

Probabilistic Seismic Hazard Assessment for Bridgetown-Barbados, Employing Subduction Interface Characteristic Earthquakes

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Abstract: A new probabilistic seismic hazard analysis was performed for the city of Bridgetown, Barbados, West Indies. Hazard computations have been performed using the standard Cornell-McGuire approach based on the definition of appropriate seismogenic sources and expected maximum magnitudes, the authors take into consideration the possibility of large subduction interface earthquakes of magnitude 8.0-9.0 beneath the Barbados accretionary prism via application of a characteristic model and slip rates. The analysis has been conducted using a standard logic-tree approach. Uniform hazard spectra have been calculated for the 5% of critical damping and the horizontal component of ground motion for rock site conditions setting 5 return periods (95, 475, 975, 2,475 and 4,975 years) and spectral accelerations for 34 structural periods ranging from 0 to 3 s. The disaggregation results suggest that the magnitude-distance pair that dominates the hazard yields M 7.4 and 8.6 and a distance of 42.5 km in the Interface Subduction Zone beneath Barbados for the 475 and 975 years RP (return period), respectively. An event with an M 8.0 at a distance of 107.5 km in the Intraplate Subduction Zone is the second scenario that dominates the hazard for both 475 and 975 years RP.

Key words: Tectonics, seismogenic sources, characteristic earthquakes, recurrence interval, disaggregation.

1. Introduction

The present work aims to assess the PSHA (probabilistic seismic hazard) [1, 2] at Bridgetown, Barbados (Fig. 1) in terms of PGA (peak ground acceleration) and response spectra for 5% of critical damping in conjunction with a disaggregation scheme to obtain the magnitude-distance pair that contributes most to the hazard. Recent studies have computed the seismic hazard for the whole Eastern Caribbean including the Island of Barbados [3].

This work attempts to overcome the shortcomings encountered in previous works: The island of Barbados differs geologically from other islands in the Eastern Caribbean for its evolution in an accretionary prism rather than a magmatic origin arc. Barbados lies just

above the inclined interface subduction zone between the descending Atlantic oceanic lithosphere of the American Plate and the overriding Caribbean Plate (Fig. 2). Despite large interface thrust earthquakes have been relatively sparse since historic times in the

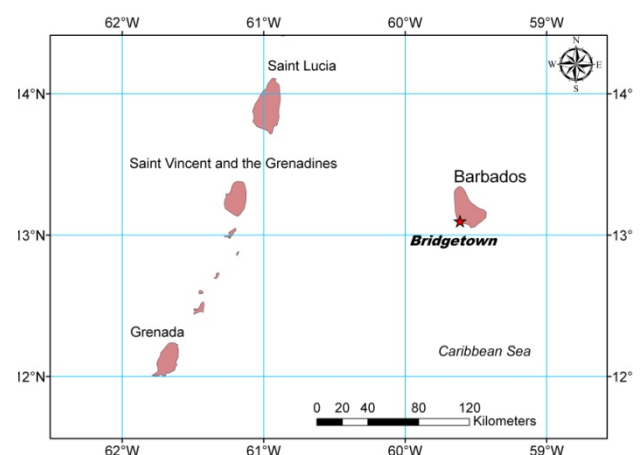


Fig. 1 Bridgetown, Barbados location, the seismic hazard is calculated for the coordinates 13.099° N, 59.613° W (see red star).

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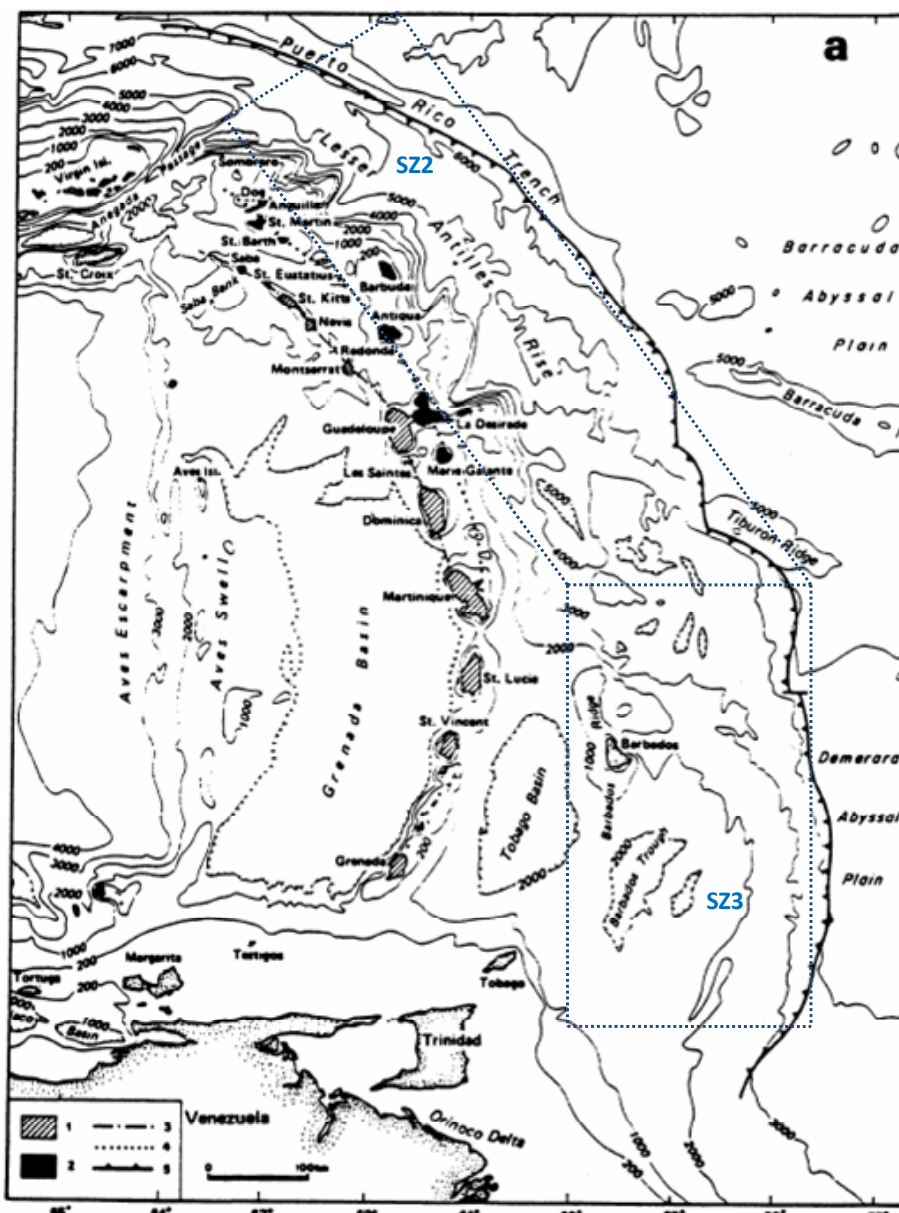


Fig. 2 The Lesser Antilles region, (a) Bathymetric map. 1—Volcanic Caribbees; 2—Limestone Caribbees; 3—axis of the inner arc; 4—axis of the outer arc; 5—deformation front. Isobaths in m; after Ref. [4]. The authors model the subduction interface zone SZ3 beneath Barbados as an inclined plane dipping to the west with an angle of $\approx 10^\circ$ delimited by the coordinates 10.71° – 14.8° N and 57.529° – 60° W, with the trench located at 57.529° W and a maximum depth of 50 km at 60° W. The authors also model the subduction interface zone SZ2 in a similar way for the northern part of the Eastern Caribbean. Reproduction of the figure with the permission of Geoff Wadge and Trevor Jackson.

northern and southern part of the Eastern Caribbean, the worldwide seismic activity trend suggests that large megathrust events of magnitude 8.0–9.0 are possible in regions of long periods of quiescence, clear examples are the recent Sumatra and Japan Earthquakes in 2004 and 2011, respectively. In this regard, the authors

employed a “characteristic model” for the Eastern Caribbean subduction zone and introduced in our tectonic model and hazard calculations the inclined geometry of the slab beneath Barbados based on detailed tectonic and geological information.

The first section of the work for this paper is devoted

to explaining in detail the tectonic environment and the seismicity evaluation for the Eastern Caribbean, including a subsection of the chosen recurrence time for the characteristic earthquakes for the interface subduction zones in accordance with the observed slip rates in the region. Secondly, the authors present the GMPEs (Ground Motion Prediction Equations) adopted to compute the hazard those that are compatible with the tectonics of the region. Thirdly, the PSHA is computed via application of a logic tree formulation in terms of PGA and elastic response spectra, a subsection of the PSHA is presented in terms of the disaggregation process to find out the magnitude-distance pair yielding the largest contribution to the hazard at Bridgetown.

2. Seismotectonic Setting and Geometrical Delimitations

The authors employed the earthquake catalogue and the Gutenberg Richter relationships (Table 1) developed by Bozzoni et al. [3]. Fig. 3 illustrates the geometrical configuration for both, the shallow and

deep zones covering the subduction, upper-crustal volcanic island-arc, transform and intra-plate faulting and transitions zones used for the hazard calculation. This configuration comprises the subduction trench to the east, and the deepest part of the Atlantic Plate to the west. The geometrical delimitation for shallow seismicity in the arc includes the islands, related epicenters, and main geological structures such as volcanoes and seismic faults.

In order to evaluate the seismicity in the region, we established 15 SZs (seismogenic zones) that affect the study area based on detailed tectonics and geological features that already been studied by different authors (Figs. 2 and 3), as follows.

2.1 Zone 1: Volcanic Island-Arc

The upper-crustal seismicity is concentrated within the upper 35 km of the Caribbean continental plate in the Lesser Antilles Arc [5], with epicenters plotting from the islands of Grenada to Anguilla within a nearly continuous belt of 100 km width along both, the axis of the principal active volcanoes and the inland and

Table 1 Main features of the SZs (seismogenic sources) and Gutenberg-Richter Parameters ($\log N = a - bM$) for the Eastern Caribbean [3]. It is noted that the depth set for the seismogenic zones SZ2 and SZ3 are variable in order to model the inclined slab beneath Barbados. M_{max} corresponds to the maximum observed magnitude in the catalogue + increment Δ of 0.5 units for SZ4-SZ11, SZ13-SZ15, an increment Δ of 0.3 has been adopted for SZ1. For SZ12 M_{max} is based on new paleoseismological and slip rates data [6, 7]. * M_{max} used as a characteristic value for SZ2 and SZ3 (see Section 3 and the forth figure).

Seismogenic zone	a	b	M_{max}	Depth (km)	Type	Main focal mechanism
SZ1	4.794	-1.012	6.9	19.1	Volcanic	Normal and strike-slip
SZ2	4.614	-0.893	8.0 >8.0-9.0*	0-50	Interface	Thrust (inverse)
SZ3	3.216	-0.725	8.0 >8.0-9.0*	0-50	Interface	Thrust (inverse)
SZ4	4.164	-0.821	8.5	86.0	Intraplate	Normal
SZ5	2.941	-0.680	8.3	97.9	Intraplate	Normal
SZ6	4.724	-0.941	8	32.3	Interface	Thrust and strike-slip
SZ7	3.043	-0.705	8	28.4	Shallow	Normal
SZ8	3.640	-0.810	7.9	74.5	Intraplate	Normal
SZ9	2.961	-0.727	6.9	24.4	Transition	Normal and strike-slip
SZ10	2.127	-0.531	7.2	43.9	Transition/Intraplate	Normal and strike-slip
SZ11	3.643	-0.783	8.3	99.5	Intraplate	Normal
SZ12	4.100	-0.949	7.7	32.5	Crustal	Normal and strike-slip
SZ13	3.392	-0.747	7.2	23.3	Crustal	Strike slip and thrust
SZ14	2.567	-0.635	8.5	14.7	Crustal	Strike slip and thrust
SZ15	2.825	-0.699	7.1	57.3	Crustal	Strike slip and thrust

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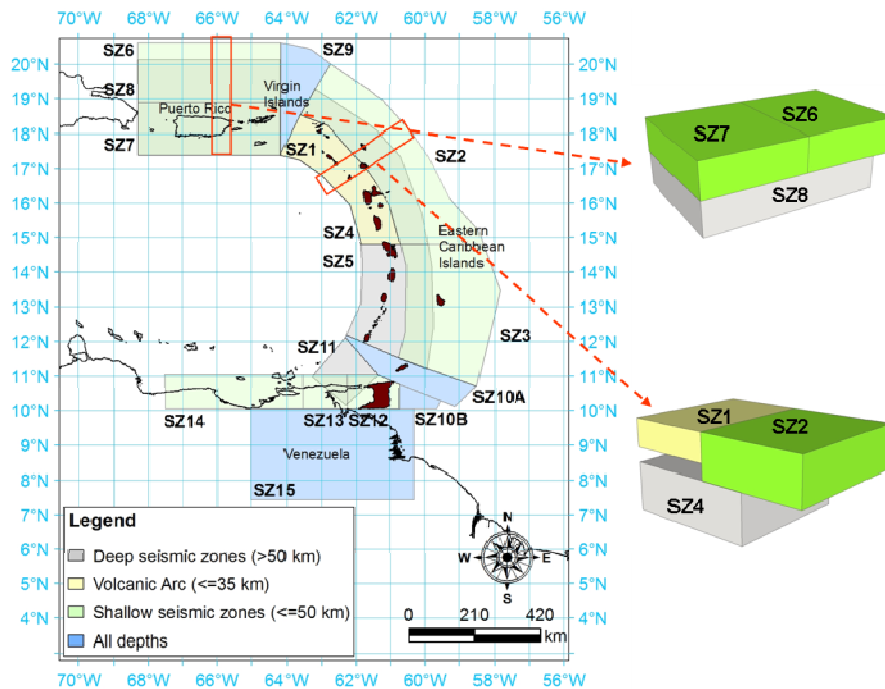


Fig. 3 Seismic source delimitation for the Eastern Caribbean [3]. The 3D view of the SZs is shown to illustrate the overlap amongst the zones. The alternate geometrical delimitations for SZ2 and SZ3 are presented in Fig. 2 and used in the seismic hazard calculations of this work.

offshore shallow faults which run parallel to the Subduction Trench. Within this zone, the magnitudes are moderate, reaching a maximum value of about 6.6 through historic times. Zone 1 comprises an area from north of Martinique to Anguilla covering the Leeward Islands, and we characterize it with a higher seismic activity than the Windward Islands at the southern part of the Lesser Antilles Arc (from Grenada to Saint Lucia). Volcanic disasters in the region over the past 300 years occurred during major explosive eruptions in the Soufriere in St. Vincent (1718, 1812, 1902, 1979), Mt. Pelé in Martinique (1902), Soufriere in Guadeloupe (1976 to 1977) and from 1995 to present in Montserrat volcanoes. However, the moderate shallow earthquakes do not necessarily occur in conjunction with volcanic eruptions and frequently appear in clusters with no discernible mainshock (swarms).

Bernard and Lambert [8] suggested that the evaluation of seismic hazard must also take into account these shallow to moderate earthquakes such as the ones that occurred on 1851 and 1897 in Guadeloupe (5.5-6.0 M_w), March 16, 1985 (6.4 M_w) at south of

Nevis, and the earthquake that occurred on November 21, 2004 (6.3 M_w) in the north-west of Dominique near the Les Saintes Islands. The fault plane solutions in this zone yield both, normal and strike-slip focal mechanisms. A marked lower level of seismicity is observed in the Windward Islands as compared with the other zones of the Eastern Caribbean, the seismic catalogue lists only two upper-crustal events (depth < 20 km) in the Windward Islands dated on September 8, 1972 (4.5 M_w) and May 19, 1990 (4.7 M_w) on Grenada and Saint Lucia respectively, confirming the quiescent characteristic of the Lesser Antilles Arc south region.

2.2 Zone 2-5: Subduction in the Lesser-Antilles

The volcanic island-arc lies about 300 km from the Eastern Caribbean Trench, where the North American plate begins to submerge underneath the Caribbean Plate reaching depths of 200 km below the islands generating earthquakes as large as magnitude 8.0 M_w (according to the historical catalogue). The authors include in Zones 2 and 3 all the shallow focus earthquakes (depth ≤ 50 km) along the inclined

inter-face seismic zone that yields underthrust focal mechanisms [9]. Convergence between the Caribbean and North American plates occurs at a rate of about 2 cm/yr [10].

As an alternative geometrical delimitation for the interface subduction zones presented in Fig. 3, the subduction zone SZ3 is modeled as an inclined plane dipping to the west with an angle of $\approx 10^\circ$ delimited by the coordinates 10.71° - 14.8° N and 57.529° - 60° W, with the trench located at 57.529° W with a maximum depth of 50 km at 60° W. Similarly, the authors also model the SZ2 interface subduction zone as an inclined plane dipping to the west (Fig. 2). It is noted that the previous tectonic model assumed a fixed depth for the interface subduction zone. Due to the proximity of Barbados to the interface subduction zone, we consider it is very important to improve the tectonic model by including a more realistic geometry of the inclined slab beneath the island in the hazard calculations.

The focal mechanisms of deeper intra-plate events (> 50 km) indicate that there is normal faulting resulting from initial flexure of the down going Atlantic slab (Zone 4 and 5) with an average westward dipping angle of 50° [11]. Zones 2 and 4 cover the latitudes from 14.8° N to 20.0° N and they are characterized with a higher seismic activity than Zone 3 and 5 (from 11.0° N to 14.8° N latitude). Bengoubou-Valeruis et al. [11] and Russo et al. [12] attribute the differences in the seismic activity to the following reasons: (1) changes in the tectonic structures mapped by Feuillet et al. [13]; (2) there being enough sediments to lubricate or decouple the two plates in the subduction zone; (3) strengthening caused by thick accretionary prism overburden which lies above the shallow reach of the subduction zone. The quiescent area coincides with the deepest part of the Barbados accretionary wedge. The upper-crustal seismic activity level observed along the volcanic-island arc also reflects also the differences observed in the seismic activity in the subduction zone.

The largest interface event listed in the catalogue dates October 10, 1974 ($7.3 M_w$) with its epicenter

located between Antigua and Barbuda (Zone 2). The largest intra-plate earthquakes within Zone 4 occurred on February 8, 1843 and on April 5, 1690, with a magnitude of 8.0 and 7.5 (M_w), respectively, with both epicenters located to the west of Antigua and Barbuda islands. Other intraplate big events occurred in Zone 5 around Martinique on January 11, 1839, December 3, 1906, and November 29, 2007 with magnitudes 7.3-7.4 (M_w).

2.3 Zone 6-8: Puerto Rico and Virgin Islands

The Puerto Rico and the Virgin Islands region is considered as a microplate that is surrounded by the obliquely subducting North American plate, the Caribbean Plate and several major faults such as the Mona Canyon to the east and Abnegada Passage to the west [14, 15] and the Muertos Trough to the south. Puerto Rico accommodates approximately 16.9 mm/yr of deformation relative to North America and 2.4 mm/yr relative to the Caribbean Plate [16]. The area is divided into three seismogenic sources as follows:

Zone 6: This zone includes the Puerto Rico Trench area with a depth less than 50 km including the megathrust faulting along the plate interface of the subducting North American Plate southward deepening. This zone also comprises the left lateral strike slip faulting that is subparallel to the Puerto Rico trench north and north-west of Puerto Rico including the Septentrional fault. On July 29, 1943 an earthquake ruptured the Puerto Trench with a magnitude of 7.5 (M_w). This seismogenic zone covers the north of Puerto Rico and the Virgin Islands.

Zone 7: This zone comprises the shallow faults (less than 50 km depth) inland Puerto Rico and offshore namely, Mona Canyon, South Lajas Fault, Great Northern and Southern Puerto Rico Fault Zone, the Anegada Trough and Sombrero Seismic Zone [16]. This seismogenic source has produced earthquakes of magnitude 7.5 and 7.3 (M_w) in the Anegada and Mona Passage in 1867 and 1918, respectively, yielding normal faulting in a broad zone of active crustal

extension and accompanied by destructive tsunamis [17]. The absence of volcanism in Puerto Rico and the Virgin Islands suggests that this zone is not an extension of the island-arc Lesser Antilles structure [18].

Zone 8: This zone includes the intra-plate subduction seismicity generated by the bending of the North-American slab with depths greater than 50 km. Moreover, recent research suggests the existence of the subducted Caribbean slab confirmed by low velocity anomalies beneath the island [19]. This seismogenic area comprises the subduction intra-plates slabs of North America southward dipping and the Caribbean northward dipping beneath the microplate. The largest earthquake listed in the catalogue within this zone is dated on March 24, 1916 (7.4 M_w).

The Muertos trough offshore southern Puerto Rico constitutes the thrust-trench locus convergence between the microplate and the Caribbean Plate northward deepening [19]. This seismic zone is excluded from our analysis since the rates of activity in this zone are poorly known [17] and it seems that based on the knowledge of the seismic history, the motion along the Muertos Trough appears to be a small fraction that of the Puerto Rico Trench [14]. The authors confirm this suggestion based on the slow slip rate in this boundary from historical literature consulted to compile the catalogue.

2.4 Transition Zone 9 and 10A

These seismogenic zones are defined as the intersections between the transform faults and subduction zones with the Lesser Antilles Arc located at the north and the south of the Eastern Caribbean. Zone 10A includes the shallow seismic activity in the southern part of the island of Tobago which is considered within the Caribbean-South American Plate boundary [20-22]. Russo et al. [12] suggest also that the northern boundary of the Eastern Caribbean-South America plate may lie as far north as the southern end of the Grenada basin. Moderate but shallow

earthquakes occurred south of Tobago on 1982 (4.8 M_w) and 1997 (6.7 M_w) with right-lateral strike slip and normal faulting mechanisms, respectively [20, 23]. The transition Zone 9 is characterized by a low-seismicity level yielding mainly normal focal mechanisms in the boundary zone between the Lesser Antilles arc and the Puerto Rico Trench.

2.5 Zone 10B: East of Trinidad

Russo and Speed [24] suggested that the earthquakes located in this zone are consistent with the detachment and bending-flexure of the South American slab moving toward the collision zone. The zone covers mainly normal faulting mechanisms with ENE-WSW striking planes and strike slip faults with an average depth of 45 km. The maximum magnitude reported in the catalogue for this zone is 6.7 M_w (March 10, 1988).

2.6 Zone 11: North of Paria Peninsula

This zone constitutes a subducting detached oceanic lithosphere with depth ranging from 50 km to 300 km and represents one of the most active seismogenic sources in the Eastern Caribbean [12]. The largest reported earthquakes occurred in October 21, 1766 and January 10, 1888 with magnitudes of 7.5 M_w and 7.0 M_w , respectively. The focal mechanisms indicate that there is a normal faulting resulting from the initial flexure of the down going slab steeply dipping to the NW at 60°. However, mixed-motion earthquakes with thrust and strike slip indicated bending of the subducting slab at deeper depths.

2.7 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. Weber [21] employed far and near field geodesy and palaeoseismology to search fossil earthquakes on the Central Range Fault, the principal active dextral strike-slip in Trinidad. He concluded that the central

range fault was locked, stored and released significant elastic motion in the recent past. He suggests a slip rate of 12 mm/year and that several more meters of motion could be stored in the fault. In the south, Weber [21] suggests a slip rate of 6 mm/year of the Los Bajos Fault with a dextral motion. Regional tectonic-geological studies conclude that El Pilar Fault might right-step into Central Trinidad [25], however, Weber [21, 26] affirms that the N68°E oblique trending in the central range fault is not associated with El Pilar Fault 90° trending of pure wrenching. More recently, Prentice et al. [6] suggested prehistoric earthquakes of $M > 7$ in this fault based on paleoseismological investigations. A detail PSHA focused only for Trinidad has been done recently by Ref. [7] incorporating larger maximum magnitudes ($M 7.7$) on these faults in a logic tree formulation, slip rates and deterministically bounded ground motions for the Bridges Reconstruction Program and Sir Solomon Hochoy Highway Extension to Point Fortin. This information has been taken into account for the new seismicity parameters presented in Table 1. The northern range and the Arima Fault comprise a complex fault system with lateral strike-slip, thrust and normal faulting. On December 2 and 3, 2004 events with a magnitude of 5.8 and 5.4 (M_w) occurred in the central north-east of Trinidad, fault plane solutions suggest mainly a normal motion with a component of right-lateral strike slip. The location of these earthquakes and the correspondent focal mechanisms coincide with the Northern Range normal fault dipping southward mapped by Algar and Pindell [27] beneath the Caroni Swamp area.

2.8 Zone 13 and 14: El Pilar Fault

These zones comprise the boundary between the Caribbean and the South American plate. The events that have their origin in the fault are shallow—less than 50 km depth—and they are characterized mainly by right lateral strike slip mechanism in the northern coast of South America. The Caribbean Plate is moving about 20 mm/yr in an easterly direction relative to

South America [28]. However, thrust focal mechanism also takes place in this region reflecting the oblique collision at crustal levels between the Caribbean and the South American Plates. The authors observed a high level seismic output in Zone 13 that extends from 63.5° W to 62.3° W longitude covering the Araya-Paria Isthmus, and a moderate seismicity level in Zone 14 that extends from 67.0° W to 63.5° W longitude covering the vicinity of Caracas to the Araya region. The maximum magnitude listed in our catalogue occurred on October 4, 1957 (6.4 M_w) in Zone 13 and on September 1, 1530 (8.0 M_w) in Zone 14.

2.9 Zone 15: South of Trinidad

Russo et al. [12] defined this zone as a passive margin edge in the foreland basin in north of south American continent, covering events with strike slip, mixed thrust and strike slip, and thrust mechanism around the Orinoco Delta region in Venezuela, with an average depth of 50 km and a maximum magnitude of 6.6 (M_w).

Figs. 2 and 3 illustrate the geometrical configuration for both, shallow and deep zones covering the subduction, upper-crustal volcanic island-arc, transform and intra-plate faulting and transitions zones that affect Barbados.

3. Characteristic Magnitude Distribution for the Interface Subduction Zones SZ2 and SZ3

Many fault that exhibit seismicity and crustal strain, indicate that an exponential distribution encompassing all magnitudes is inappropriate. The continuous exponential distribution may be adequate for events up to 8.0 M_w in the subduction zones, however, larger earthquakes may occur with a characteristic magnitude namely $M = 8.0$ to 9.0 whose frequency of occurrence is higher than obtained by “extrapolating” the exponential part of small earthquakes (Fig. 4). The authors employ truncated exponential distributions that could more accurately model the understanding of future events in the interface subduction zone beneath

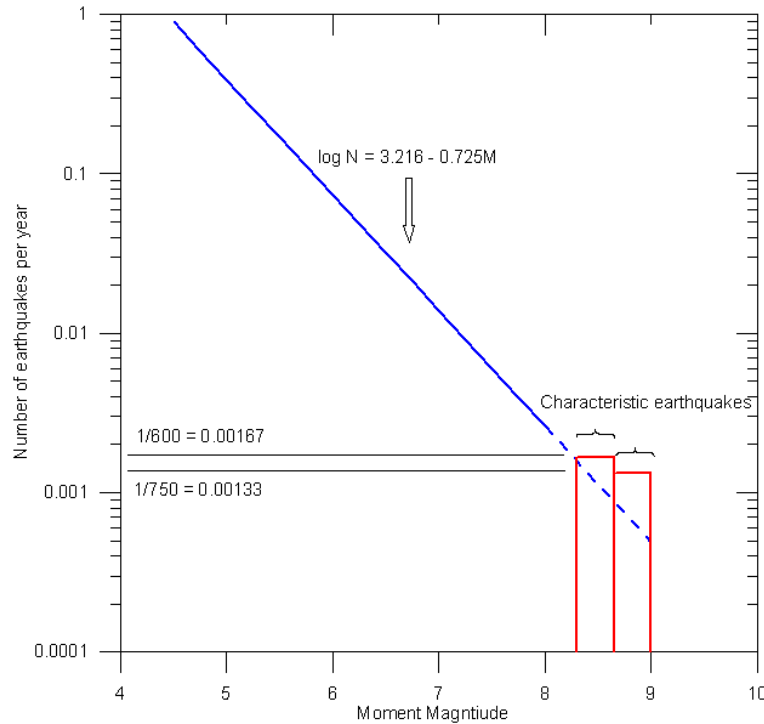


Fig. 4 Seismicity model for the Subduction Interface Zone (SZ3) beneath Barbados. Characteristic earthquakes are considered with a recurrence interval of 600 years for characteristic magnitudes 8.30-8.65. An additional option is a recurrence interval of 750 years for characteristic magnitudes 8.65-9.00 (Table 2).

Barbados, namely: (1) a distribution between $M_{min} = 4.5$ and $M_{max} = 8.0$ with a standard “b” value (Table 1); (2) a distribution between $M_{min} = 8.0$ and $M_{max} = 9.0$ with a “ $b = 0.0$ ” representing the equal likelihood of a characteristic event in that magnitude range.

The activity rate of the minimum magnitude M_{min} for the exponential part is computed from the classical Gutenberg Richter (G-R) relationship (Table 1). The activity rate for the characteristic part can be estimated via paleoseismological investigations, crustal strain data (geodesy) or the recurrence interval between large events. The recurrence interval of large earthquakes in the Eastern Caribbean is very uncertain since there is too little activity to estimate what the largest possible seismic moment could be to constrain the frequency of occurrence. The Headquarters for Earthquake Research and Promotion in Japan had determined the recurrence interval of an M 9.0 earthquake to be 600 years based on historical records of earthquakes in 869, 1611 and 2011. Suppasri et al. [29] concluded that the recurrence interval for an event comparable to the Sumatra 2004

tsunami is approximately 520 years.

Since there are no historical accounts of such big megathrust events in the trench of the southern part of the Eastern Caribbean near Barbados in the past five centuries, our analysis is based on slip rates in the subduction interface zone. Recently, DeMets et al. [10] affirmed by employing GPS stations located in the Caribbean and Central American region, that the Caribbean Plate is in fact moving 2 cm/yr relative to the North American Plate, indicating the possibility of large strain accumulation that could trigger large earthquakes as the afore mentioned examples.

The authors incorporated into the logic tree, two different characteristic magnitudes with a width of 0.35 units with equal weights, namely: (1) 8.3-8.65; (2) 8.65-9.0. To calculate the associated slip rates for the exponential and characteristic part, the procedure below is followed:

The classical Gutenberg and Richter relationship (G-R) is written as follows:

$$\log N = a - bM \quad (1)$$

where, N is the number of earthquakes per year with magnitude equal to or above M , a , b : constants for the Gutenberg and Richter relationship (Table 1).

If one wants to relate a slip rate $\dot{s}$ to an activity rate (number of earthquakes per year) for the seismicity represented by the exponential form in Eq. (1), the following formulas yields [30]:

$$v_{M_{min}} = \dot{s} \mu a_T \frac{\gamma(1-\beta/\gamma)}{k\beta \exp[\beta(M_{min}+d/c)]} (Mo_{max}^{1-\beta/\gamma} - Mo_{min}^{1-\beta/\gamma})^{-1} \quad (2)$$

and

$$\log Mo = cM + d \quad (3)$$

where,

v_{min} : activity rate for the minimum magnitude (M_{min})

using the Gutenberg and Richter relationship in Eq. (1);

μ : rigidity of the earth crust equal to 3.0×10^{11} dyne/cm²;

a_T : rupture area of the fault;

β : $b(\ln 10)$, where b is from the Gutenberg and Richter relationship $\log N = a - bM$;

c , d : constants $c = 1.5$ and $d = 16.05$ in Eq. (3) to obtain the seismic moment Mo giving a moment magnitude M ;

γ : $c(\ln 10)$;

Mo_{max} : moment magnitude in *dyne-cm* for the maximum magnitude M_{max} employing Eq. (3);

Mo_{min} : moment magnitude in *dyne-cm* for the minimum magnitude M_{min} employing Eq. (3).

In the case of the characteristic part, the slip rate can be found by inverting Eq. (5) after obtaining the seismic moment rate (dyne-cm/year) $\dot{Mo}$ and employing the following expressions:

$$\dot{Mo} = \frac{v_{char}}{\gamma} \frac{Mo_{max} - Mo_{min}}{M_{max} - M_{min}} \quad (4)$$

$$\dot{Mo} = \dot{s} \mu a_T \quad (5)$$

where, v_{char} is the activity rate for the characteristic

earthquakes. When evaluating the seismicity for the interface subduction zone SZ3, the authors employed in the logic tree two characteristic models with M 8.3-8.65 and an M 8.65-9.0 and an exponential part with a G-R relationship $\log N = 3.216 - 0.725 M$ (Table 1) for M 4.5-8.0.

The authors model the characteristic magnitudes of 8.30-8.65 with a $v_{char} = 0.00167$ earthquakes per year which is equivalent to a 600 year return period (Table 2), a rupture area of 450 km $\times$ 90 km [31] and using Eq. (4) and inverting Eq. (5) indicates a slip rate of 0.85 cm/yr. When analyzing the characteristic magnitudes of 8.65-9.0 with a return period of 750 years ($v_{char} = 0.00133$ earthquakes per year) a rupture area of 450 km $\times$ 220 km yields a slip rate of 0.92 cm/ yr. Historical seismicity indicates a $v_{4.5} = 0.9$ earthquakes/year and $b = 0.725$ for the magnitude ranges $4.5 \leq M \leq 8.0$; inverting Eq. (2) yields a slip rate of 0.22 cm/yr. The total slip rate resulting from the exponential and the characteristic part for the SZ3 yields 1.99 cm/yr (= 0.22 + 0.85 + 0.92 cm/yr).

The same analysis is performed for the interface subduction zone SZ2 employing the exponential part (Table 2) and the same two characteristic model with M 8.3-8.65 and a M 8.65-9.0 setting 650 years and 850 years recurrence interval, the total slip rates yields 1.98 cm/yr, respectively (Table 3).

The average slip rate of the interface subduction zone in the Eastern Caribbean is suggested to be 2 cm/yr on the basis of geodetic data. The previous example demonstrates that for the two characteristic models and the exponential part, the slip rate is nearly 2 cm/yr for the region validating the recurrence interval between large subduction earthquakes for the Eastern

Table 2 Seismicity models for the interface subduction zone SZ3 beneath Barbados, the activity rate is presented for the minimum magnitude M_{min} for the exponential part being 4.5 and for the characteristic earthquakes.

Magnitudes	b value	M range	Recurrence interval (yr)	Activity rate (earthquakes/yr)	$\dot{s}$ (slip rate)
Exponential	0.725	4.5-8.0	1.1	0.9	0.22 cm/yr
Characteristic	0	8.3-8.65	600	0.00167	0.85 cm/yr
Characteristic	0	8.65-9.00	750	0.00133	0.92 cm/yr
All	-	4.5-8.65	-	-	1.99 cm/yr

Table 3 Seismicity models for the interface subduction zone SZ2. The activity rate is presented for the minimum magnitude M_{min} for the exponential part being 4.5 and for the characteristic earthquakes.

Magnitudes	b value	M range	Recurrence interval (yr)	Activity rate (earthquakes/yr)	$\dot{s}$ (slip rate)
Exponential	0.893	4.5-8.0	0.25	3.94	0.38 cm/yr
Characteristic	0	8.3-8.65	650	0.00154	0.78 cm/yr
Characteristic	0	8.65-9.00	850	0.00118	0.82 cm/yr
All	-	4.5-8.65	-	-	1.98 cm/yr

Caribbean and their use in the Seismic Hazard computations.

4. Ground Motion Prediction Equations

The GMPEs are regionally dependent and the choice of appropriate relations depends on the tectonic environment around the site of interest. No specific GMPEs have been developed for Barbados and the Eastern Caribbean. In order to be compatible with the tectonic environment of the region, the following GMPE's are employed to compute the seismic hazard:

(a) For subduction zones:

Youngs et al. [32]; Atkinson and Boore [33]; Zhao et al. [34]; Kanno et al. [35]; Lin and Lee [36].

(b) For crustal zones:

Kanno et al. [35]; Zhao et al. [34]; Abrahamson and Silva [37]; Boore and Atkinson [38]; Campbell and Bozorgnia [39];

(c) For the volcanic zone:

Sadigh et al. [40]; Zhao et al. [34]; Kanno et al. [35]; Abrahamson and Silva [37]; Chiou and Youngs [41].

To incorporate the GMPEs in the PSHA computation, the correspondent distance definition of each GMPEs has been used, incorporating suitable empirical relations between rupture length and magnitude for crustal and subduction earthquakes [42, 43]. Details of the formulation of each GMPEs can be found in the original articles cited in the reference section of this report.

5. Logic Tree Formulation and Hazard Computation

Epistemic uncertainties in the hazard assessment have been addressed in a logic-tree framework by

considering the following parameters: (1) the maximum cutoff magnitudes; (2) the GMPEs.

The logic tree for the horizontal component consists of a total of 15 branches for the interface subduction zones (SZ2-SZ3), see Fig. 5: Five branches are associated to the normal exponential G-R relationships with five GMPEs while the remaining 10 branches refer to the two characteristic magnitude models and the five GMPEs; five branches are associated for the rest of seismogenic sources employing the five GMPEs. Concerning GMPEs, equal weights have been associated with GMPEs since no strong motion data is available for Barbados. Each seismogenic zone in the Cornell-McGuire method has been treated separately: All the branches for each seismogenic zone have been weighted averaged to obtain a mean hazard curve for each seismogenic zone. The 15 mean hazard curves (1×15 seismogenic zones) have then been summed at the site of interest to produce a single hazard curve representing the Cornell-McGuire final computation.

Seismic hazard results are presented in terms of uniform hazard spectral accelerations for the horizontal component and 5% damping, calculated for:

- (1) stiff ground conditions (NEHRP site classification B) and flat topographic surface representing outcropping ground conditions;
- (2) 5 percent structural damping of the critical;
- (3) 5 return periods $RP = 95 - 475 - 975 - 2,475 - 4,975$ years;
- (4) 34 spectral periods (from 0 to 3 s);
- (5) A truncation value of 3σ (sigma) in the GMPEs.

The PSHA results are presented in terms of Hazard Curves (Figs. 6-8) for the PGA and the acceleration spectral ordinates for 0.2 s and 1.0 s, and the elastic

response spectra for 5% damping is presented in Fig. 9 for 95, 475, 975, 2,475 and 4,975 years RP. The spectrum for 2/3 of 2,475 years RP is also presented. Note the similarity with the spectrum for 975 years RP.

6. Disaggregation of Seismic Hazard

The probabilistic seismic hazard assessment combines the contributions from all the considered sources to provide an estimate at the site of a ground motion parameter of interest with a certain probability of exceedance during a specified lifetime of the structure. Therefore, the physical image of an earthquake in terms of magnitude and source-to-site distance is not clearly visualized in the PSHA. However, through a disaggregation analysis it is

possible to identify one or more earthquakes and find the largest contribution to the hazard [44, 45].

In fact, the disaggregation process separates the contributions to the mean annual rate of exceedance of a specific ground-motion value at a site due to a magnitude (M) and a source to site distance (R) providing the earthquake scenarios that dominate the hazard at the site.

Disaggregation in terms of M – R pairs has been computed for one site located in Barbados (Fig. 10), the PGA and 475 and 975 years return period. The magnitude-distance pair that dominates the hazard indicates an M 7.4 and 8.6 and a rupture distance R of 42.5 km in the interface subduction zone (SZ3) for the 475 and 975 years RP (return period), respectively. The

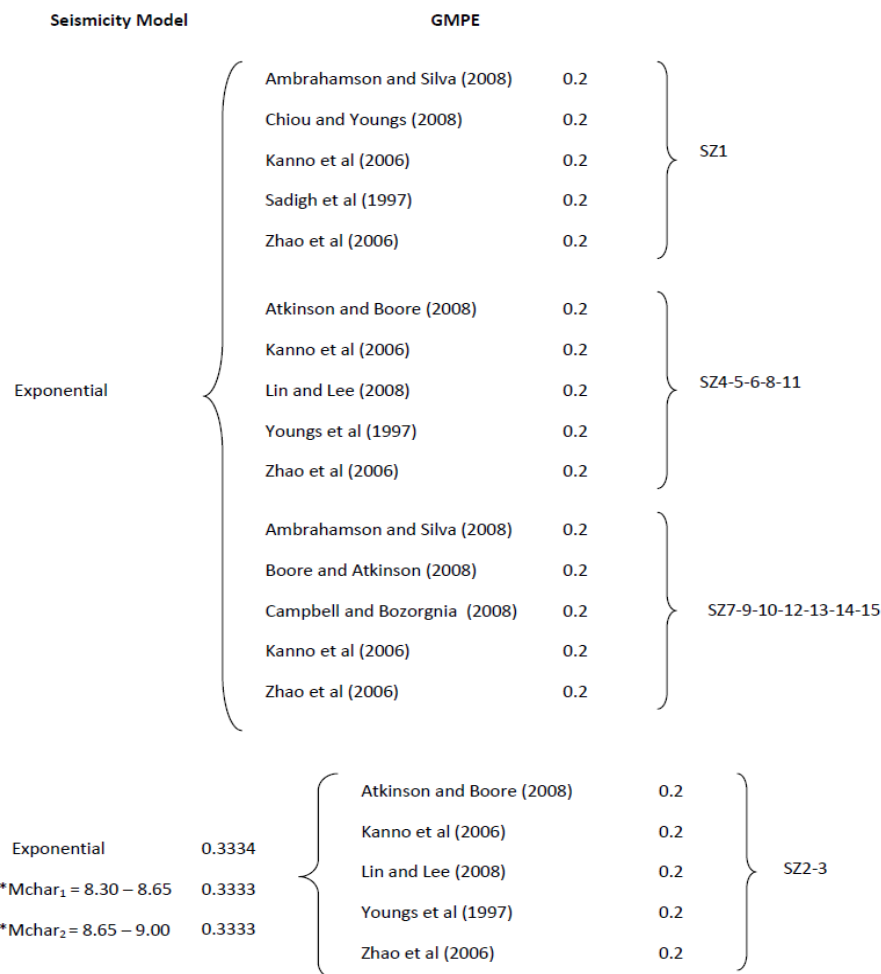


Fig. 5 Logic tree adopted for the horizontal component of ground motion. M_{char} = magnitude for the characterisite earthquakes in the interface subduction zones. The weights used in hazard calculations correspond to the numbers written to the right of each branch of the tree.

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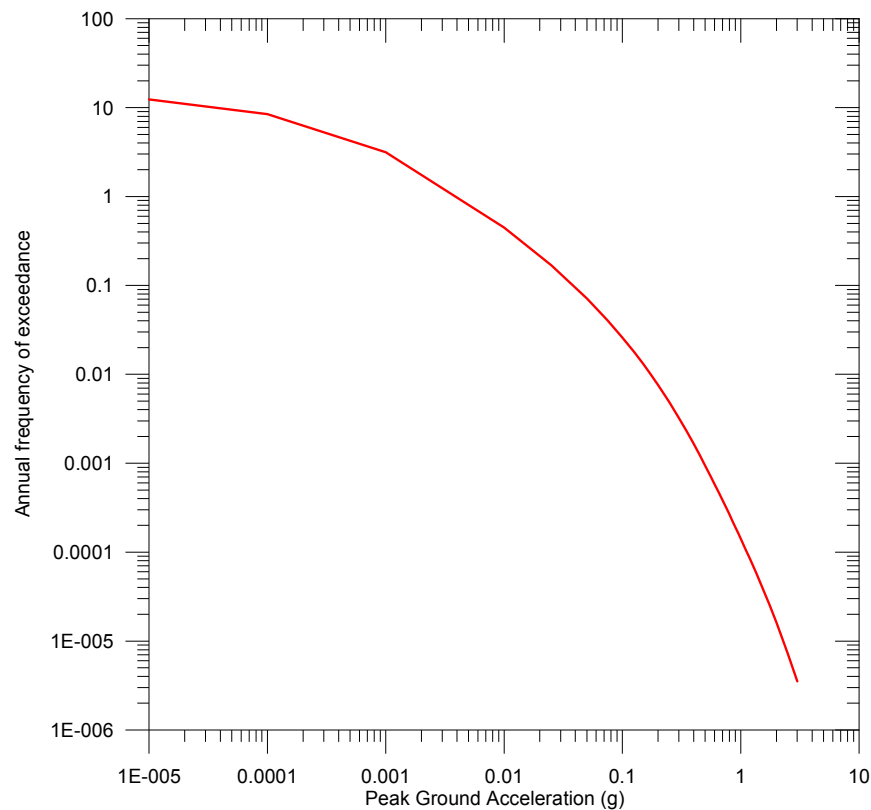


Fig. 6 Peak ground acceleration hazard curve for Bridgetown, Barbados location.

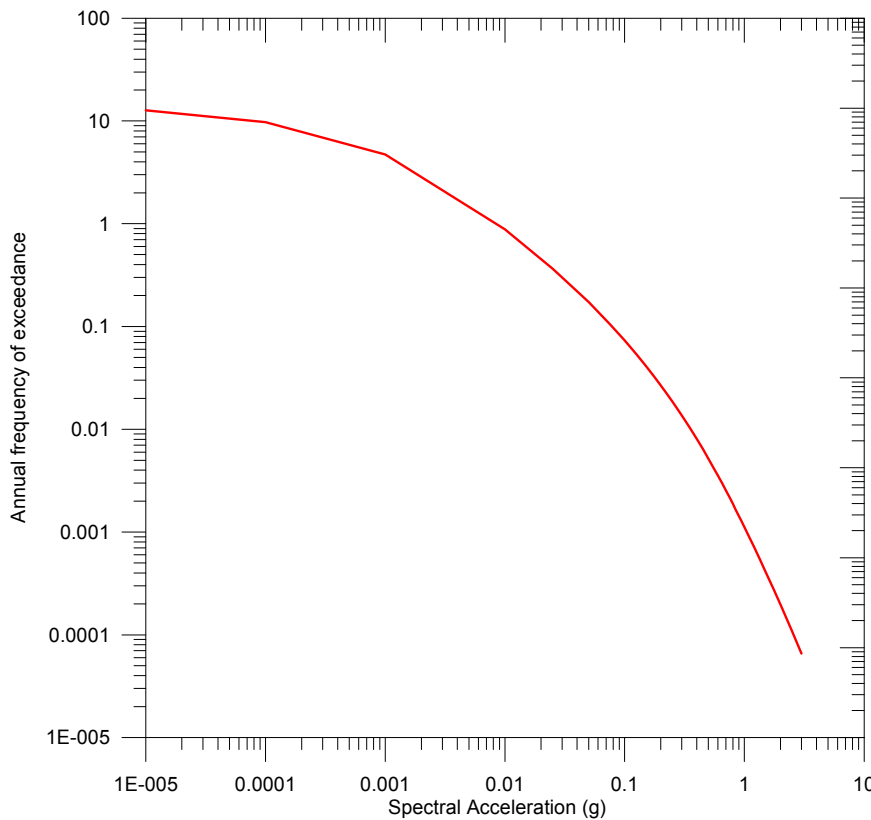


Fig. 7 Spectral acceleration hazard curve at 0.2 s for Bridgetown, Barbados location.

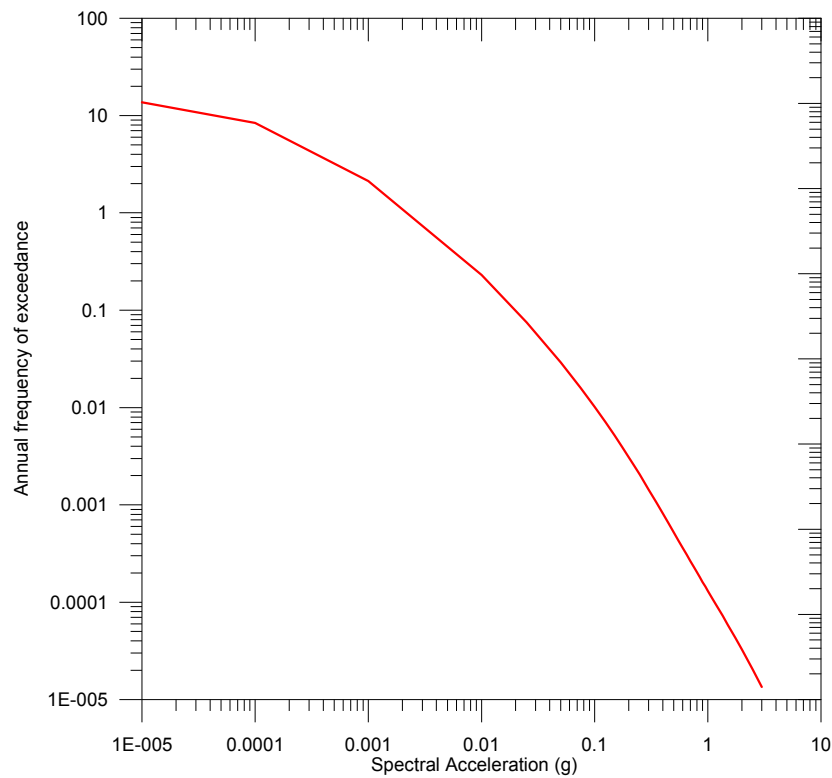


Fig. 8 Spectral acceleration hazard curve at 1.0 s for Bridgetown, Barbados location.

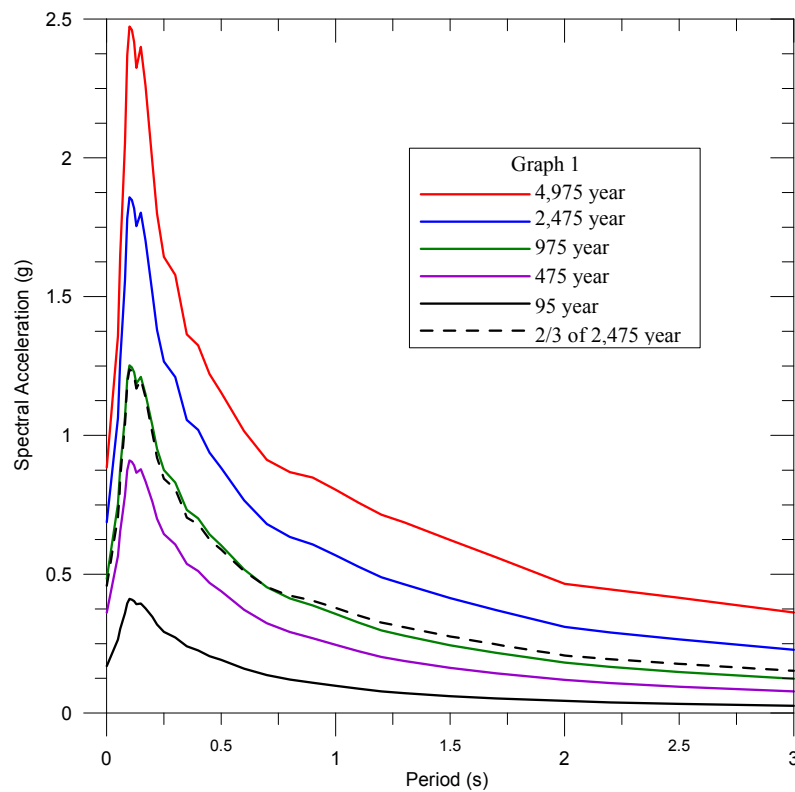


Fig. 9 Elastic design response spectra for Bridgetown, Barbados setting 95, 475, 975, 2,475 and 4,975 years RP (return period). Units of acceleration are in “g”. The spectra for 2/3 of 2,475 year RP is also presented. It is noted the similarity with the spectrum for 975 year RP. Peak ground acceleration values can be taken at the “0” period.

Probabilistic Seismic Hazard Assessment for Bridgetown-Barbados, Employing Subduction Interface Characteristic Earthquakes

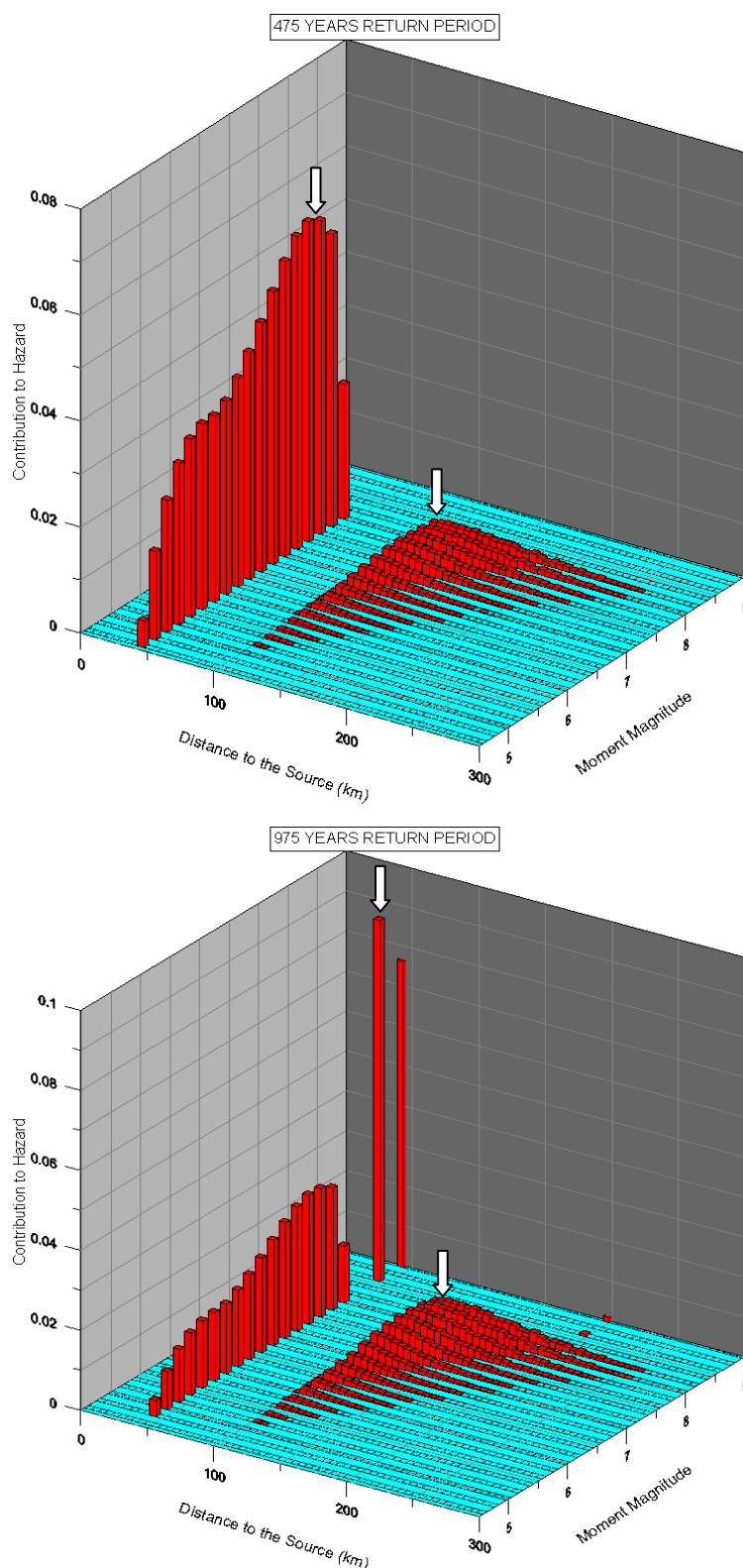


Fig. 10 Disaggregation plots for the peak ground acceleration corresponding to 475 years (above) and 975 years return period (bottom). The magnitude-distance pair that dominates the hazard yields a M 7.4 and M 8.6 with a rupture distance of 42.5 km in the interface subduction zone (SZ3) for the 475 and 975 years RP, respectively (indicated by the white arrows). An event with a M 8.0 at a rupture distance of 107.5 km in the intraplate subduction zone (SZ5) is the second scenario that dominates the hazard for both 475 and 975 years RP.

distance to the source of 42.5 km represents the closest distance from the site to the inclined interface zone Beneath the island. An M 8.0 at a rupture distance of 107.5 km in the intraplate subduction zone (SZ5) is the second scenario that dominates the hazard for both, the 475 and 975 years RP (Fig. 10).

7. Conclusions

The scope of the work presented here was to carry out a seismic hazard assessment for Bridgetown, Barbados based on a state-of-the-art PSHA study. PSHA has been performed using the classical Cornell-McGuire approach. Design response spectra have been developed for 5% of critical damping and the horizontal ground motion on outcropping bedrock conditions, thereby neglecting local site amplification effects at this stage.

The present study has shown that Barbados is characterized by a high seismic hazard, the horizontal peak ground acceleration expected on stiff ground yields 0.36 g, setting a 10% probability of exceedance in 50 years lifetime for the structure, which corresponds to 475 years RP. The level of hazard prescribed by this research is substantially larger than previous works (i.e., Bozzoni et al. [3] suggest 0.22 g for 475 years RP), this increment is attributed to two reasons: (1) Former works did not consider the possibility of megathrust earthquakes beneath Barbados, in fact the maximum magnitudes considered in previous works used for this zone yields 7.0-7.5 based solely on 500 year of earthquake history, much lower than the maximum magnitudes employed in this work: a M 8.0 within the exponential G-R relationship and the characteristic earthquakes within the magnitude range of M 8.3 to 9.0 based on slip rates; (2) only the classical method of Cornell-McGuire was taken into account in the computation of the disaggregation process for this work; the authors did not introduce in the logic tree formulation the free-zone method proposed by Woo [46] and used by Bozzoni et al. [3] as well, it has been observed that the free zone

methods yield lower hazards results than the classical Cornell method in areas of sparse seismicity in terms of short period components of ground motion [47, 48].

The authors recommend the use of the 2/3 of 2,475 years RP seismic loads (which is equivalent to the 975 years RP) prescribed by the IBC (International Building Code) [49, 50] and make use of the 0.46 g for the PGA in the future design of short period structures in Barbados (Fig. 9), indeed, the Magnitude-Distance Pair (M - R) dominating the hazard at this level indicates an interface earthquake of M 8.6 at a distance R of 42.5 km beneath the island of Barbados and with important contribution of an M 8.0 at a distance R of 107.5 km in the intraplate subduction zone for the 975 years RP. It is noted that the definition of distance employed here is the closest distance to the rupture fault. The authors have performed the PSHA employing available GMPE's for interface subduction zones which maximum magnitudes in the range of 8.0-8.5, better results would be available employing GMPE's incorporating the new strong motion data of recent interface subduction earthquakes in Chile and Japan (M 9.0).

If a mega earthquake has not occurred in a region within the past 500 years—for which historical data is available—it does not mean that an earthquake will not occur in the future (as the cited cases in Japan and Sumatra). Barbados is just above the inclined subduction interface zone having slow slip rates yielding long recurrence intervals in this region. The validation of this preliminary characteristic model provided in this work for mega interface subduction events in the Caribbean could be done focusing on seismic plates coupling research and tsunami geological sedimentation studies in the Islands, including Barbados.

For 95 years, RP the magnitude distance pair that contributes the most to the hazard gives an M 6.8 with a distance of 42.5 km (subduction interface event) and an M 7.6 at a distance of 107.5 km (subduction intraplate event) corresponding to a PGA of 0.17 g. This seismic load can be used to design provisional structures during

the construction phase of buildings in Bridgetown. For the 2,475 years RP, the magnitude-pair yields an M 8.7 and a distance of 42.5 km (subduction interface event) and M 8.1 and a distance of 102.5 km (subduction intraplate event) for a 0.68 g of PGA.

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