Probabilistic Seismic Hazard Assessment Study for the Eastern Caribbean Region

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ABSTRACT:
The aim of this paper is to illustrate the results of a probabilistic seismic hazard study that has been carried out in the Eastern Caribbean Region (9-19°N, 58-65°W). The analysis was implemented using a standard logic tree approach which allowed taking into account systematically the model-based (i.e. epistemic) uncertainty. Hazard computations were performed for a grid with a space resolution of 0.025 degrees, with an average spacing of the nodes of about 2.8 km, using the standard Cornell-McGuire approach based on the definition of appropriate seismogenic zones. A comprehensive earthquake catalogue was updated for the region from a merger of available databases. A thorough investigation was undertaken to identify the most suitable ground motion prediction equations to be used. Uniform hazard spectra were calculated for horizontal component (stiff soil site and level ground condition), 4 return periods (95, 475, 975, 2475 years) and 22 structural periods (from 0 to 3 sec.).

Keywords: Eastern Caribbean islands, seismic hazard, subduction zone, ground motion prediction equations.

1. INTRODUCTION

Nowadays the growth of big cities in seismically active areas all around the world requires very detailed evaluation of seismic hazard in order to prevent loss of life, property damage and socio-economic disruption due to earthquakes. One of these regions is the Eastern Caribbean area which is located in a very active seismic zone on the Caribbean/South American/North American plate boundaries. The population of the Caribbean remained low until the 20th century. In recent times, the rapid growth of tourism in those islands has resulted in increasing construction. Few seismic hazard studies were undertaken in the past for the Eastern Caribbean Region; therefore further new investigations in seismic hazard assessment are required.

This article describes the Probabilistic Seismic hazard Analysis (PSHA) performed to produce probabilistic seismic hazard maps for the Eastern Caribbean Region (9-19°N, 58-65°W), which encompasses the Leeward and Windward Islands. The standard Cornell-McGuire method (1968) was adopted, using a standard logic tree approach which allowed taking into account systematically the model-based (i.e. epistemic) uncertainty. Hazard computations were performed over a grid of sites with a space resolution of 0.025 degrees, with an average spacing of the nodes of about 2.8 km. A critical review of past hazard studies proposed for the region was undertaken as a preliminary task. At the outset, the seismotectonic setting of the Eastern Caribbean Region was reviewed to identify reasonable seismogenic zones, which are a fundamental aspect for the hazard computation by the Cornell-McGuire approach. Further important phases required by the PSHA, as the compilation and processing of a composite earthquake catalogue for the region under study, and the selection of suitable ground motion prediction equations (GMPEs) are discussed. As a final result, uniform hazard spectra were computed for the horizontal component, under the assumption of stiff soil site and level ground condition, for 4 return periods (95, 475, 975, 2475 years) and 22 structural periods (between 0 and 3 sec.).

1.1. Past seismic hazard studies for the Eastern Caribbean Region

Researchers ignored the seismic hazard in the Caribbean Region until the 1950's. During the period from 1950 to 1970 a series of damaging earthquakes occurred and attracted scientist's attention to the seismic hazard problem in the region. The earliest attempts to perform hazard assessments in the Caribbean Region were undertaken by Pereira and Gay (1978) for Trinidad, Tobago and Jamaica and by Taylor et al. (1978), who included in their work the Lesser Antilles. They developed hazard maps applying the concept of probabilistic seismic hazard introduced by Cornell (1968). The most serious and common problem of these works was that magnitudes and locations of the earthquakes of the adopted catalogue were not well known. Sheperd and Aspinall (1983) improved the quality of both locations and magnitudes and produced an improved hazard map for Trinidad and Tobago. Since 1990 a numerous group of researchers from Caribbean, Mexico, Central America and South America produced a series of hazard maps for these regions. In those studies magnitudes of used recorded earthquakes were re-computed and expressed using the moment-magnitude scale. Among those studies the most important results were published by Tanner and Shepherd (1997). The most recent seismic hazard assessments in the Caribbean Region were presented by Shepherd and Lynch (2003) for Trinidad and Tobago and by Tanner and Shedlock (2004) for Mexico, the Caribbean and Central and South America.

2. SEISMIC CHARACTERISTICS

Caribbean seismicity is concentrated along the Caribbean/South American/North American (and associated smaller) plate boundaries and it is mainly generated by the Caribbean plate, which is overriding the North and South American plates on the East, while the Cocos plate is subducting beneath the Caribbean plate on the West.The origin of seismicity in the Caribbean is mostly, but not exclusively, due to the subduction activity between the Caribbean and the North American plates. The interplay and complexities between shallow crustal and subduction seismicity of the Caribbean region were thoroughly investigated together with their association with fault movements whenever this information is available.

2.1. Earthquake Catalogue

The earthquake catalogue is not only a fundamental element for the seismic hazard study, but it also represents an important instrument to study the seismicity of a region. The catalogue should be composite, homogeneous, well-defined and obtained from a merger of all the available databases in a consistent framework. The work of Tanner and Shepherd (1997) describes the employed methods to construct the earthquake catalogue for the Latin America and the Caribbean, namely the IPGH (*Instituto Panamericano de la Geografía e Historia*) catalogue, which cover the period from 1530 to 1996. This catalogue was updated in order to cover also the period from 1997 to 2009, including only the events with M_W equal or greater than 4.0, on the basis of all the available databases (International Seismological Center (ISC), National Earthquake Information Center (NEIC), Advanced National Seismic System (ANSS) and National Geophysical Data Center (NGDC)). Therefore, the composite catalogue compiled for the area under study (7-22.5° N, 56-68.3° W, see Fig. 2.1) spans a period from 1530 to 2009 and includes 3478 events with M_W between 4.0 and 8.0. The depth of events ranges between 0 and 299 km. Fig. 2.1a shows the events of the catalogue with $M_W \geq 4.5$, used in the PSHA.
Since different magnitude scales are assigned to a same event in the various accounted databases, to homogenize the measures of magnitude in the composite catalogue into the moment magnitude M_W, empirical relations were developed to convert M_S and m_b into M_W. In the cases of M_D and M_L, it was not possible to determine specific M_L – M_W and M_D - M_W correlations for the area under study, due to the lack of enough independently estimated pairs of magnitudes in the composite catalogue. As a consequence the most suitable correlations were selected from the literature.

2.2. Seismogenic sources

The standard Cornell-McGuire approach is based on the definition of appropriate seismogenic zones. The studied area was divided in the 15 seismogenic zones shown in Fig. 2.1 b and listed in Tab. 2.1.

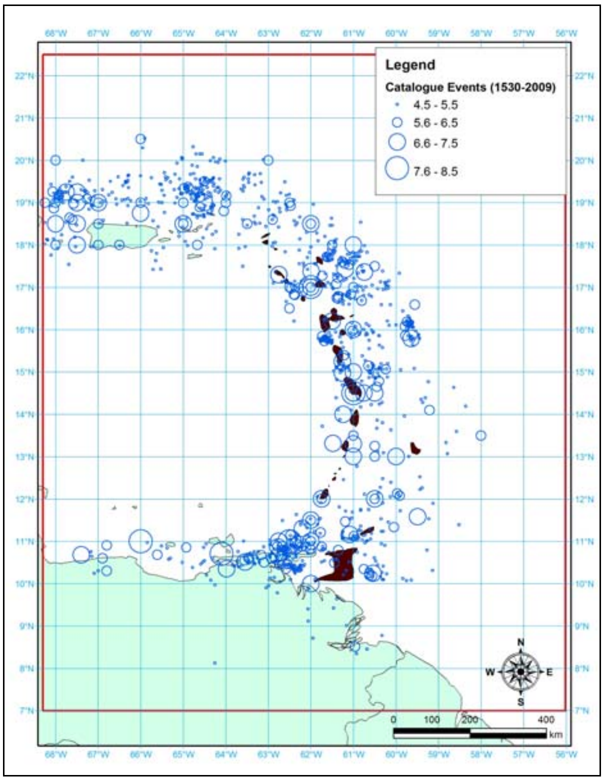

Figure 2.1. a Events of the composite catalogue with $M_W \geq 4.5$

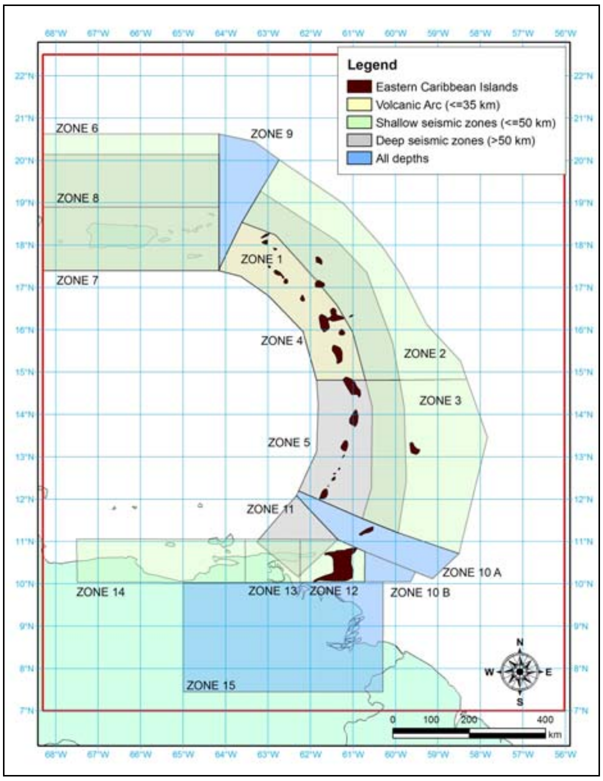

Figure 2.1. b Geometrical delimitation of seismogenic sources in the Eastern Caribbean

Table 2.1. Main features of the seismogenic zones

NAME	DEPTH (km)	TYPE	MAIN FOCAL MECHANISM
Zone 1	19.1	Upper-Crustal (Volcanic arc)	Normal and Strike-Slip
Zone 2	29.6	Interface	Thrust (Inverse)
Zone 3	29.4	Interface	Thrust (Inverse)
Zone 4	86.0	Intraplate	Normal
Zone 5	97.9	Intraplate	Normal
Zone 6	32.3	Interface	Thrust and Strike-Slip
Zone 7	28.4	Crustal (Shallow)	Normal
Zone 8	74.5	Intraplate	Normal
Zone 9	24.4	Transition	Normal and Strike-Slip
Zone 10	43.9	Transition/Intraplate	Normal and Strike-Slip
Zone 11	99.5	Intraplate	Normal
Zone 12	32.5	Crustal (Shallow)	Normal and Strike-Slip
Zone 13	23.3	Crustal (Shallow)	Strike slip and Thrust
Zone 14	14.7	Crustal (Shallow)	Strike slip and Thrust
Zone 15	57.3	Crustal (Deep)	Strike slip and Thrust

Zone 1: Volcanic Island-Arc. Zone 1 covers the area from North of Martinique to Anguilla, including the Leeward Islands, which are characterized by a higher seismic activity than the Windward Islands (from Grenada to Saint Lucia). The moderate shallow earthquakes typical of the volcanic zone frequently appear in clusters with no discernible mainshocks (swarms). The upper-crustal seismicity concentrates within the uppermost 35 km of the Caribbean continental plate in the Lesser Antilles Arc. From the island of Grenada to Anguilla the epicenters are concentrated in a nearly continuous belt 100

km width, which develops along both the axis of the principal active volcanoes and the inland and offshore shallow faults which run parallel to the Subduction Trench.

Zones 2-5: Subduction in the Lesser-Antilles. The volcanic island-arc lays about 300 km from the Eastern Caribbean Trench, where the North American plate begins to subduct underneath the Caribbean plate, reaching depths of 200 km below the islands and generating large earthquakes of magnitude up to 8.0 M_W. Zones 2 and 3 include all the shallow focus earthquakes (depth $\leq$ 50 km) along the inclined inter-face seismic zone that yields underthrust focal mechanisms. Convergence between the Caribbean and North American plates occurs at a rate of about 37 mm/yr. Focal mechanisms of deeper intra-plate events (>50 km) indicate that normal faulting is due to the initial flexure of the downgoing Atlantic slab (Zone 4 and 5), with an average westward dipping angle of 50 degrees (Bengoubou-Valeruis et al., 2008). Zones 2 and 4 are characterized by a higher seismic activity if compared with Zones 3 and 5. Zones 2 and 3 partially overlap Zones 4 and 5 respectively and Zones 4 is partially overlapped by Zone 1.

Zones 6-8: Puerto Rico and Virgin Islands. The region of Puerto Rico and the Virgin Islands is considered as a microplate surrounded by the obliquely subducting North America plate, the Caribbean plate and several major faults, as the Mona Canyon to the East, the Abnegada Passage to the West and the Muertos Trough to the South. Zone 6 includes the Puerto Rico Trench area with depth up to 50 km. Zone 7 comprises shallow faults (depth less than 50 km) in the inland of Puerto Rico and offshore. Zone 8 includes the intra-plate subduction seismicity generated by the bending of the North-American slab, with depth greater than 50 km. A recent research suggests the existence of the subducted Caribbean slab, thus this seismogenic area comprises both the subducting North America and Caribbean slabs, respectively southward and northward dipping beneath the microplate. Zone 6 and 7 overlap Zone 8 (see Fig. 2.1 b).

Transition Zones 9 and 10A. These represent the intersections between the transform faults and subduction zones, and the Lesser Antilles Arc located at the north and at the south of the Eastern Caribbean. Zone 10 includes the shallow seismic activity in the south part of the island of Tobago. Zone 9 is located at the boundary between the Lesser Antilles arc and the Puerto Rico Trench. It is characterized by a low level of seismicity and it mainly generates normal focal mechanisms.

Zone 10B: East of Trinidad. Earthquakes located in this zone are consistent with the detachment and bending-flexure of the South American slab which moves toward the collision zone (Russo and Speed, 1992). The zone is mainly characterized by normal faulting mechanism with E-NE/W-SW striking planes and strike slip faults with an average depth of 45 km.

Zone 11: North of Paria Peninsula. This zone constitutes a subducting detached oceanic lithosphere with depth ranging from 50 to 300 km and represents one of the most active seismogenic sources in the Eastern Caribbean (SRC, 2009). The focal mechanisms indicate that there is a normal faulting resulting from the initial flexure of the down going slab with a steeply NW-dipping of 60 degrees. However, mixed-motion earthquakes with thrust and strike slip indicated bending of the subducting slab at deeper depths.

Zone 12: Trinidad Faults. This zone includes the faults mapped in Trinidad namely, the Northern-Range and Central Range, and Darien Ridge and Arima and Los Bajos Fault, characterized by earthquake with depth less than 50 km (SRC, 2009).

Zones 13 and 14: El Pilar fault. These zones comprise the boundary between the Caribbean and the South American plates. Earthquakes originated by the El Pilar fault in the northern coast of South America are shallow events, with depth less than 50 km and mainly characterized by right lateral strike slip mechanisms. The Caribbean Plate is moving at about 20 mm/yr in an easterly direction relative to South America. However, thrust focal mechanisms also take place in this region, reflecting the oblique collision at crustal levels between the Caribbean and the South American Plates. A high level of seismicity characterizes Zone 13, while a moderate seismicity level characterizes Zone 14.

Zone 15: South of Trinidad. Russo et al. (1993) defined this zone as a passive margin in the Foreland basin in the north of South American continent. It includes events with strike-slip, mixed thrust and strike-slip and thrust mechanisms around the Orinoco-Delta region in Venezuela, with an average depth of 50 km.

3. PROBABILISTIC SEISMIC HAZARD ANALYSIS

To make the composite catalogue consistent with the earthquake occurrence model adopted in the classical Cornell-McGuire approach, it was declustered, thus aftershocks and foreshocks were removed. Subsequently an analysis of completeness was performed to define the Gutenberg-Richter (G-R, 1954) recurrence parameters. After a careful examination, various GMPEs were selected to characterize each of the identified seismogenic zones, depending on the dominant typology of earthquakes (subduction, crustal or volcanic) and prevalent focal mechanism. Finally, the PSHA was performed using a logic tree approach which allowed taking into account the epistemic uncertainty.

3.1. Catalogue Processing

3.1.1. Declustering

The declustering process represents a crucial phase of the study, especially for the studied case. In fact the applied method by Gardner and Knopoff (G-K, 1974) was calibrated on data from California, which is characterized by different seismo-tectonic setting and seismicity if compared with the Eastern Caribbean Region. Furthermore, the identified seismic zonation is very complex, characterized by the overlapping of different zones and by the typical volcanic seismicity. For these reasons, an *ad hoc* declustering was applied to the catalogue, following the steps: application of the G-K method to the catalogue, excluding Zone 1 since characterized by earthquake which frequently appear in clusters with no discernible mainshocks (swarms); check of the removed events with $M_W>6$; specific analysis of events of Zone 1. Thus, the declustered catalogue includes the events not removed by the G-K method, all the events of Zone 1 and the events with $M_W>6$ manually reinserted because previously wrongly removed by the G-K method. The total number of events of the catalogue reduced to 770.

3.1.2. Analysis of completeness

A second important processing step of the catalogue, to make it suitable for a probabilistic seismic hazard analysis using Cornell-McGuire approach, is the definition of time windows in which the catalogue is presumed to be complete, namely completeness periods for different magnitude classes and each seismogenic zone. Two different methods were used: the visual cumulative (VICU) method (Tinti and Mulargia, 1985) and the method by Stepp (1973). Since the results obtained applying these two methods were not so different, they were integrated to obtain a unique, final evaluation of completeness periods, to compute the G-R magnitude-frequency recurrence relationship (see Table 3.1).

Table 3.1. PSHA computation parameters for each seismogenic zone

NAME	COMPLETENESS PERIODS EVALUATION								MAXIMUM MAGNITUDE		G-R VALUES	
	4.75	5.25	5.75	6.25	6.75	7.25	7.75	8.25	M_{max1}	M_{max2}	a	b
Zone 1	1960	1950	1950	1910	1897	-	-	-	6.6	6.9	4.794	-1.012
Zone 2	1960	1950	1950	1919	1889	1810	-	-	7.3	7.8	4.614	-0.893
Zone 3	1960	1960	1960	1910	1900	1900	-	-	7.0	7.5	3.216	-0.725
Zone 4	1970	1970	1970	1930	1830	1830	1690	1530	8.0	8.5	4.164	-0.821
Zone 5	1960	1958	1950	1910	1830	1830	1690	-	7.8	8.3	2.941	-0.680
Zone 6	1960	1960	1960	1910	1810	1810	1690	-	7.5	8.0	4.724	-0.941
Zone 7	1963	1963	1963	1910	1843	1843	1690	-	7.5	8.0	3.043	-0.705
Zone 8	1960	1950	1950	1938	1938	1908	-	-	7.4	7.9	3.640	-0.810
Zone 9	1960	1960	1960	1930	-	-	-	-	6.4	6.9	2.961	-0.727
Zone 10	1970	1970	1970	1970	1970	-	-	-	6.7	7.2	2.127	-0.531
Zone 11	1969	1959	1959	1910	1819	1819	1690	-	7.8	8.3	3.643	-0.783
Zone 12	1960	1950	1950	1910	-	-	-	-	6.4	6.9	2.580	-0.664
Zone 13	1960	1960	1960	1910	1910	-	-	-	6.7	7.2	3.392	-0.747
Zone 14	1960	1950	1950	1910	1810	1810	1690	1530	8.0	8.5	2.567	-0.635
Zone 15	1967	1967	1967	1937	1937	-	-	-	6.6	7.1	2.825	-0.699

3.2. Ground-Motion Prediction Equations

GMPEs are regionally dependent and the choice of appropriate attenuation relationships depends on the tectonic setting of the site of interest. Unfortunately, not even one GMPE was developed for the Caribbean islands, therefore relations calibrated for other regions with similar seismotectonic setting were considered. After a careful examination, five GMPEs were selected to characterize each of the identified seismogenic zones, depending on the dominant typology of earthquakes (subduction, crustal or volcanic) and prevalent focal mechanism. In order to attribute to the GMPEs appropriate weight in the logic tree adopted for the PSHA, seismic response estimated by the attenuation relationships were compared with available strong motion recordings. The following GMPEs were adopted: Youngs et al. (1997), Atkinson and Boore (2003-2008), Zhao et al. (2006), Kanno et al. (2006) and Lin and Lee (2008) for the subduction zones; Zhao et al. (2006), Kanno et al. (2006), Abrahamson and Silva (2008), Boore and Atkinson (2008) and Campbel and Bozogornia (2008) for the crustal zones; Sadigh et al. (1997), Zhao et al (2006), Kanno et al. (2006), Abrahamson and Silva (2008) and Chiou and Youngs (2008) for the volcanic zone.

3.3. Hazard Computation

Seismic hazard assessment was performed using the classical Cornell–McGuire approach implemented in EZ-FRISK 7.31 (http://www.riskeng.com/SoftwareHTML/software.html). Each source area was characterized by minimum and maximum magnitudes and by G-R earthquake recurrence rates. Epistemic uncertainty was accounted for by a logic-tree framework, considering the maximum cutoff magnitude and the GMPEs as controlling parameters. Two maximum magnitude have been considered: the maximum historical magnitude and the previous increased of 0.5. While equal weights were assigned to the maximum cut-off magnitudes (M_{max1} and M_{max2} in Table 3.1), higher weights were attributed to GMPEs that were believed to be characterized by a higher likelihood of being correct, on the basis of the comparison with strong-motion data. The logic tree to estimate the horizontal ground motion is composed of 10 branches for each zone, 2 branches for each maximum cut-off magnitude and 5 branches for each GMPE.

3.4. Results

Seismic hazard results are presented in terms of hazard maps and uniform hazard spectral accelerations for the horizontal component, calculated for:

- stiff ground conditions and flat topographic surface representing outcropping conditions;
- 5 percent structural damping of the critical;
- 4 return periods RP = 95 - 475 - 975 - 2475 years;
- 22 structural periods considering the spectral accelerations at 0.2 seconds and 1.0 second for the 2475 year return period to guarantee compliance with North American Building Codes;
- 2099 computation points corresponding to a resolution of the spatial grid of 0.025° with an average spacing of the nodes of about 2.8 km.

Fig. 3.1 shows for example the peak ground acceleration map for 475 years return period. The uniform hazard spectra computed for Port of Spain (Trinidad) for the four return periods considered are plotted in Fig. 3.2. Further details and all the computed results are reported in Lai et al. (2010).

4. CONCLUSIONS

A seismic hazard macrozonation of the Eastern Caribbean based on a PSHA was performed. The horizontal peak ground acceleration expected on stiff ground, with a 10% probability of exceedance in 50 years, corresponding to 475 years return period, ranges between 0.205 g and 0.360 g. The computed hazard spectra, thanks to the adopted dense grid (a node every 2.8 km), can be used by the engineers in the Eastern Caribbean for seismic design of structures.

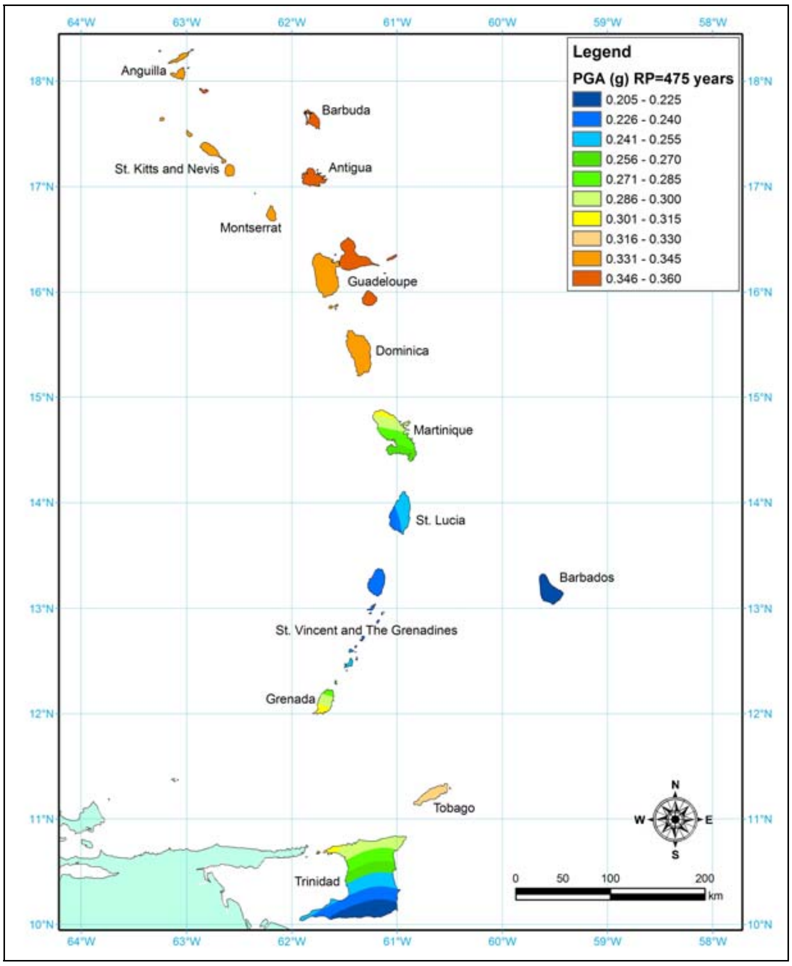

Figure 3.1. Map of PGA values (g) for 475 years return period for the Eastern Caribbean islands

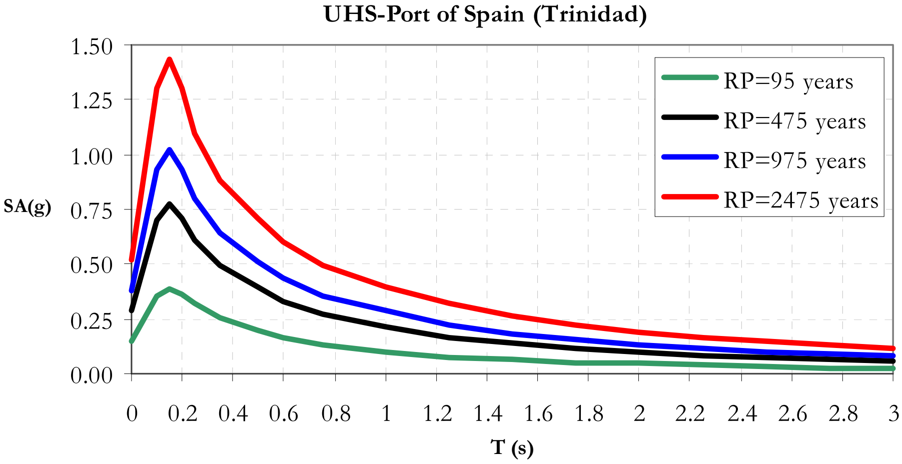

Figure 3.2. Uniform hazard spectra computed for Trinidad (Port of Spain) for four return periods

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