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Computation of Risk Coefficients (C_{RS}, C_{R1}) for Obtaining Risk-Targeted Earthquake Hazard Values for Several Caribbean Territories

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Abstract: *The most critical input data for the calculation of the earthquake force on a structure are the spectral accelerations S_s and S_1 which are obtained from maps. For building codes before 2012, these values are uniform hazard – all locations have the same probability of being exceeded. However, the codes since 2012 require S_s and S_1 that are uniform risk – all structures must have the same probability of collapse. To convert from uniform hazard to uniform risk requires the risk coefficients C_{RS} and C_{R1}, and these are not available for the Caribbean region. Therefore, the government agencies responsible for approving structural design do not allow use of building codes after 2009, and hence, the advantages of those codes are not available. If engineers use such codes with uniform hazard values, this would contradict the aim of the codes and design forces can be underestimated. Obtaining the uniform risk coefficients by the usual approach is costly and time consuming since special-purpose software implementing numerical analysis is required and not available in the Caribbean. In this paper, the risk coefficients are determined for several Caribbean territories by an alternative approach based on an analytical solution reported to give excellent results compared with the conventional approach. The calculated risk coefficients for the Caribbean are in the ranges of 1.03 to 1.11, and 1.02 to 1.19 for C_{RS} and C_{R1}, respectively. Engineers can now safely and consistently use the latest building codes for the structural design of Caribbean structures.*

Keywords: *Risk Coefficients, Caribbean Risk-Targeted Seismic Ground Motion*

1. Introduction

The earthquake-resistant structural design of buildings is performed by use of an appropriate building code and the documents to which it refers. For approximately the past 40 years, territories of the English-speaking Caribbean that are prone to significant earthquakes utilise the American building codes as the model codes. These codes are either directly referenced, or are used as the basis from which local building codes are derived. In particular, at this point the main codes are the International Building Code (IBC) (2018) by the International Code Council, and the Minimum Design Loads for Buildings and Other Structures (ASCE 7) (2017) by the American Society of Civil Engineers.

In determining the earthquake force exerted on a structure, a vital input datum is the peak acceleration of the structure – the spectral acceleration, S_a, for the first vibration mode of the structure, a damping ratio of 5% of critical, and for firm soil conditions (i.e., S_a (T_1,5%)). Henceforth, only the term S_a will be used and expressed in units of acceleration due to gravity, g). In order to reflect the severity of the earthquake that should be considered, the peak spectral acceleration value is the value with only a 2% chance of being exceeded within the service life of the structure, which is taken as 50 years. To cater for any regular building of natural period, T, the S_a is simply read from a graph (or its equivalent expressed as an equation). This graph – the spectral acceleration response spectrum, is constructed from the S_a at two specific natural periods – 0.2 and 1.0 second, which are referred to as S_s and S_1, respectively. Hence, the most important input data required for calculating the earthquake force on a building is the S_s and S_1. Even if the building is irregular, these parameters provide bounds on any solution method such as linear or nonlinear dynamic analysis. S_s and S_1 are obtained from seismic hazard maps which show the values in terms of contours: hence by interpolation, the values can be readily determined for any location on the map.

Seismic hazard maps have been available for Caribbean territories since around 1980, and are prepared by the Seismic Research Center (SRC) of The University of the West Indies (UWI). The maps for the United States are prepared by the United States Geological Society (USGS) based on a standard procedure – the Cornell-McGuire Probabilistic Seismic Hazard Analysis (PSHA) procedure (1968), which is used by the SRC for its maps as well. The building codes and PSHA have evolved over the years, with new versions of the former being released about every 3 years. Between releases, if advances in PSHA warrant a change, then this change is incorporated in the next version of the building code.

The 2012 version of the IBC, and the corresponding ASCE 7-10, incorporated a major paradigm shift in terms of what the seismic hazard maps indicate. Prior to 2012, the values shown in the maps represent uniform hazard. That is, for all locations within the United States (with some exceptions), the chance of exceeding the value is 2%. However, it was acknowledged since the ATC 3-06 (Applied Technology Council, 1981), the historical root document of the NEHRP model codes on which the ASCE 7 is based, that damage to a structure due to an earthquake depends on the unique characteristics of the structure - its fragility, together with the acceleration. This is because for a given structure, the same level of damage can result from different S_a. Hence, it is more reasonable to consider this fact in the determination of the seismic hazard, such that the risk of damage to the structure is the same for all structures regardless of location. Thus, the paradigm shift is that the S_s and S_1 are determined with respect to uniform risk and not to uniform hazard.

The ASCE 7 incorporates a practical way of obtaining the uniform risk acceleration values – simply multiply the uniform hazard values by conversion factors. The latter are called the risk coefficients C_{RS} and C_{R1} for S_s and S_1, respectively, and these values are also available as maps. When the risk coefficients are applied, the resulting values are referred to as "risk-targeted" values. Unfortunately, owing to significant resource constraints, neither risk-targeted maps, nor risk coefficient maps are available for the Caribbean. The result is that governmental approving agencies have limited the allowable codes to the IBC 2009/ASCE 7-05, therefore any technological improvements or corrections since 2012 cannot be taken advantage of in Caribbean building design. If an engineer ignores the need for using risk-targeted maps and proceeds to use post-2012codes, this would violate the manner in which the codes are expected to be used, and may expose the engineer to litigation in the event of undesirable performance of the building.

This paper concerns C_{RS} and C_{R1} values for use with the existing uniform hazard maps for several Caribbean territories. This is as regards how they were derived, the values themselves, and recommended usage. These C_{RS} and C_{R1} values can be employed by governmental approving agencies as an interim measure until a more detailed study is undertaken.

2. Approaches for Computing Seismic Risk of Collapse

Computing C_{RS} and C_{R1} values involves reverse-engineering the procedure by which the probability of collapse of a structure, also called the collapse risk, or the mean annual frequency of collapse (MAF), is determined. If the event is expressed in terms of S_a as the Intensity Measure (IM), then data about the seismicity of the site, and the fragility of the structure are known, and the MAF calculated for a given S_a. However, for computing C_{RS} and C_{R1} values, the MAF is known, and the S_a corresponding to collapse is calculated. If S_a is the S_S, then the C_{RS} is simply the calculated S_S divided by the uniform hazard S_S, and likewise for the C_{R1}. The main approach used in the United States for computing the seismic risk of collapse is a special case of the PEER Triple Risk Integral (Moehle and Deierlein, 2004):

$$v(DV>x) = \int\int\int G \langle DV \mid DM\rangle\, dG \langle DM \mid EDP\rangle\, dG \langle EDP \mid IM\rangle\, d\lambda(IM) \qquad (1)$$

The terms *v*, DV, DM, EDP, and λ(IM) mean – annual probability that loss > x, decision variable (e.g., downtime, casualties, and damage), damage measure (e.g., cracking, fracture, and buckling), engineering demand parameter or response (e.g., drift, beam rotation), and seismic hazard which is the annual probability of exceeding the ground motion intensity measure (e.g., PGA, $S_a(5\%,T_1)$, etc.). The term "G" refers to each of the X|Y in Equation (1) as the conditional probability P(X>x | Y=y). Equation (1) is a general equation that considers the entire chain of consequences – shaking which leads to response, which leads to damage, that leads to loss. For the purposes of this study, only "shaking leading to damage" is considered, where "damage" is "collapse". Hence, the triple integral becomes the following single integral, since "response" and "loss" are not included. Only such an IM-based format will be considered henceforth.

$$\text{MAF} = \int_0^{+\infty} \frac{d(P(collapse\ |S_a = s))}{ds} H(s)ds \qquad (2)$$

P(collapse | S_a = s) is the fragility of the structure, "s" is any particular value of S_a under consideration, and H(s) is the seismic hazard at the site and is the mean annual probability of S_a exceeding any particular value "s". H(s) is expressed as the "hazard curve" for the location of the structure – a graph of exceedance probability vs S_a , and is determined from the PSHA of the site. The fragility of the structure is determined via analysis of the damage statistics given the results of numerous analyses of the structure at collapse.

If done numerically, the computation of the MAF using Equation (2) yields the most accurate result. However, this requires the preparation of special-purpose software and can be tedious. Therefore, it would be advantageous if Equation (2) can be computed analytically hence resulting in a formula.

2.1 SAC Closed-Form (Analytical) Solution

Jalayar (2003) proposed approximating the hazard curve with a power law, and the fragility curve with a lognormal function. Hence, Equation (2) becomes analytically integrable and the approximate MAF is then given by,

$$\text{MAF} = H(\hat{s}_c)e^{\frac{1}{2}k_1^2\beta_{sc}^2} \qquad (3)$$

$\hat{s}_c$ is the median value of the S_a at collapse of the building, and β_{sc} is the standard deviation of the log of the S_a at collapse of the building. k_1 is a parameter of the hazard curve power law (and k_0) given by,

$$H(s) = k_0 e^{-k_1 \ln s} \tag{4}$$

Equation (3) is more commonly referred to as the SAC equation given its prominent use in the joint venture research programme by the Structural Engineers Association of California (SEAOC), the Applied Technology Council (ATC) and CUREE (Consortium of Universities for Research in Earthquake Engineering) after the Northridge earthquake of 1994.

2.2 Vamvatsikos Closed-Form (Analytical) Solution

Use of Equations (3) and (4), as recommended by Jalayar (2003), result in very high though conservative error comparing with the exact solution given by Equation (2). The main causes for the error are how the power law of Equation (4) is applied, and the equation itself. Equation (4) represents a straight line in log-log space, and Jalayar (2003) determined the "k" parameters by taking a tangent to the hazard curve at the S_a corresponding to the earthquake demand (i.e. 2% in 50 years in this case = 0.02/50=0.0004).

Bradley and Dhakal (2008) indicated that the portion of the hazard curve due to the higher frequency S_a contributes most to the integral of Equation (3), and Dolsek and Fajfar (2008) recommended using the region bounded by $0.25\hat{S}_c$ and $1.25\hat{S}_c$ and this procedure is referred to as a "biased fit". Dolsek and Fajfar (2008) suggested obtaining the biased fit "k" parameters using linear regression analysis of the hazard curve in this zone, rather than the approach by Jalayar (2003).

Vamvatsikos (2015) noted that it is simpler and more consistent to use two points selected on the basis of the dispersion of the fragility curve and then use the simple straight line equation of the resulting line, which is a secant to the hazard curve, to obtain the "k" parameters. He proposed the points 0.5 and 1.5 standard deviations to the left of $\hat{S}_c$ and refers to the procedure as a "first-order biased fit". Very significant improvement was observed when this approach was applied to the well-known Van Nuys site and for the case of β_{sc} of 0.5, $\hat{S}_c$ of 2.0g, and T_1 of 0.7 sec. The result was a calculated MAF of 0.0014 compared to the exact value of 0.0015, hence an error of -6.7%. The "tangent fit" approach resulted in an error of 240%.

Vamvatsikos (2015) proposed further refinement using a procedure termed "second-order hazard fitting". In this case, Equation (4) is replaced by Equation (5), and three points are used to obtain the three "k" values – at 0.5, 1.5, and 3.0 standard deviations to the left of $\hat{S}_c$.

$$H(s) = k_0 e^{-k_2 (\ln s)^2 - k \ln s} \tag{5}$$

As mentioned previously, it was determined that a significant source of error is the assumption of a linear relation in log-log space for the hazard curve. The use of Equation (5) is a more realistic approximation for the hazard curve as it considers the well-known curvature of the hazard curve via the k_2 parameter in the region of interest.

The Vamvatsikos second-order hazard fitting approach results in the following equation when the analytical integration of equation (2) is performed:

$$\text{MAF} = \sqrt{p'}\, k_0^{1-p'}\, [H(\hat{s}_c)]^{p'} e^{\frac{k_1^2(1-p')}{4k_2}} \tag{6a}$$

$$\text{MAF} = \sqrt{p'}\, k_0^{1-p'}\, [H(\hat{s}_c)]^{p'} e^{0.5p' k_1^2(\beta_{Sc}^2 + \beta_{USc}^2)} \tag{6b}$$

$$p' = \frac{1}{1 + 2k_2(\beta_{Sc}^2 + \beta_{USc}^2)} \tag{7}$$

β_{USc} represents the epistemic uncertainty in the capacity (β_{Sc} represents the aleatory uncertainty). Equations (6a) and (6b) are equivalent, but (6b) can be used if $k_2 = 0$ (i.e. $p' = 1$). Note that $0 < p' \leq 1$.

When Equations (6a) and (7) were applied to the aforementioned Van Nuys problem, the error reduced from -6.7% for the first-order biased fit, to less than 1% compared with the exact value.

The error due to the approximations increases with increasing uncertainty (i.e., total β), and increasing curvature of the hazard curves. This is because of the increased area under the capacity lognormal curve, and increased neglect of points on the hazard curve other than the three data points used to obtain the "k" parameters, respectively. Therefore, validation of the second-order biased fit approach requires consideration of such conditions. Vamvatsikos (2015) applied the equation to five sites in New Zealand with hazard curves having considerable curvature for T_1 of 1.5 sec. The results are shown in Figure 1.

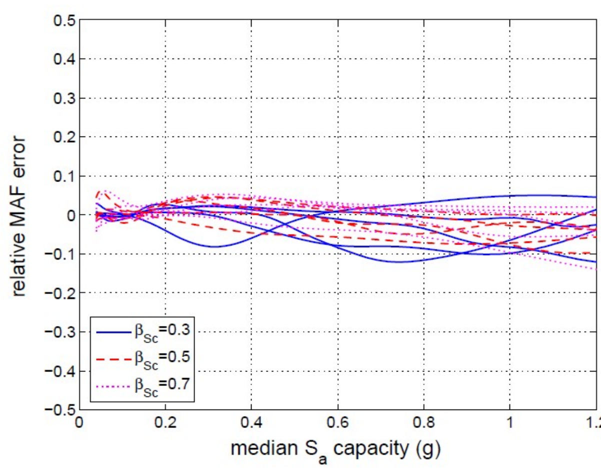

Figure 1. Relative Error of the Vamvatsikos Second-Order Biased Fit Method
Source: Excerpted from Vamvatsikos (2015)

Furthermore, for these five sites, the MAF was calculated for β values of 0.3, 0.5, and 0.7 and for $\hat{S}_c$ varying from 0.0 to 1.2g. As shown, the underestimation error rarely exceeds 10%; and according to Vamvatsikos (2015), the actual error is significantly less because fewer ground motions than is typically used were applied in the calculation of the five hazard curves. Therefore, his final conclusion is that for all practical purposes, the second-order biased fit analytical solution (i.e. Equations (6) and (7)) results in a very close match to the exact value which is obtained by the more tedious and costly numerical integration method.

3. Methodology for Computing C_{RS}, C_{R1} for the Caribbean

To determine the C_{RS} and C_{R1} for the United States, the USGS use the numerical integration of equation (2) to iteratively reverse-engineer the required s_c. This is done using the known hazard curves for the site, a MAF of 0.0002 (i.e. 1% over a 50 year service life), and a "generic fragility curve" as a lognormal function with total β of 0.8. Note that the S_a of the hazard curves were converted to geometric mean values by multiplying the uniform hazard values by 1.1 and 1.3 for S_s and S_1, respectively. The required s_c is the value of the fragility curve at the 10th percentile (Luco, 2009, 2015).

For computing the C_{RS}, C_{R1} for the Caribbean, the same overall procedure used by the USGS was employed except that the Vamvatsikos analytical second-order biased fit Equation (i.e., (6) and (7)) was used for the integration. However, two changes were made to this procedure. Firstly, the right-hand sides of Equations (6a) and (6b) were multiplied by 1.1 to cater for the previously mentioned error. Secondly, instead of using three points to obtain the "k" parameters, second-order polynomial regression analysis of the hazard curves was used. This should be more accurate, since more points are involved in calculating the "k" parameters.

The procedure was applied to several Caribbean locations, including:

- Trinidad (Port-of-Spain; Chaguanas; Arima; San Fernando; Sangre Grande; Rio Claro; La Brea; Point Lisas; Tabaquite; Diego Martin; Guayaguayare, and Princes Town)
- Tobago
- Dominica
- Antigua
- Barbados

For the practical convenience of using one value for an entire country, in the case of Trinidad, since only 12 locations were considered, the mean value was not used as this may be too unconservative. Based on the Central Limit Theorem, the recommended value for Trinidad was determined using the mean plus one sigma of the calculated risk coefficients (i.e. the 84th percentile). For the other territories, the median value of the largest S_a contour band for the island was used. The details of the procedure are as follows:

1. Construct the hazard curves for each location: For S_S and S_1 each, 7 data points are considered sufficient for the regression analysis. Four were obtained using the 4 SRC maps (Seismic Research Center, 2018), and 3 were determined using the following Equation (8) from FEMA (FEMA, 1997) which provides S_a for any exceedance probability given values at 10% and 2%, and between those percentages. Therefore, the hazard curves were determined for the following exceedance probabilities over 50 years: 2, 3, 5, 7, 9, 10, and 41%. These correspond to return periods of 2475, 1642, 975, 689, 531, 475, and 95 years, respectively.

$$\ln (S_i) = \ln(S_{i10/50})+[\ln(S_{i2/50}) - \ln(S_{i10/50})][0.606 \ln(P_R) - 3.73] \quad (8)$$

"i" refers to "s" or "1" accordingly; $S_{i10/50}$ is the S_a at 10% exceedance probability over 50 years; $S_{i2/50}$ is the S_a at 2% exceedance probability over 50 years, and P_R is the return period in years.

2. For each hazard curve (i.e. for each location), and S_s and S_1 each, construct data pairs by taking the natural log H() and the natural log of S_a() (after converting to the geometric mean value).
3. For each hazard curve (i.e. for each location), and S_s and S_1 each, from Equation (5) perform second-order polynomial regression analysis to obtain its "k" parameters.
4. For each hazard curve (i.e. for each location), and S_s and S_1 each, substitute in Equation (7), and the adjusted Equation (6) (i.e. by multiplying the RHS by 1.1) for a total β of 0.8. Then use of MS-EXCEL to "goal-seek" for the $\hat{s}_c$ results in a MAF of 1% over 50 years (= 0.0002 annually).
5. For each hazard curve (i.e. for each location), and S_s and S_1 each, determine the value of S_c at the 10th percentile by considering the dispersion. Therefore, $S_{c,10\%} = \hat{s}_c\, e^{-1.28\beta} = 0.359155\hat{s}_c$.
6. For each hazard curve (i.e. for each location), and S_s and S_1 each, calculate C_{RS} as $S_{c,10\%}$ divided by the uniform hazard S_S at 2% in 50 years, and the C_{R1} as $S_{c,10\%}$ divided by the uniform hazard S_1 at 2% in 50 years.
7. In order to recommend single C_{RS} and C_{R1} values to use for Trinidad, calculate the mean plus one sigma of the values from step 6, and use the resulting values.

4. Results and Discussion

The hazard curve data are shown in Table 1. A possible source of error for the case of the data for Trinidad is that the data were obtained by linear interpolation of contour values. However, in the maps, the contour lines are not shown beyond the perimeter of the island, so for locations near the coast, the extension of those lines outside the perimeter had to be estimated. Figure 2 shows a main straight line tangential to the lowest curve at the value of S_a for the 2% exceedance probability.

Table 1 Hazard Curve Data (Geometric Mean)

Location	**S_s**							**S_1**						
	2475	1642	975	689	531	475	95	2475	1642	975	689	531	475	95
Port-of-Spain	1.683	1.454	1.167	1.059	0.963	0.922	0.479	0.545	0.461	0.374	0.322	0.290	0.276	0.127
Chaguanas	1.584	1.367	1.137	0.995	0.904	0.866	0.442	0.506	0.427	0.348	0.297	0.267	0.254	0.121
Arima	1.679	1.444	1.191	1.042	0.945	0.903	0.455	0.494	0.420	0.347	0.297	0.267	0.255	0.122
San Fernando	1.455	1.256	1.045	0.914	0.831	0.795	0.407	0.473	0.400	0.324	0.279	0.250	0.238	0.113
Sangre Grande	1.668	1.430	1.177	1.025	0.927	0.886	0.440	0.473	0.402	0.328	0.282	0.254	0.242	0.117
Rio Claro	1.488	1.280	1.057	0.925	0.839	0.802	0.402	0.439	0.373	0.304	0.262	0.236	0.225	0.109
La Brea	1.440	1.242	1.040	0.902	0.820	0.784	0.402	0.478	0.404	0.325	0.281	0.252	0.239	0.113
Point Lisas	1.503	1.300	1.085	0.950	0.865	0.828	0.424	0.493	0.416	0.337	0.290	0.260	0.247	0.117
Tabaquite	1.487	1.284	1.067	0.934	0.849	0.813	0.436	0.458	0.389	0.317	0.274	0.247	0.235	0.113
Diego Martin	1.715	1.479	1.219	1.074	0.976	0.934	0.493	0.553	0.468	0.380	0.327	0.294	0.280	0.129
Guayaguayare	1.420	1.216	1.000	0.870	0.787	0.751	0.371	0.417	0.353	0.283	0.247	0.221	0.211	0.100
Princes Town	1.439	1.259	1.034	0.944	0.865	0.832	0.400	0.451	0.383	0.311	0.270	0.243	0.231	0.112
Tobago	2.035	1.708	1.375	1.169	1.043	0.990	0.495	0.487	0.431	0.357	0.329	0.304	0.292	0.097
Dominica	1.760	1.530	1.210	1.130	1.032	0.990	0.495	0.617	0.515	0.487	0.347	0.309	0.292	0.162
Antigua	1.925	1.638	1.136	1.154	1.038	0.990	0.495	0.682	0.616	0.487	0.366	0.313	0.292	0.162
Barbados	1.210	1.044	0.825	0.759	0.690	0.660	0.275	0.487	0.431	0.292	0.329	0.304	0.292	0.098

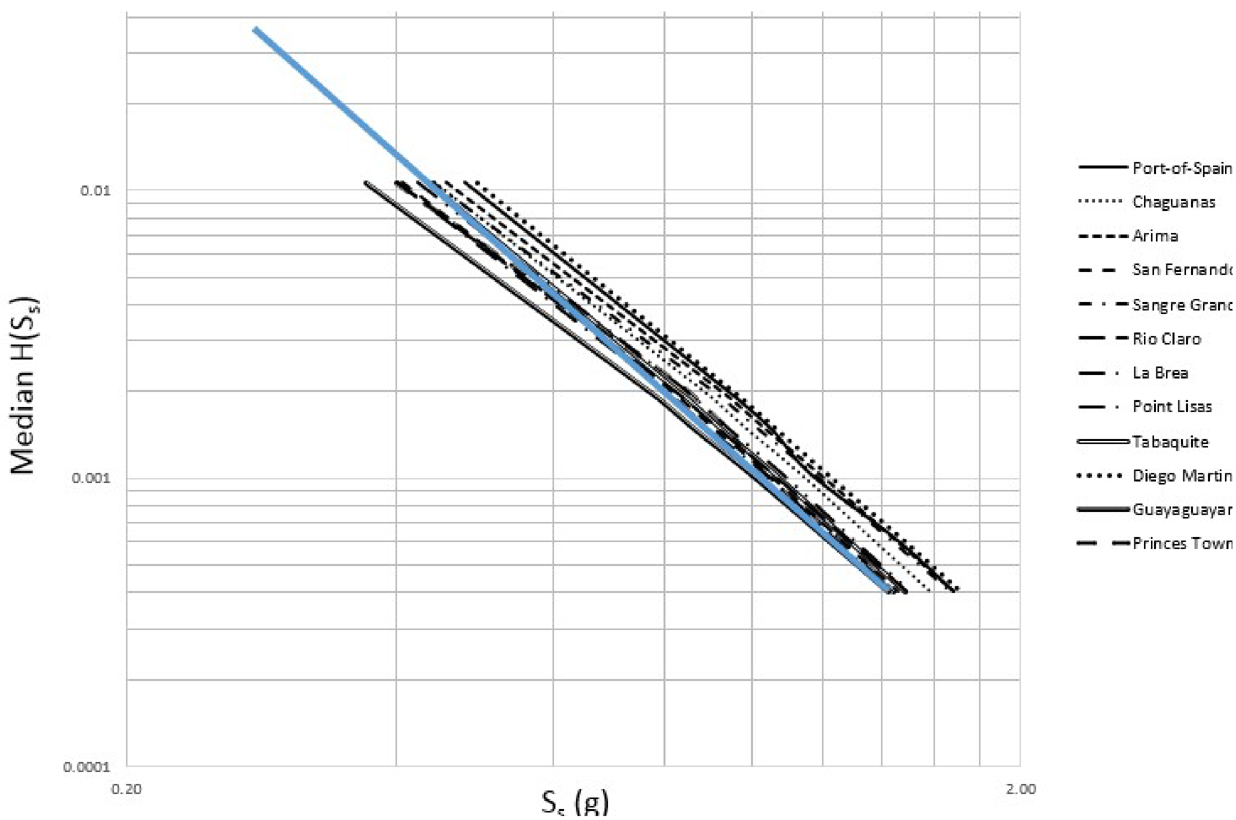

Figure 2. Hazard Curves for Locations within Trinidad

By comparing with the shape of the hazard curve, the expected concave curvature is apparent. Therefore, the hazard curves for Trinidad are reasonable so the error is deemed negligible. For the other Caribbean territories, since the data were determined by using the median of the highest contour band, a possible source of error is that this approach does not identify one specific consistent location on the island for all the maps of data for the various return periods. This approach was preferred due to the relatively small size of those islands. As will be discussed subsequently, such error can manifest as a smearing out of the curvature of the hazard curve among the data points.

Another possible source of error in the hazard curve data is the use of equation (8) for S_s values greater than 1.5g. In the case of the Trinidad data, this occurred for 4 of the 12 curves at a maximum of 3.9%, and for the other islands, 2 times at a maximum of 2.3%. Given these small margins, the effect is expected to be negligible.

The results of the regression analysis are shown in Table 2. The main parameter of interest is the curvature parameter k_2 which is expected to be non-zero but a small value relative to k_1 which is a measure of the overall slope. The k_0 value is the intercept of the hazard curve on the median H() axis. In terms of expectation, this value can vary considerably but as shown by Vamvatsikos (2015) for left biased-fit procedures, the effect on seismic risk computations is negligible. Therefore as shown for Trinidad, the "k" values are reasonable within the present context and with the goodness-of-fit parameter R^2 of at least 99.8% for S_s and 99.9% for S_1, the regression analysis results for Trinidad are acceptable. As regards the other islands, Table 2 indicates that for S_s for Tobago and Antigua, and for S_1 for Dominica and Antigua, the k_2 values are slightly negative (but less so for the S_s). This is due to the aforementioned "smearing out" of the points in the hazard curves due to their likely representing different locations for the different return periods. The effect of this occurrence is discussed below.

Variation from the target risk of 0.0002 is a source of error in the computation of the risk coefficients. As shown in Tables 3 and 4, the actual target risk used is slightly higher and this is due to the difficulty of the MS-EXCEL solver to converge exactly on the target. The goal-seek algorithm was only able to come within a higher radius of convergence than the ideal, therefore the final value was obtained by manually tweaking the $\hat{s}_c$.

A second possible source of error in the computation is that the "k" values of the biased fit procedure are not based on the same region of the hazard curve for each curve. This type of error may be relevant only when comparing the risk coefficients results of different locations. As stated previously, for consistency among all curves in determining the "k" values for the biased fit, Vamvatsikos (2015) recommended using points measured in terms of a number of standard deviations to the left of $\hat{s}_c$. He recommended points at 0.5, 1.5, and 3.0 standard deviations.

Table 2. Regression Analysis Results

Location	S_s				S_1			
	k_0	k_1	k_2	R^2	k_0	k_1	k_2	R^2
Port-of-Spain	0.001667	2.64839	0.18128	0.9990036	0.0000772	2.85394	0.22581	0.99997
Chaguanas	0.001443	2.65441	0.25885	0.9999756	0.000068	2.71430	0.1551	0.99992
Arima	0.001622	2.56932	0.23266	0.9999812	0.000056	2.95449	0.21997	0.99986
San Fernando	0.00115	2.69873	0.25409	0.9999758	0.000056	2.75765	0.16193	0.99999
Sangre Grande	0.001553	2.5236	0.22518	0.9999806	0.000025	2.92596	0.17198	0.99998
Rio Claro	0.001191	2.62731	0.25361	0.9999767	0.000020	2.94841	0.16892	0.99998
La Brea	0.001115	2.69253	0.24823	0.9998986	0.000059	2.72177	0.1558	0.99998
Point Lisas	0.001275	2.71237	0.28821	0.9999712	0.000063	2.73533	0.16198	0.99999
Tabaquite	0.001213	2.71412	0.12918	0.999977	0.000046	2.92952	0.19939	0.99998
Diego Martin	0.001758	2.64706	0.15262	0.9999762	0.000080	2.85719	0.23137	0.99997
Guayaguayare	0.001024	2.58124	0.22846	0.9999801	0.000039	2.81481	0.16455	0.99993
Princes Town	0.001223	2.89163	0.57663	0.9987425	0.000046	2.88038	0.17935	0.99997
Tobago	0.002085	2.30289	-0.0057	0.9998776	0.000015	5.28120	1.05981	0.99791
Dominica	0.001966	2.64171	0.33553	0.9965291	0.000201	1.56276	-0.3275	0.9781
Antigua	0.001879	2.40941	-0.0946	0.9865074	0.000282	1.20904	-0.4165	0.98572
Barbados	0.000686	2.8152	0.53512	0.9971696	0.000025	4.42177	0.77956	0.99659

Table 3 C_{RS} Risk Coefficient Results

Location	P'	Median Cap S_s	Mean $H(S_s)$	Mean MAF	Cap S_s,10%	Risk Coeff.
Port-of-Spain	0.811661783	5.17	1.31812E-05	0.000200963	1.856833632	1.103287957
Chaguanas	0.751126109	4.825	1.16548E-05	0.000200484	1.732925004	1.094018311
Arima	0.770529102	5.06	1.36525E-05	0.000200913	1.817326533	1.082386262
San Fernando	0.754586194	4.44	1.17029E-05	0.000200102	1.59465016	1.095979491
Sangre Grande	0.776259306	4.98	1.51234E-05	0.000200983	1.788594098	1.07229862
Rio Claro	0.754936589	4.48	1.30902E-05	0.000200236	1.609016377	1.08132821
La Brea	0.75887868	4.39	1.20632E-05	0.000200225	1.576692387	1.094925269
Point Lisas	0.730507363	4.59	1.04624E-05	0.000200366	1.648523476	1.096822006
Tabaquite	0.858113704	4.65	1.37959E-05	0.000200559	1.670072802	1.123115536
Diego Martin	0.836569243	5.31	1.38287E-05	0.000200422	1.907115393	1.112020638
Guayaguayare	0.773734752	4.23	1.53919E-05	0.000200417	1.519227517	1.069878533
Princes Town	0.575346577	4.36	4.95865E-06	0.000200041	1.565917724	1.055912154
					av. =	1.090164416
					stdev.=	0.018814536
					cov =	0.017258439
					av+stdev=	1.108978951
Tobago	1	6.02	0.0000334	0.000200579	2.162115757	1.062464745
Dominica	0.699557298	5.35	0.0000091	0.000200969	1.921481611	1.091750915
Antigua	1	5.69	0.0000285	0.000200835	2.043594461	1.061607512
Barbados	0.593488437	3.47	0.0000090	0.000200484	1.246269381	1.029974695

Table 4 C_{R1} Risk Coefficient Results

Location	P'	Median Cap S_s	Mean $H(S_s)$	Mean MAF	Cap S_s,10%	Risk Coeff.
Port-of-Spain	0.775775752	1.57	2.03572E-05	0.000200886	0.563874043	1.034631271
Chaguanas	0.834352947	1.473	2.33322E-05	0.000200263	0.529035965	1.045525623
Arima	0.780295521	1.45	1.8173E-05	0.000200067	0.52077539	1.054201194
San Fernando	0.828316333	1.375	2.29275E-05	0.000200887	0.493838732	1.044056515
Sangre Grande	0.819578057	1.068	2.06148E-05	0.000200741	0.383578011	0.81094717
Rio Claro	0.822219789	0.994	2.04659E-05	0.000200396	0.357000509	0.813213004
La Brea	0.833731812	1.386	2.38428E-05	0.000200892	0.497789442	1.041400506
Point Lisas	0.82827498	1.43	2.32344E-05	0.000200619	0.513592281	1.041769333
Tabaquite	0.796676476	1.341	1.91767E-05	0.000200637	0.481627447	1.051588312
Diego Martin	0.771513033	1.592	2.01762E-05	0.000200448	0.571775463	1.033952012
Guayaguayare	0.826016882	1.215	2.23768E-05	0.00020004	0.436373861	1.046460099
Princes Town	0.81329339	1.325	1.9962E-05	0.000200144	0.47588096	1.055168425
					av. =	1.006076122
					stdev.=	0.090860955
					cov =	0.090312207
					av+stdev=	1.096937077
Tobago	0.424347744	1.437	1.94302E-06	0.000200483	0.516106369	1.059766672
Dominica	1	1.755	8.35211E-05	0.000200722	0.6303178	1.021584764
Antigua	1	2.115	0.000113981	0.00020016	0.759613758	1.113803165
Barbados	0.50054298	1.398	5.13266E-06	0.00020039	0.502099307	1.189808784

However, for the procedure used in the present study, the boundaries are not constant but typically within 1.3 ± 10%, and 3.0 ± 10% standard deviations to the left of $\hat{S}_c$. Given the small magnitude of these variations, the effect on the calculated risk coefficients is deemed negligible. It is also noteworthy to mention that the boundaries used by Vamvatsikos (2015) for left-biasing (i.e., 0.5 to 3.0 standard deviations) are different than the boundaries used in the present study (i.e approximately 1.3 and 3.0). However, since the more refined approach of regression analysis using 7 points was used in the present study, the result is expected to be more accurate than the Vamvatsikos (2015)'s approach which is based on 3 points.

The risk coefficient maps for the United States indicate C_{RS} and C_{R1} values typically in the range of 0.88 to 0.97 for the former, and 0.87 to 0.95 for the latter, with some notable exceptions. As regards the island of Hawaii in the Pacific, and Tortola and Puerto Rico in the Caribbean, the values are 1.28, 1.05, and 1.0, respectively. Likewise for these islands and for C_{R1}, the values are 1.18, 1.0, and 1.01.

For the present study, the values for the various Caribbean territories range from 1.03 to 1.11 for C_{RS}, and 1.02 to 1.19 for C_{R1}. By comparison with the United States values, especially for the island states, the extent of deviation from the uniform hazard values seems reasonable.

5. Conclusions and Recommendations

Table 5 shows the C_{RS} and C_{R1} values for various locations in Trinidad, and Table 6 shows the recommended values for various islands. Given these values, it is possible to use consistently and safely the building codes and associated documents for the period after 2012 to the present. The risk of litigation is eliminated, if these values are adopted by the relevant authorities, especially since the values are typically greater than unity.

Table 5. Risk Coefficient Values for Different Locations in Trinidad

Location	C_{RS}	C_{R1}
Port-of-Spain	1.10	1.03
Chaguanas	1.09	1.05
Arima	1.08	1.05
San Fernando	1.10	1.04
Sangre Grande	1.07	0.81
Rio Claro	1.08	0.81
La Brea	1.09	1.04
Point Lisas	1.10	1.04
Tabaquite	1.12	1.05
Diego Martin	1.11	1.03
Guayaguayare	1.07	1.05
Princes Town	1.06	1.06

Table 6. Risk Coefficient Values for Different Caribbean Countries

Caribbean Country	C_{RS}	C_{R1}
Trinidad	1.11	1.10
Tobago	1.06	1.06
Dominica	1.09	1.02
Antigua	1.06	1.11
Barbados	1.03	1.19

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