{Pe}\right) - P\left(DS \geq d_{i+1} \middle| S = s_{Pe}\right) & i = 2,3,4 \\ P\left(DS \geq d_i \middle| S = s_{Pe}\right) & i = 5 \end{cases} \tag{5}$$

The term s_{Pe} represents the intensity of the hazard *S* with a likelihood of annual exceedance P_e (Section 4). The third term RC_i^n is the building repair to replacement ratio associated to an occupancy type *n* in a damage state $DS=d_i$. This mapping process between damage states and economic losses is one of the most significant research issues at the present time. In this study the loss model is assumed to be deterministic. The values of repair to replacement ratio for the building types used in this work can be found in Gerbaudo (2007).

One value of interest for the decision-makers is the expected annual loss. The expected or mean value of a random variable, such as probable loss, is the mathematical centroid of the probability distribution for the random variable; that is, it is determined as the sum (or integral) of all the values, such as economic losses, that can occur multiplied by their probability of occurrence (ASTM 1999). In equation form:

$$EAL = E\left[PL\right] = \int_{\lambda(s)} \lambda(s) PL\left(\lambda(s)\right) \cdot d\lambda \tag{6}$$

The Scenario expected loss is calculated using the Equation (4) and replacing the intensity of the hazard by the corresponding to the particular event.

7 MULTI-HAZARD RISK ASSESSEMENT OF THE CITY OF MAYAGUEZ

7.1 Earthquake risk assessment results

The expected loss percentage for each construction class in each census track is calculated, combining the fragility curves with the PGA and considering the soil type of the census. Then, using the mean square foot cost data from RMS Means (R.S. Means 2007) and the area of each building type, the dollar exposure is calculated for each census track. The monetary loss is calculated as the multiplication of the dollar exposure by the loss percentage. The repair ratio is the total loss divided by the total exposure. An example of loss calculation for one census track is shown in Table 5. The scenario aggregated losses for the entire city of Mayagüez range from 1.5 to 2 billion US dollars (Table 6).

Building type	**Footprint Area**	**Total Area (sqf)**	**Unit Cost (US$/sqf)**	**Exposure (US$)**	**Loss (US$)**			
					1918 Mayagüez	**Lajas M7**	**1867 Mayagüez**	**EAL**
Industrial	4.7%	47442	150	7116262	1019480	1006865	315878	4329
Wood	3.0%	29923	33	987449	300332	297661	134312	1570
Shear Wall 1 S	62.0%	623919	75	46793898	21336972	21232006	14063718	148002
Shear Wall 2 S	21.1%	423925	75	31794405	19299657	19214464	12804343	133147
CMRF 1 S	0.0%	0	45	0	0	0	0	0
CMRF 2 S	0.0%	0	45	0	0	0	0	0
Low-Rise Steel	0.0%	0	68	0	0	0	0	0
Mid-Rise Steel	0.9%	45307	68	3080872	103287	101167	8994	297
High-Rise Steel	0.0%	0	68	0	0	0	0	0
Multistory	8.1%	407762	75	30582185	1959631	1939241	819811	9918
Total	100%			120355071	44019360	43791403	28147056	297264
			Repair ratio =		37 %	36 %	23 %	0.25 %

Table 5: Earthquake loss in census track 821.04 (Soil type D)

Nº Census track	Nº buildings	Exposure	Earthquake Losses			
			1918 Mayagüez	Lajas M7	1867 Mayagüez	EAL
24	23644	$4,952,367,661	$2,028,455,700	$1,886,515,680	$1,550,727,838	$15,043,308

Table 6: Total earthquake scenarios losses

The losses obtained for these three earthquake scenarios ranges from 30% to 40 % of the total dollar exposure. This percentage of losses is equivalent to the losses to an inventory of bad construction quality buildings subject to an earthquake of high VIII to IX intensity in the scale of Mercalli according to a report of Swiss Re (2005). This is not a surprise, if one considered the bad performance of the concrete shear wall structures as determined by Mieses (2007) and the poor soil properties in the western area of the city. The clear effect of the local soil conditions are demonstrated with a map of the spatial distribution of the damages over the city of Mayagüez for the 1918 earthquake scenario (Figure 6). In this figure, the soil type designations follows the NEHRP provisions whereby soil type D is stiff soil, E is soft soil, and F is soil requiring site specific evaluation (Building Seismic Safety Council 2001). As shown, the more heavily damaged areas are also the sectors with soils type F and E.

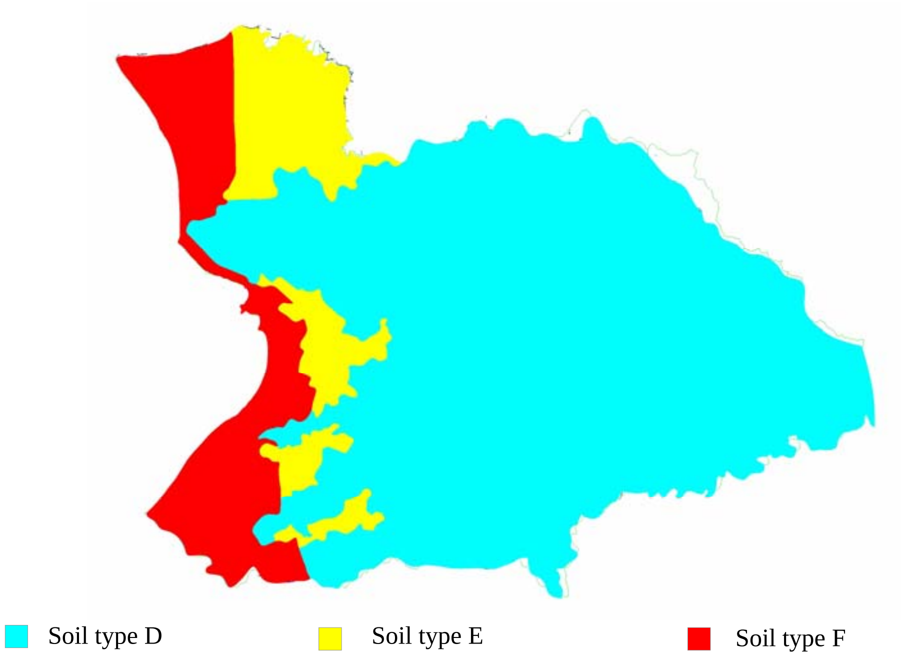

Figure 5: Soil class map of Mayagüez (Llavona 2003)

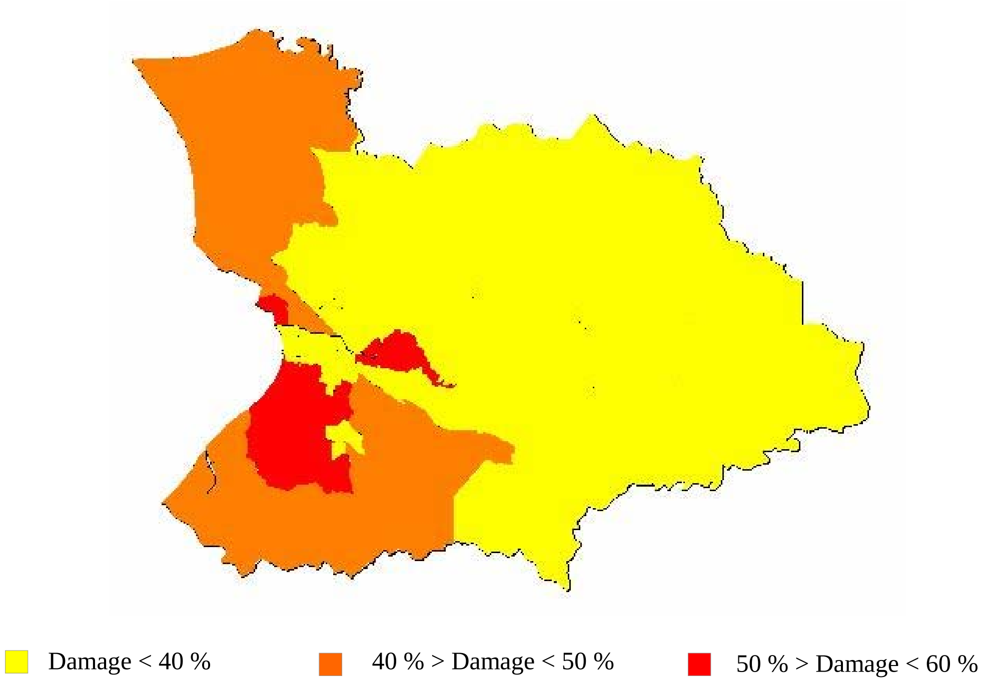

Figure 6: Spatial distribution of damages for the historic earthquake of 1918

7.2 Earthquake mitigation alternatives

The effects of mitigation schemes to reduce the percentage of losses from earthquakes are quantified in this section. The first option considered is the improvement to shear wall construction by actually providing adequate number of shear walls in both direction and sizing them properly. The results of implementing this retrofitting scheme (Table 7) show a reduction of almost 10 percent in the total aggregation of the losses and more than 15 % in some census tracks. The second mitigation alternative analyzed is the soil treatment changing the soil type F with certain level of susceptibility to liquefaction to a soil type E. In this case, the loss reductions varied from 1 to 5 percent in the total aggregation of the losses and almost 15 % in some census tracks (Table 7).

Scenario	Action		
	None	SW strengthening	Soil improving
1918 Mayagüez	$2,028,455,700 (41%)	$1,597,312,568 (32 %)	$1,818,521,626 (37 %)
Lajas M 7	$1,886,515,680 (38%)	$1,459,521,691 (29 %)	$1,646,248,953 (33 %)
1867 Mayagüez	$1,550,727,838 (31%)	$1,098,943,407 (22 %)	$1,483,698,461 (30 %)

Table 7: Total economic losses due to earthquakes for several mitigation actions.

7.3 Hurricane risk assessment results

Three different historic hurricane scenarios with high wind speeds in the city of Mayagüez are used. These are San Ciriaco (1899), San Felipe II (1928) and Georges (1998) with sustained wind speeds of 138 mph, 161 mph and 109 mph, respectively.

The expected loss percentage for each construction class in each census track is calculated by combining the fragility curves with the wind speeds and considering the exposure and the topographic features of the census. Then, following a procedure similar to earthquake, the repair ratios for the census track are calculated. An example of loss assessments for one census track is shown in Table 8. The aggregated losses for the entire city of Mayagüez range from 72 to 260 millions US dollars (Table 9).

Building type	**Footprint Area (%)**	**Area (sqf)**	**Unit Cost (US$/sqft)**	**Loss (US$)**			
				San Ciriaco	**San Felipe**	**Georges**	**EAL**
Industrial	12.7%	189530	150	1340510	2634600	263117	41589
Small Institutional	0.0%	0	47	0	0	0	0
Large Institutional	0.0%	0	118	0	0	0	0
Wood-zinc 1S	20.0%	297839	33	4034676	7175624	689248	115968
Mixed 2S	21.8%	647682	47	5470365	9076622	1161957	160252
Mixed 3S	1.8%	80369	47	1257544	1817703	327157	37115
Concrete 1S	20.0%	297499	65	80983	103250	28164	1799
Concrete 2S	21.7%	646943	65	166646	207610	63284	5330
Concrete 3-4S	1.9%	82639	65	30884	85870	1116	1554
Concrete 5-7S	0.1%	4722	65	1765	4907	64	89
Concrete 8-10S	0.0%	0	65	0	0	0	0
Concrete 11-13S	0.1%	21619	65	8079	22464	292	406
Total	100%			12391452	21128650	2534399	364101
		Repair ratio =		8.79%	14.99%	1.80 %	0.26 %

Table 8: Hurricane loss in census track 804 (Exposure C).

Nº Census track	Nº buildings	Exposure	Hurricane Losses			
			San Ciriaco	San Felipe	Georges	EAL
24	23644	$4,952,367,661	$169,085,862	$259,517,290	$71,692,028	$15,043,308

Table 9: Total hurricane losses

7.4 Hurricane mitigation alternatives

The effects of mitigation schemes to reduce the percentage of losses from hurricanes are quantified in this section. The first option considered is the reduction in spacing between fasteners. The results of implementing this retrofitting scheme (Table 10) show a reduction of only 1 to 2 percent in the total aggregation of the losses and more than 10 % in some census tracks. The total losses for the retrofitted inventory were reduced by half (Table 10). Also analyzed are the addition of reinforcing zinc straps to reduce low-cycle fatigue of zinc sheets and the use of metal straps in roof-to-wall connections. Both of these retrofitting options produce results similar to the first scheme.

Scenario	Action	
	None	Retrofitted
San Ciriaco	$165,683,838 (3.3 %)	$64,328,133 (1.3 %)
San Felipe	$253,202,890 (5.1 %)	$107,334,033 (2.2 %)
Georges	$70,814,974 (1.4 %)	$25,514,069 (0.5 %)

Table 10: Total economic losses due to hurricanes scenarios for typical and retrofitted inventories.

8 CONCLUSIONS

The results from running deterministic earthquake and hurricane loss scenarios for the target city of Mayagüez revealed economic losses on the high end of the spectrum. This is explained in part by some questionable construction practices in the Island, especially with regards to shear wall structures. The coastal areas in the western part of the city suffered the most damages under earthquake scenarios because of the liquefaction problems. The estimated losses for the hurricane scenarios were between 5 to 10 percent of the expected losses from a major earthquake. However, these calculations did not consider the damages caused by floods during a hurricane, and the losses to the interior of the buildings when an element of the building’s envelope fails. Again, the biggest damages were found in the coastal areas in parts due to topography and the concentration of light frame industrial structures.

The ability to change one or all default settings permitted to test different hypothesis and the cost-benefit of various alterations, soil treatments and retrofitting schemes. In fact, based on our models, mitigation measures can save more than 400 million US dollars in earthquakes and from 50 to more than 100 million US dollars for hurricanes in Mayaguez alone. These savings lend support to the idea of providing incentives, such as reductions in insurance premiums, to increase mitigation efforts.

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