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Monte Carlo Based Seismic Hazard Model for Southern Ghana

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Abstract

Seismic hazard assessment involves quantifying the likely ground motion intensities to be expected at a particular site or region. It is a crucial aspect of any seismic hazard mitigation program. The conventional probabilistic seismic hazard assessment is highly reliant on the past seismic activities in a particular region. However, for regions with lower rates of seismicity, where seismological data is scanty, it would seem desirable to use a stochastic modelling (Monte Carlo based) approach. This study presents a Monte Carlo simulation hazard model for Southern Ghana. Six sites are selected in order to determine their expected ground motion intensities (peak ground acceleration and spectral acceleration). Results revealed that Accra and Tema as the highly seismic cities in Southern Ghana, with Ho and Cape Coast having relatively lower seismicities. The expected peak ground acceleration corresponding to a 10% probability of exceedance in 50 years for the proposed seismic hazard model was as high as 0.06 g for the cities considered. However, at the rather extreme 2% probability of exceedance in 50 years, a PGA of 0.5 g can be anticipated. Evidently, the 2% in 50 years uniform hazard spectrum for the highly seismic cities recorded high spectral accelerations, at a natural vibrational period within the ranges of about 0.1-0.3 sec. This indicates that low-rise structures in these cities may be exposed to high seismic risk.

Keywords: Seismic Hazard; Monte Carlo Simulation; Uniform Hazard Spectrum; Seismic Hazard Curve; Ghana.

1. Introduction

Earthquakes are highly stochastic in nature. From their spatio-temporal occurrence to associated ground motion intensities, there seems to be no reliable form of deterministic model available for adequate characterization. Given their highly uncertain nature, many experts (seismologists, engineers and researchers) have adopted and advocated the use of the probabilistic approach in quantifying the seismic hazard to be expected for a particular region. Once the hazard is quantified, the vulnerability of buildings [1–3], particular older-type reinforced concrete structures can be confidently assessed. Currently, the development of hazard maps has been crucial, and plays a fundamental role in hazard mitigation. Ayele [4] presented a seismic hazard map, which has been implemented in the 3rd generation building code of Ethiopia. Ezzelarab [5], having adopting the probabilistic approach, evaluated the seismic hazard of north-western part of Egypt. Gaspar-Escribano [6] conducted an uncertainty assessment of developed seismic hazard model for Spain. Hassan [7] comprehensively evaluated existing seismic hazard maps of Egypt, to identify short falls such as under-estimated hazard in the event of an earthquake. Usually, one is interested in an optimal mitigation level that minimized the total cost (the summation of the expected loss and mitigation cost), and this is highly dependent on the reliability of the hazard model adopted. When the mitigation level is high, one anticipates a reduction in the expected loss but at the expense of increased construction cost. Ideally, the chosen hazard level should not be too strong (imposing unnecessary cost) or too weak (permitting unwarranted risk). As noted by Rosenblueth [8], there is a need to incorporate societal and economic requirements (how much of its resources to spend in the event of an earthquake) in the setting of seismic

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mitigation/probability levels, for structural design. Nonetheless, this form of complex problem can be crudely analyzed when a hazard model seems not to under-predict or over-predict the hazard. Seismic hazard maps provides essential information that decision makers and investors use in deciding on whether or not to go for an earthquake resistant structure. The development of such maps requires models, processes, data and fault characterization, which evolves over time. Nonetheless, these information becomes highly uncertain and less accurate in developing countries. They depend on the underlining assumption and preconception that the researcher makes, and as such can lead to inaccurate hazard estimates. Hence it becomes imperative to consider how a hazard model and its associated map is performing, and how to improve upon its estimates substantially.

Various approaches exist in literature for conducting probabilistic seismic hazard analysis [9]. Irrespective of the seismic hazard assessment method employed, results are highly reliant on the past seismic activities in that region. However, for regions with lower rates of seismicity, where seismological data is scanty, it would seem desirable to use a stochastic modelling (Monte Carlo based) approach, as opposed to the conventional approach of analytically integrating all the hazard contributions using the total probability theorem. This is analogous to researchers employing stochastic-based models in the development of ground motion prediction equations for stable continental regions. Moreover, there is transparency in the procedure, the computations are straight forward, and can be easily extended to seismic risk analysis. It also allows the analyst to ascertain the probable earthquake scenarios that can be selected for subsequent structural analysis (seismic hazard deaggregation). Nonetheless, since the entire process is based on the use of random numbers, results are not unique, and will only converge to the true solution when a significant number of simulations are performed. The prime focus of this study is to apply the Monte Carlo approach in quantifying the seismic hazard of southern Ghana. The proposed hazard model (simulation algorithm) is investigated herein, for later generation of regional seismic hazard map in future studies.

2. Seismicity of Southern Ghana

In spite of low seismic activity in recent times, Southern Ghana has experienced damaging earthquakes dating as far back as 1615 with the most damaging earthquake occurring in June, 1939. Seismic activity in Ghana is concentrated at the intersection of the two major fault zones in Ghana – the Akwapim Fault Zone and the Coastal Boundary Fault. The Akwapim Fault Zone, an exemplification of a Pan African thrust, consists of a system of faults with strike-slip movements. However, the Coastal Boundary Fault is predominantly characterized by normal faults and marks the northern margin of the Keta Basin [10]. Damaging historical earthquakes in Ghana have been documented by Junner [11], Ambrasseys and Adams [12] and more recently by Amponsah et al. [13] and Musson [14]. The prominent seismic events are that of 1636, 1862 and 1939. The earthquake of 1636, which is the earliest recorded earthquake in Ghana occurred in the Axim district of Southwestern Ghana. Its surface magnitude (M_s) was 5.7 with a maximum intensity of IX on the Medvedev–Sponheuer–Karnik (MSK) scale [12]. In July 1862, a strong earthquake of magnitude (ML) 6.5 and maximum intensity IX on the Modified Mercalli Scale (MMS) struck the capital city of Accra [15]. It caused severe damage to many structures including the castle and some forts. The earthquake of 1939 – magnitude 6.5 on the Richter scale and maximum intensity IX – is by far the most damaging earthquake experienced in Ghana. According to Junner [11], an estimated 17 people lost their lives, 133 more were injured and it caused one million pounds worth of damage to buildings. In recent times, seismic activity has been low as majority of the seismic events recorded have been tremors with magnitudes less than 4.0.

3. Methodology

3.1. Earthquake Catalogue

Data on seismic events used in this study are obtained from the earthquake catalogue of Ghana compiled by Amponsah et al. [13] for the time period 1615-2003. It is worth noting that magnitudes less than 3.0 were excluded from this catalogue. All earthquake magnitudes in the catalogue were homogenized to moment magnitudes (M_w) by using empirical models of Tobyáš and Mittag [16] and Bora [17] .

3.2. Source Characterization

Two areal source zones (Figure 1) are used in the study to define the most probable locations of future earthquakes in Southern Ghana. The source zones are delineated based on historical and instrumental records in the earthquake catalogue and geological knowledge of tectonics of the study area. The distribution of events within a source zone are assumed to be uniform. Separate examination of seismicity in each source zone is done using the Gutenberg-Richter relationship, which describes the annual rate of occurrence of events within a magnitude bound.

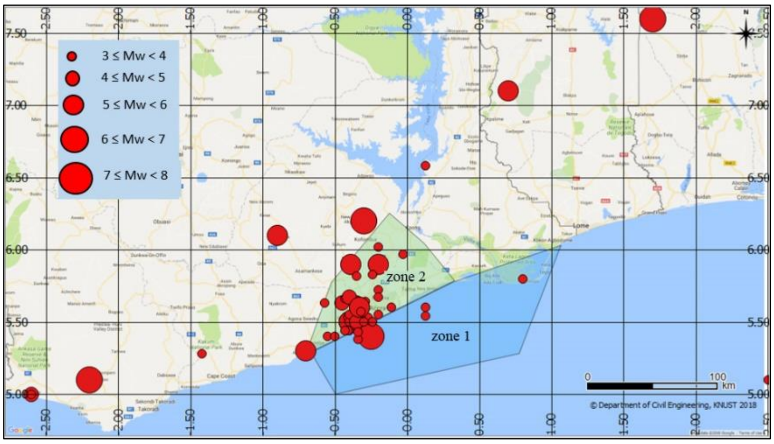


Figure 1. Seismic source zones and activities in Southern Ghana

3.4. Simulation Algorithm

Using Monte Carlo simulation, the first step is to generate a synthetic earthquake catalogue which has similar characteristics (magnitude-recurrence relation) as that of historical earthquake scenarios in a particular zone. The procedure is as follows:

The magnitude-recurrence function-theoretic form for a particular source zone is obtained as

$$log_{10}\lambda_M = a + bM_w \tag{1}$$

Where λ_M is annual occurrence rate, M_w is the moment magnitude of events in a particular zone, and a and b are regression coefficients. These parameters are obtained from compiling a database of historical records, and performing a simple linear regression analysis.

A bounded Gutenberg-Richter relationship for λ_M is later obtained as

$$\lambda_M = N_o\left(\frac{e^{-\beta M_{min}} - e^{-\beta M_{max}}}{1 - e^{-\beta M_{max}}}\right) \tag{2}$$

Where $N_o = 10^a$ and β are Gutenberg-Richter parameters. In computing β, the minimum and maximum magnitudes (M_{min} and M_{max}) should be specified before subsequent numerical analysis. In the present study N_o, β and λ_M were estimated for the two demarcated seismic zones given in Figure 1 (see Table 1) . λ_M depicts the activity rates of the two zones, as seen in Table 1. Zone 2 appears to be 2.5 times seismically active than Zone 1. For instance, whereas the expected return period for an event with moment magnitude 4.0 is 21.2 years for Zone 1, it is anticipated that Zone 2 will require just over 8 years for an earthquake of moment magnitude 4.0 to recur.

Table 1. Source zone model parameters

Zone	Gutenberg-Richter Parameters		
	N_o	β	λ_M
1	0.244	0.3123	0.0472
2	4.263	0.8848	0.1184

Assuming a Poisson distribution for the occurrence of earthquakes in a particular zone, the inter-arrival times can be computed by randomly simulating a number from the uniform distribution (u), and computing the time (t) to the next event as

$$t = \frac{1}{\lambda_M} ln(u - 1) \tag{3}$$

The spatial location of the seismic event is then obtained by adopting Monte Carlo simulation schemes such as acceptance-rejection method [18] to ensure that the location of a particular event falls within the seismic zone. Subsequently, rupture distances can be obtained given a particular site of interest, and later used in attenuation models for predicting ground motion intensities.

The moment magnitude of an event is then computed using parameters obtained thus far as:

$$M_w = \frac{1}{\beta} ln\left(e^{-\beta M_{min}} - (1-u)(e^{-\beta M_{min}} - e^{-\beta M_{max}})\right) \quad (4)$$

The preceding steps are basic. However, depending on the selected ground-motion prediction equation(s), particularly those for which distance measures are based on extended fault plane, other parameters such as fault width, length, dip and strike can be simulated [19].

Finally, with a selected Ground Motion Prediction Equation (GMPE), an intensity measure of an earthquake scenario (peak ground acceleration, spectral acceleration) can be computed. Normally, a logic tree formalism which adopts different GMPEs from literature is used to account for the epistemic uncertainty in the estimated ground motion intensity measure.

The entire process above is then repeated. It is also imperative to store the inter-arrival times of events during the Monte Carlo repetitions so as to ascertain the simulation period of analysis. With a selected simulation period, a synthetic catalogue of earthquake scenarios which are characteristic of past historical observations are obtained. Later, a very large number of catalogues can be generated for subsequent analysis and development of the primary output of any probabilistic seismic hazard analysis. A typical simulated synthetic catalogue for Zone 2 is shown in Table 2. Figure 2 shows a flow chart of the simulation algorithm implemented.

The above algorithm can then be easily modified for multiple source zones and different parameters if so desired.

Table 2. Synthetic earthquake catalogue

Event	Time (years)	Magnitude	Latitude	Longitude	Rupture Distance (km)
1	16.29511	4.168865	6344343	10571.87	33.15835
2	57.85548	4.007913	6344496	7956.002	30.54302
3	58.14481	6.89287	6347414	-39780.1	17.43975
4	68.64526	4.364303	6349142	-64065.2	41.71641
5	70.89184	5.487726	6343940	-23677.5	4.479212
6	71.36401	6.635799	6346342	1897.394	24.32903
7	77.85767	4.660841	6346259	4770.954	27.20079
8	88.77442	4.343823	6345055	7664.241	30.1897
9	93.60085	4.87594	6345128	-4857.25	17.77285
10	94.19433	6.495107	6342057	-19382.3	6.845296
11	99.67825	4.780989	6350172	-65649	43.334
12	104.9005	4.816957	6345901	16331.51	38.76002
13	109.8382	4.858754	6348251	-58112.7	35.75371
14	111.3489	5.810481	6344146	8595.253	31.22129
15	114.482	5.215887	6341967	-11781.8	12.28787
:	:	:	:	:	:

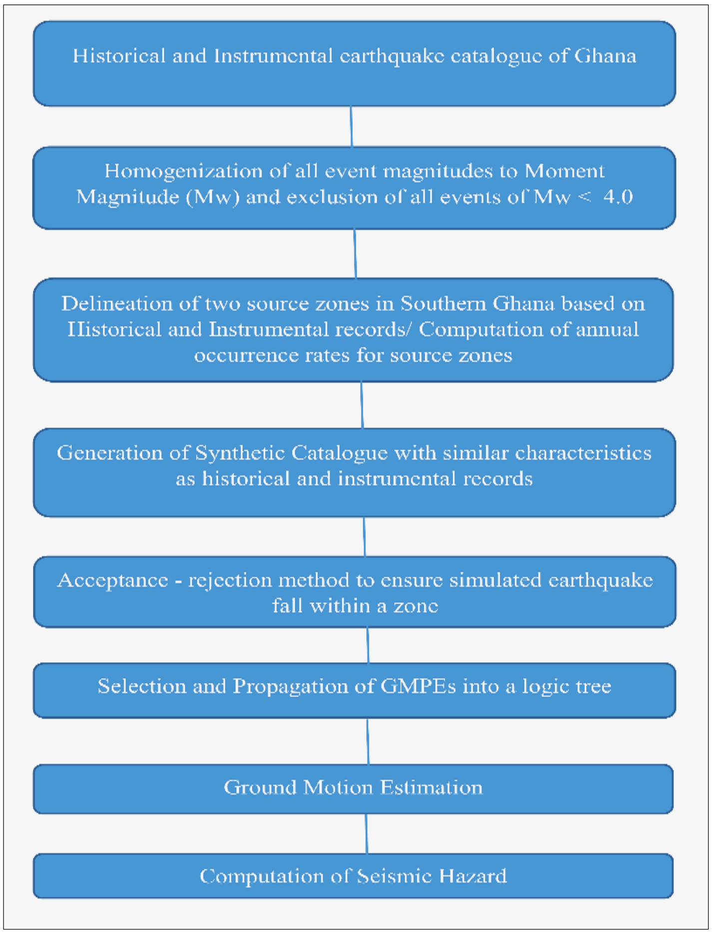


Figure 2. Flow chart of simulation algorithm

As previously stated, the compiled database of historical records considered in this study spanned 1615-2003. Hence, the simulation period for one generated synthetic catalogue was capped at 388 years. Monte-Carlo simulations of 500 independent catalogues were later generated. Four GMPEs which have been developed for stable continental regions of Eastern North America were selected. These are the models of Silva et al. [20], Tavakoli [21], Atkinson and Boore [22] and Pezeshk et al. [23]. In this study, the ergodic assumption is invoked; estimates from selected GMPEs are representative of ground motion intensities of Southern Ghana. A plot of how the ground motion intensities attenuates with distance for six different magnitude scenarios is shown for each GMPE in Figure 3. These GMPEs were later propagated into a logic tree of equal weights, and the mean prediction used to estimate ground motion intensities (peak ground/spectral acceleration) for various synthetically generated earthquake scenarios. It is worth noting that the inexistence of any GMPE locally developed for Southern Ghana necessitated the use of the selected GMPEs, which have been developed in regions with lower rates of seismicity. Statistical analysis is conducted on these intensity values in order to construct a site-specific Seismic Hazard Curve and Uniform Hazard Spectrum (primary outputs of any probabilistic seismic hazard assessment).

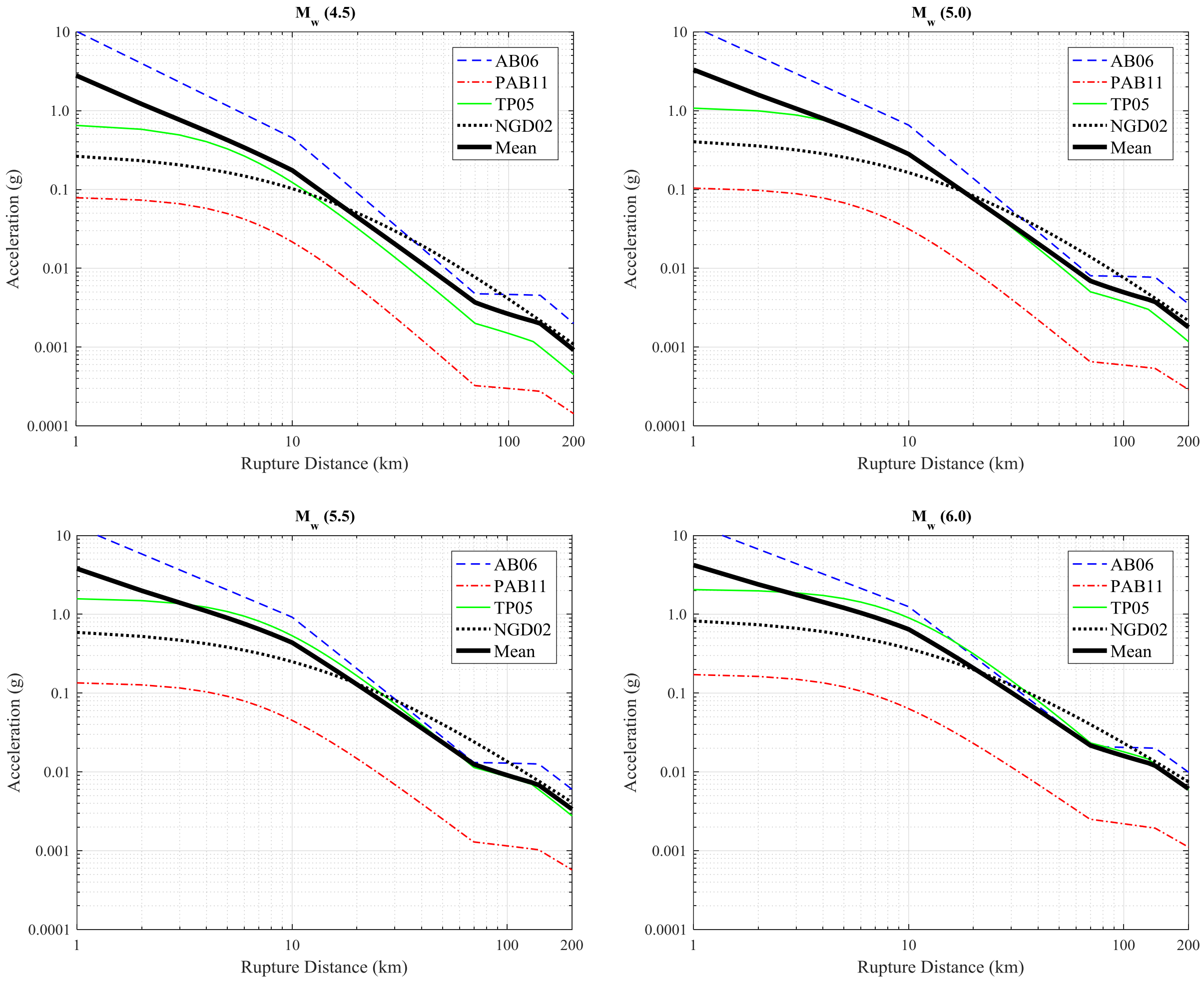
3.5. Seismic Hazard Curve

Seismic Hazard Curve (SHC) and the Uniform Hazard Spectrum (UHS) are basically the primary outputs of any seismic hazard assessment. SHC primarily informs the analyst on how probable certain ground motion intensities will be exceeded within a time interval. It is normally reported as annual probability of exceedance. However, other alternatives such as the probability of exceedance in 50 years has been widely accepted and adopted by most of the seismic design guidelines [24, 25]. Usually, ground motion intensities corresponding to either a 10% or 2% probability of exceedance in 50 years are reported.

For the stochastic approach to seismic hazard assessment, a site-specific SHC can be developed by first organizing the estimated ground motion intensities in an ascending order (after aggregation of the available synthetic catalogue). The exceedance rate for each value of ground motion intensity is then computed by finding the proportion of intensity values that are higher than it, and dividing by the total years of simulation. This process is repeated for all estimated ground motion values to obtain the seismic hazard curve. Table 3 shows a typical data for constructing an SHC, with the 2% and 10% probability of exceedance in 50 years noted accordingly.

Table 3. Construction of Seismic Hazard Curve

	Annual Probability of Exceedance	Peak Ground Acceleration
:	:	:
:	0.002185	0.008992
10% in 50 years	0.002105	0.009849
:	0.002073	0.010848
:	0.002017	0.011793
:	:	:
:	:	:
:	0.000448	0.349226
2% in 50 years	0.000404	0.361221
:	0.000392	0.387205



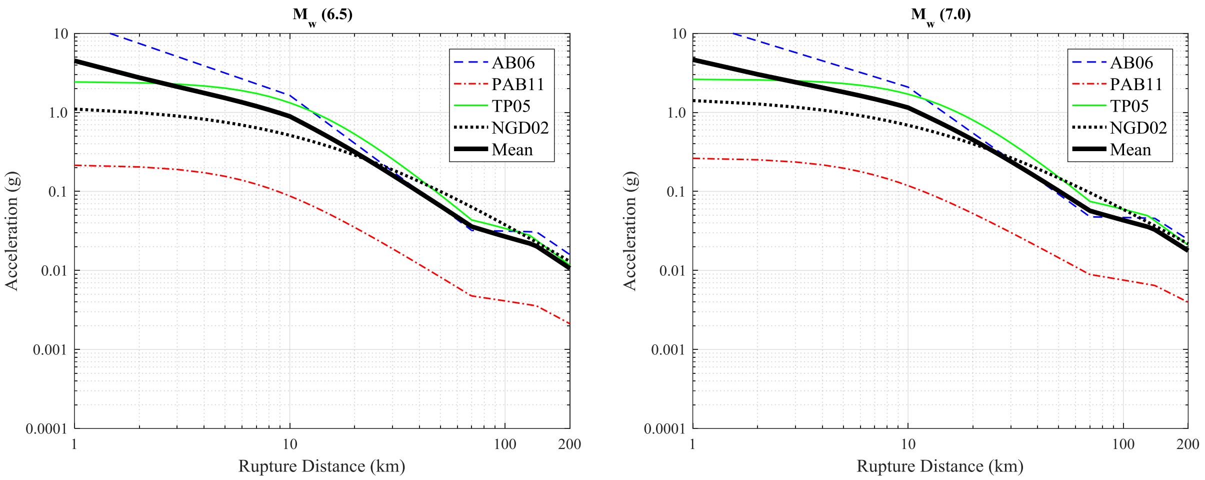


Figure 3. GMPE considered for in this study; the attenuation for the four selected GMPE with distances for various moment magnitudes is shown. Also shown is the mean curve

3.6. Uniform Hazard Spectrum

The uniform hazard spectrum relates the distribution of the expected ground motion intensities for a period range, all possessing the same annual probability of exceedance. The chosen probability level is linked with the hazard curve. For each earthquake scenario in the compiled synthetic catalogue, estimates of the ground motion intensities are computed for different vibrational periods using the period dependent attenuation model. At each period value, one locates the expected ground motion intensity corresponding to a target probability level. This process is repeated for the selected range of periods. This is schematically shown in Table 4.

Table 4. Construction of Typical Uniform Hazard Spectrum

	RATE	PGA	SA (0.2)	SA (0.4)	SA (0.6)	SA (0.8)
:	:	:	:	:	:	:
:	0.00219	0.00899	0.01439	0.01169	0.00782	0.00584
10% in 50 years	0.00213	0.00985	0.01576	0.0128	0.00857	0.0064
:	0.00207	0.01085	0.01736	0.0141	0.00944	0.00705
:	0.00202	0.01179	0.01887	0.01533	0.01026	0.00767
:	:	:	:	:	:	:
:	:	:	:	:	:	:
:	0.00045	0.34923	0.55876	0.45399	0.30383	0.227
2% in 50 years	0.0004	0.36122	0.57795	0.46959	0.31426	0.23479
:	0.00039	0.38721	0.61953	0.50337	0.33687	0.25168

4. Results on Seismic Hazard Assessment of Southern Ghana

Six cities within southern Ghana were identified for seismic hazard analysis (see Table 5). The proposed Monte-Carlo-based simulation algorithm is implemented to produce their corresponding hazard curves and uniform hazard spectra. It is worth noting that the location for each site within a particular city is the same as that used by a recent study by Ahulu et.al [3].

Figure 4 shows the SHC for peak ground acceleration (PGA) of the six sites considered. Also shown are PGAs values corresponding to a 2% and 10% in 50 years exceedance rate. Results indicated that for a 10% in 50years event, the maximum PGA could range between 0.01-0.06. At this probability level, Ho and Cape Coast were identified as having low seismicities, whereas places in Accra and Akosombo may possess relatively high hazard. However, at a 2% in 50 years probability level, Tema produced the largest expected PGA of 0.5 g with Cape Coast producing the least (0.07 g). In order to determine the city for which the seismic hazard could be anticipated as highly critical, the slope between the 2% and 10% in 50 years PGA values was employed. The ranked results (Table 5) revealed that the seismic hazard to be expected at Tema is highest when the PGA is the selected intensity measure. After which cities like Accra and Koforidua marginally follow. Cape Coast has the lowest seismicity, and is of the order of about two in comparison to Ho, which follows as the next.

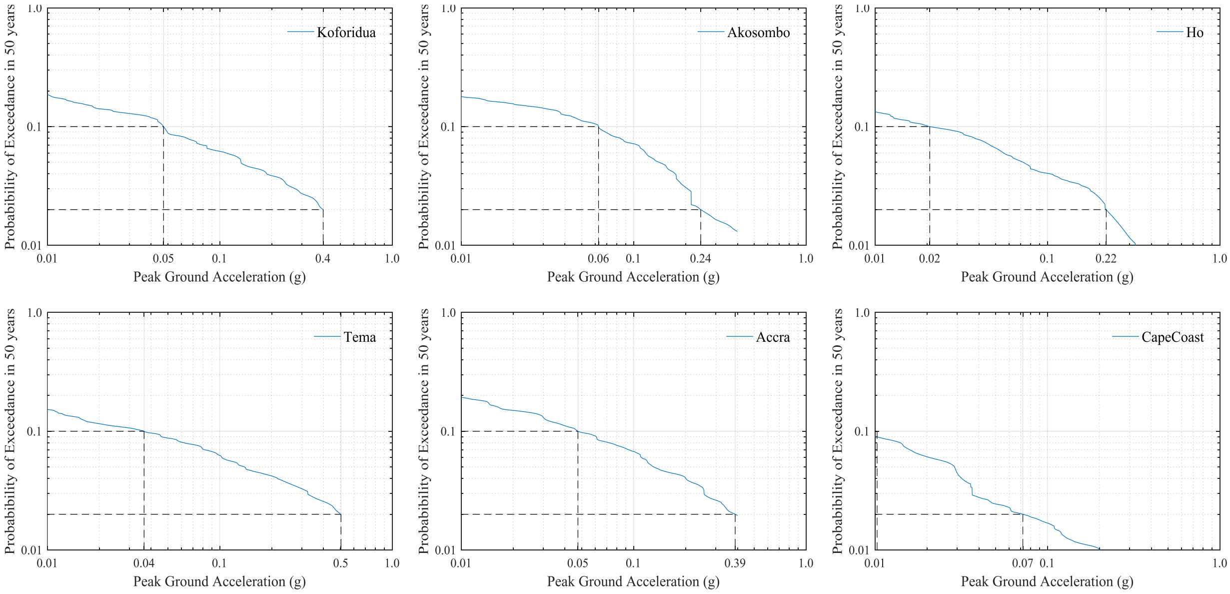


Figure 4. Seismic Hazard Curves for Selected Sites

Table 5. Construction of Typical Uniform Hazard Spectrum

City	Location		2% in 50years	10% in 50 years	Rank
	Longitude	Latitude			
Accra	-0.182	5.555	0.39	0.05	2
Akosombo	0.050	6.346	0.24	0.06	4
Cape Coast	-1.255	5.100	0.07	0.01	6
Ho	0.408	6.649	0.22	0.02	5
Tema	0.035	5.657	0.50	0.04	1
Koforidua	-0.226	6.068	0.40	0.05	3

The Uniform Hazard Spectra (UHS) for the six sites, is shown in Figure 5. These spectra are of large importance to structural engineers in the designing of systems that could resist seismic action that are consistent to the hazard posed. The 2% and 10% in 50years UHS was constructed for each city. It can be observed that the spectrum peaks within the period range of 0.1-0.3 secs, and attenuates as the period lengthens. The maximum spectral acceleration attainable was about 1.5 g for the Tema site. Evidently, both UHSs for Cape Coast had spectral acceleration values lesser than 0.1 g. Hence, for this city, a structural designer can decide not to give any form of seismic consideration whatsoever. 10% in 50 years UHS yielded spectral accelerations which were far lesser than the 2% in 50 years, particularly for the site in Accra. Generally, the 10% in 50 years' probability level which intuitively corresponds to a return period of 1 in 475 years, produces very low intensities, and thereby reflecting the seemly low seismicity region of southern Ghana, compared to other jurisdictions.

One notable extension of probabilistic seismic hazard analysis is the production of seismic hazard deaggregation results. Here, the likely earthquakes scenarios that are consistent with the hazard (ground motion intensities) are identified and can be subsequently used to performing seismic risk assessment [26]. Figure 6 shows the deaggregation results for the six selected sites at the 10% in 50years probability level. Generally, earthquake scenarios with moment magnitude of 4.5-5.0 occurring at very short distances of less than 20 km dominated the fairly high seismic cities (Accra, Tema, Koforidua and Akosombo). This reflects the influence of near-field seismic sources on the hazard contribution within these sites. Conversely, likely hazard consistent earthquakes for the relatively low seismicity cities, are expected to have rupture distances greater than 100km (Figure 6).

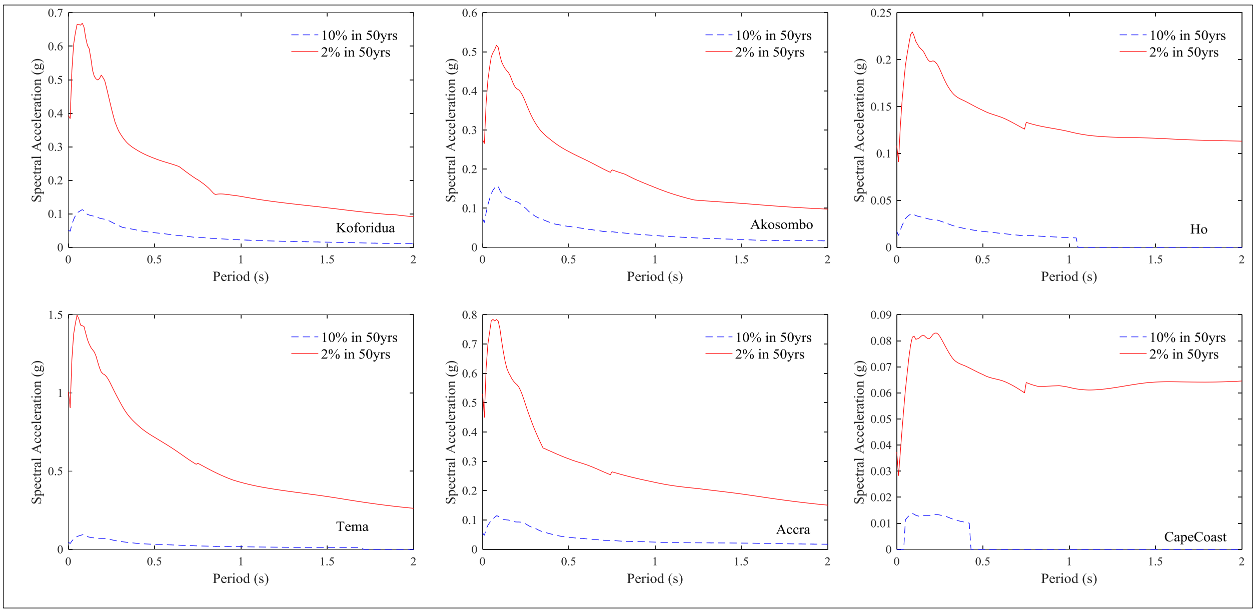


Figure 5. Uniform Hazard Spectrum of Selected Sites

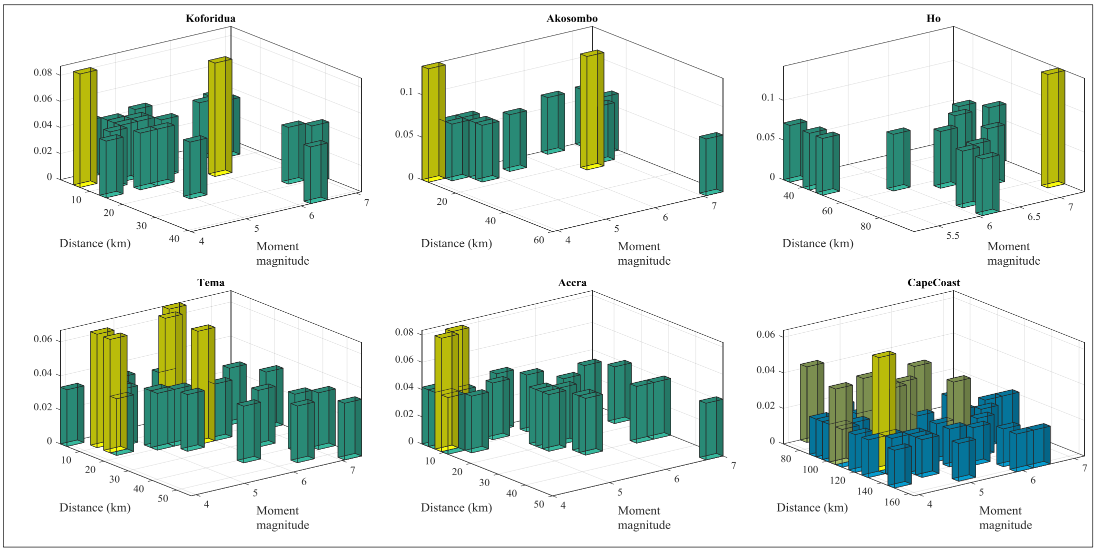


Figure 6. Seismic Hazard Deaggregation of Selected Sites (10% in 50years)

5. Discussions on Seismic Hazard Assessment of Southern Ghana

Previous studies on the probabilistic seismic hazard assessment of Southern Ghana has been undertaken by several authors, employing different methodologies including the deterministic and conventional probabilistic assessment methods. Of all the earlier publications on the subject matter, Grunthal et al. [27] and Ahulu et al. [3] are the only two who employed the probabilistic assessment approach, the more recent being that of Ahulu et al. [3] which was based on the total probability theorem. Grunthal et al. (1999) and Ahulu et al. [3] obtained PGA values of 0.16g and 0.2g for Accra respectively at a 10% probability rate of exceedance.

PGA values obtained from this study, based on the Monte Carlo approach, are comparatively lower than those obtained from previous studies. PGA values of 0.05 and 0.39 g obtained for a 10% and 2% probability rate of exceedance respectively for Accra are comparatively lower than values in previous studies. The difference in values between estimates of the current study and previous studies may be attributed to the variations in GMPEs used for the analysis. All GMPEs considered in this study were for stable continental regions whereas Ahulu et al. [3] used two GMPEs for active -shallow-crust regions. Also, two zones were used in this study whereas Ahulu et al. [3] used three source zones, and thereby one expects the hazard contribution from this extra zone to increase the ground motion intensity. Nonetheless, this study neglected the third source zone due to the relatively fewer number of historical records available within it. The earthquake catalogue used is this study and subsequently the synthetic earthquake catalogue generated for the study could have accounted for the difference in hazard estimates obtained. Studies by Ahulu et al. [3] were based on the total probability theorem whereas in the present study a different approach was adopted – the Monte-Carlo method. These reasons partly account for the differences in estimated values.

6. Conclusion

This study presented a Monte Carlo approach in quantifying the seismic hazard of southern Ghana. This is against the background that southern Ghana was partially destroyed [28] during three major earthquakes in 1862, 1906 and 1939. The proposed hazard model (simulation algorithm) has been used to assess the seismic hazard of six selected sites in this region. Two major outputs, i.e, the Seismic Hazard Curve and Uniform Hazard Spectrum were developed at 2% and 10% probability of exceedance in 50 years. The Monte Carlo based seismic hazard assessment revealed that Accra and Tema as the highly seismic cities in Southern Ghana, with Ho and Cape Coast having relatively lower seismicities. The expected peak ground acceleration corresponding to a 10% probability of exceedance in 50 years for the proposed seismic model was as high as 0.06 g for the cities considered. However, at the rather extreme 2% probability of exceedance in 50 years, a PGA of 0.5 g can be anticipated. Evidently, the 2% in 50years uniform hazard spectrum for the highly seismic cities recorded high spectral accelerations, at a natural vibrational period within the ranges of about 0.1-0.3 sec. This indicates that low-rise structures in these cities may be exposed to high seismic risk. At 10 % in 50 years, the anticipated spectral accelerations were about 0.1 g. Seismic hazard deaggregation results revealed that earthquakes with very low magnitudes with source-to-site distances lower than 20 km, usually dominate for cities with relatively high hazard. It is worth noting that results presented in this study are median predictions, and as such, future studies should consider propagating and quantifying both epistemic and aleatorical uncertainties in the estimates.

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