Available online at www.elixirpublishers.com (Elixir International Journal)

Earth Science

Elixir Earth Sci. 73 (2014) 26218-26224

ISSN: 2229-712X

b-value Estimation for the Greater Accra Metropolitan Area

M. S. Doku[1], P. E. Amponsah[2] and Dickson Adomako[3]

[1]School of Nuclear and Allied Sciences, University of Ghana.

[2]Ghana Atomic Energy Commission, National Data Centre, University of Ghana.

[3]Ghana Atomic Energy Commission, Ghana Space and Technology Centre, University of Ghana.

ARTICLE INFO

Article history:

Received: 24 June 2014;

Received in revised form: 25 July 2014;

Accepted: 6 August 2014;

Keywords

Seismological,
Metropolitan Area,
Geology,
Estimation.

ABSTRACT

A seismological investigation for earthquake hazard in the Greater Accra Metropolitan Area was undertaken. The research was aimed at employing a mathematical model to estimate the seismic stress for the study area by generating a complete, unified and harmonized earthquake catalogue spanning 1615 to 2012. Seismic events were sourced from Amponsah, P., Leydecker, G. and Muff R. (2012) based on Ambraseys and Adams, (1986), Geological Survey Department (GSD), Ghana Atomic Energy Commission's National Data Center (NDC), National Earthquake Information Service (NEIS), United States Geological Survey (USGS) and the International Seismological Centre (ISC).The least square estimation method and the maximum likelihood estimation method were employed to evaluate b-values of 0.6 and 0.9 respectively for the study area. A thematic map of epicentral intensity was developed to help relate the distribution of events with respect to the virtually fractured, jointed and sheared geology of the Greater Accra Metropolitan Area (GAMA). The results obtained are indicative of the fact that the stress level of GAMA has a telling effect on its seismicity and also the events are prevalent at fractured, jointed and sheared zones of weakness.

Introduction

Globally nobody is immune from disasters or disaster related losses. Therefore, this gives us enough reason to study them to know how best they can be handled in case they strike. Disasters are hazard situations that pose a level of threat to life, property or the environment. There are two major types of disasters. These are natural and man-made disasters. Hazards, on the other hand, are exposure or vulnerability to harm or risk (Microsoft Encarta Premium, 2009). Natural disasters include floods, fires, tropical cyclones, earthquakes, tsunamis and others which are environmentally related. However, hazards that strike in low vulnerability regions never become disasters

In Ghana, disasters that can be identified include drought, earthquake, epidemics, storm, mass movement, extreme temperature, flood, insect infestation etc. The National Disaster Management Organization (NADMO) of Ghana in collaboration with other Agencies has been in the fore front trying to mitigate these hazard situations.

The Ghana Building Code (GBC) has clearly appreciated the relevance of mitigating measures to be taken to avert future disaster when flood and earthquakes occur in unplanned areas (GBC, 1988). The code, which was recently reviewed under the Africa Adaptation Program on Climate change recognized that buildings are the essential components of all human settlements and the focal point for all human endeavours for quality living. The review also observed that the GBC was not observable by development authorities, thus it lacks legal backing.

One major disaster which has received some attention in Ghana is earthquake. Before the first documented earthquake in 1615, knowledge about earthquake was very scanty and not well understood.

In Ghana, with special attention to the Greater Accra Metropolitan Area (GAMA), there is a tendency to conclude from a seismological and geological perspective that the stable continental region is really 'stable'. However, the history of earthquakes in Ghana and the sub region (dating back to 1615) proves otherwise (Amponsah, 2002). The major ones are the 1615 earthquake at Elmina and the 1636 earthquake with epicenter at Axim (5.7 M) which buried some miners alive after the collapse of the Portuguese mines. In 1862, Accra recorded 6.5 M earthquake killing three people (Junner, 1941). The most affected areas were the Usher and James forts and the Christianborg Castle which were rendered inhabitable. Additionally, the earthquake was registered as far as Togo. The 1939 earthquake (with epicenter located at Nyanyano) of the same magnitude as that of 1862 (intensity IX) and injuring 133 people has gone down in Ghana's history as the worse incident. However, the 6.5 M earthquake of intensity VIII on the modified mercalli scale killed 17 people (Amponsah *et al.*, 2012). The GAMA with population of 77000 experienced 17 deaths in the intensity VIII earthquake of 1939 (Amponsah, 2004). According to the 2010 population and housing census, GAMA currently has a population of about 3, 000, 000 (Ghana Statistical Service, 2010). Hence, there is the need to catalogue earthquake events to help understand what is happening in the area in order to plan for the future. Earthquakes have had huge impacts on various countries such as Haiti, Turkey and Ghana where there were loss of lives and properties. However, effective application of science and engineering principles to the development of the built environment has helped reduce the risk faced by earthquake-threatened cities of the developed world like the United States of America. Apparently, this cannot be said of developing countries like Ghana, where clear building codes have not been established and where simple regulations exist they are not followed (Allotey *et al.*, 2010).

Ghana recorded first earthquake in 1914, (Junner, 1941). Since then various significant attempts have been made by successive governments to help expand knowledge in seismic

Tele: +233 302 900 389
E-mail addresses: sel_max246@yahoo.com

activities in the country and the sub-region. These national policy initiatives have led to the creation of national database of seismic activities and have gone a long way to support knowledge in geology of the coast of Ghana. With a continuum of risks associated with earthquakes, the installation of Milne's single-boom seismograph in the country was important. The instrument was used to locate hypocenters and to record earthquake magnitudes. In 1973, a seismograph observatory equipped with A World Wide Standard Seismograph Network (WWSSN) system was established at Kukurantumi in the Eastern Region of Ghana.

The observatory operated continuously until October 1974 and then intermittently until continuous recording began again in 1977 (Amponsah, 2004). It had a nine station radio telemetric network with a central recording station at the head office of the Geological Survey Department in Accra until 2003 (analogue recording system) (Amponsah, 2004). Currently a digital recording system has been procured by the Government of Ghana. The facility is located in the Achimota forest, Accra, working under the authority of the Ghana Geological Survey Department (Opoku, 2012). The new network, with the central observatory in Accra would help enhance the monitoring of earthquakes and other forms of seismic activities. There are six seismic substations located at Morontuo, Kukurantumi, Shai Hills, Akosombo, Ho and Weija respectively. These stations are generating and transmitting data to the central observatory. Between 1636 and 2006, magnitudes ranging from 4.0 to 6.5 were recorded (Opoku, 2012). The seismic data being generated would help in a more efficient and effective land use planning, revision of building codes and policy formulation and the designating standards for official structures such as nuclear power plants, bridges, dams, overhead transportation systems and shopping centers. Events recorded can be used to locate earthquake prone areas through the generation of isoseismal maps and epicentral intensity maps. Peak ground acceleration can be calculated for and therefore hazard maps can be easily generated as well.

Table 1.1: Ghana's Seismicity

Year	Magnitude	Remarks
1615	-	Felt in Elmina
1636	5.7	Felt in Axim. Buildings as well as underground workings of Portuguese mines collapsed.
1862	6.5	Every building in Accra was razed to the ground. The Osu Castle and Forts in Accra were rendered uninhabitable. The shocks were felt in Togo where water in the Mono river fell much below its normal level.
1906	5.0	Many buildings in Accra particularly castles and forts were cracked. The earthquake was felt in other areas as far as Togo.
1939	6.5	Intensity was greatest in areas between Accra, Weija, Gomoa Fete and Nyanyano. The computed peak ground acceleration ranges from 0.14g to 0.57g corresponding to VII to IX on the Modified Mercalli Scale. In Accra 16 people were killed with 133 injuries.
1964	4.5	Felt mainly in Akosombo.
1969	4.7	Felt mainly in Accra.
1997	3.8	Felt mainly in Accra
2003	4.8	Felt in some parts of Accra
2011	4.0	Near Coast of Ghana/Togo
2012	4.2	Near the Coast of Accra

Currently measures are ripe for the installation of strong motion accelerometers on the Bui, Barekese and Owabi dams as well as quarry sensor equipment to be installed on mining and quarry sites to monitor man-made seismic hazard levels in the country (Wereko, 2012). To enhance the effective monitoring of earthquakes, the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) in conjunction with the Ghana Atomic Energy Commission (GAEC) has established the National Data Center (NDC) which has also been accessing seismic data from the International Data Centre since August, 2010. Interestingly, records obtained up to December, 2012 indicate earthquake events as high as magnitude 4.0 in and around the Greater Accra Metropolitan Area.

Table 1.1 gives a brief breakdown of Ghana's seismicity indicating concentration of activities in GAMA.

Geology and Seismotectonics of GAMA and Surrounding Areas

The geology of the Greater Accra Metropolitan Area, (GAMA) comprises six geological formations. These are:

❖ Unconsolidated and poorly consolidated sediments and soils of Quarternary and Tertiary age; covering areas such as Korlebu, Abossey Okai, Mataheko, Adabraka, Achimota, Dansoman and Odorkor. This formation is dominated by Red Continental Deposits; Marine Fluvial or Lacustrine Sediments; Consolidated Beach Sediments and Unconsolidated or Slightly Consolidated Cobble Colluviums (Muff and Efa, 2006). The area is mostly interspersed with thickly bedded sandstones and mica schists.

❖ The Accraian Group of Devonian age comprising the Upper Sandstone-Shale Formation, Middle Shale Formation and Lower Sandstone Formation covers areas such as North Kaneshie, Osu, Kanda, Kpehe, Alajo and the city center Accra (the capital). This area is mostly underlain by thickly bedded sandstones interbedded with shale.

❖ The Voltaian Supergroup of Lower Paleozoic age is mainly made of Quartzose and impure sandstones. The system covers areas such as Anamorley and parts of Olobu and Ablekuma.

❖ The Togo Structural Units are made up of quartz veins, phyllite and phyllonite, quartz schist (sericitic quartz schist) and quartzites. The Structural Units cover areas such as Weija, Mandela, Nyanyano, Anyaa, Oblogo, Sowutuom, Burma Camp, Dome, Ofankor, Kwabenya and parts of the Ghana Atomic Energy Commission. The Togo Structural Units are of Upper Precambrian age. Key among these rocks includes granitoid and biotite gneiss, quartzite minor mica schist and thickly bedded sandstones.

❖ The Dahomeyan Supergroup comprises the basement rocks of Middle-Late Precambrian age. This comprises quartz schist, Orthogneiss, Metamicrogabbro and Amphibolites and Scistose Marbles. Madina, parts of Atomic Energy Commission and Mpehuasem are located on this formation. The Supergroup is specifically underlain by garnet amphibolite gneiss covering Amrahia, Ashaiman, Tema and Nungua as well.

❖ Also, forming part of the Greater Accra Metropolitan Area geology is the Middle Precambrian aged Granitic intrusions made of deeply weathered Granitoid-Pegmatite Complex and covering Adzen Kotoku, Amasaman and Oduman.

The geology of GAMA is generally interspersed with lineaments, concealed, observed and thrust faults and shear zones as pictured in the geological map (Fig 3.2). The weak coastal boundary faults with mild stones along the coast characterized by shear zones, joints and fractures re-emphasize the non-uniformity in geology in GAMA. Additionally, they are older fault zones reactivated by continental fragmentation (Singh *et al*., 2009; Rajendran, 2000). Key faults in the study area include

i. Longitudinal faults

(a) Eastern boundary faults

(b) Western boundary faults

ii. Faults parallel and sub-parallel to the coast
iii. Northerly striking faults and
iv. Transverse faults

Generally, GAMA is low-lying. With reference to Nyanyano, the epicenter of the 1939 earthquake, prominent ranges of hills running from north-east direction from the coast and rising to more than 600 feet above sea level occur. In fact, the area is slightly undulating (Junner, 1941).

The effects of earthquakes on buildings and other structures vary greatly depending on the underlying rocks. The tectonogeological units of GAMA are interspersed with the five distinct tectonogeological units of Ghana. These include

- The paleoproterozoic complex of the West African Craton (WAC)
- The Voltaian basin of the WAC
- The Akwapim Togo belt
- The Pan-African province of neoproterozoic metamorphic age
- Several small sedimentary basins of Post-African age

The tectonic setup of GAMA and its offshore area is characterized by three areas with distinct tectonic elements namely, the Akwapim fault zone, faults in the coastal area and near coast shelf with the coastal boundary fault as main feature, and the Romanche fracture zone (Amponsah *et al.*, 2012).

Attoh *et al*. (2005) were also convinced that neotectonic activity along the Pan-African structures may involve tectonic inversion as well as tectonic reactivation along the seismic Pan-African fracture zone (which may have occurred in the Paleozoic era and again more recently along the Pan-African sutures)

To understand the phenomena of intraplate seismicity of the study area, the connection between the Pan-African Structures and seismic activity along the coast of Ghana must be well examined. This is evident in the several events recorded on and off-shore GAMA. The seismic stratigraphic record of the Ghana margin also strongly indicates that sub-aerial erosion related to uplift was later than or accompanied the folding, rather than earlier and as such transpressional deformation likely contributed to the uplift along the Cote d'Ivoire – Ghana Transform Margin (CIGTM) (Attoh *et al*. 2003). Fig. 2.1 shows the geology of the study area.

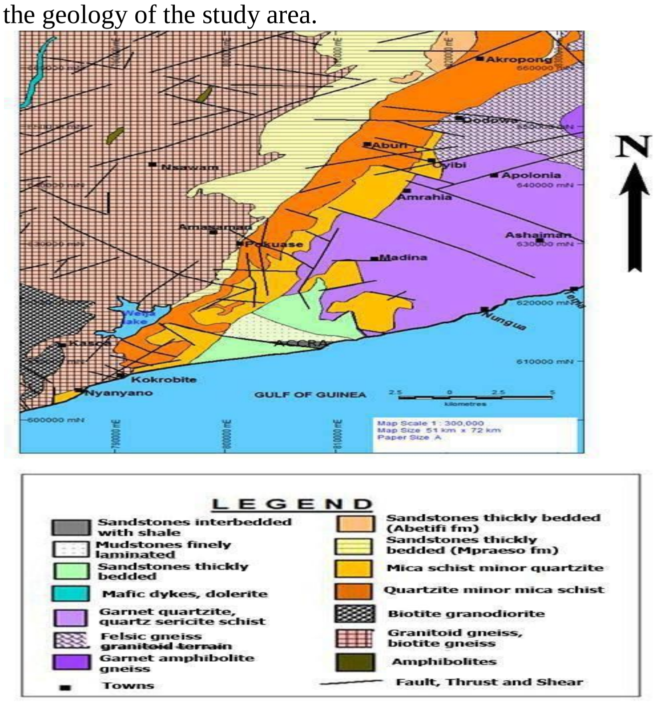

Fig. 2.1: Geology of the Study Area (Extracted from the Geological Map of Ghana, 2009)

In certain areas in Accra such as Weija, where the Akwapimian rocks have been observed to contain bands of soft Phyllite and are fractured and faulted, the area has recorded a lot of seismic activity.

Methodology

Data Acquisition

The main sources of seismic data in Ghana are the Seismic networks of the GSD and the NDC of GAEC (from ISC). Other online data was used. During this research, online data was acquired from the ISC.

Seismic events spanning 1615 to May 2003 was obtained from Amponsah, P., Leydecker, G. and Muff R. (2012) based on Ambraseys and Adams, (1986), the Geological Survey Department of Ghana (GSD), the Ghana Atomic Energy Commission's National Data Center's events from the ISC network, the National Earthquake Information Service (NEIS), the United States Geological Survey (USGS) and Events from June 2003 to December 2009 were obtained from the International Seismological Centre (ISC, 2012) using rectangular grid.

Earthquake Catalogue and Magnitude Unification

The Matlab Programming Software was used to generate the magnitudes of events without magnitudes. In that, the input data include years and their corresponding magnitudes. Some of these include 1636, 1862 and 2012 with their corresponding average magnitude for events being 5.8 M, 5.7 M and 6.2 M. This was done in the editor window. After entering this data and running it, the output data was then displayed in the command window. For years with multiple records, an average of the event magnitude was calculated. In order to validate the program, years of known magnitude of events were commanded. On running the program the results affirmed the already known magnitudes. The results are accordingly expounded in Chapter five

Some events from Amponsah *et al*. (2012) were relocated to reflect the present day areas that experienced the earthquake. This would help in better interpretation of the earthquake hazard in the Greater Accra Metropolitan Area. In some cases the events were not exactly at city centers and the relocation of the events would help in estimating the best intensity of the seismic events if they should occur in present day. In some cases where the relocation is unable to clearly identify the epicenter from the Google Maps Application Software, the Global Positioning System (GPS) was used to identify the area concerned. This was mainly done in areas such as Weija, Nyanyano and the City of Accra which have recorded significant earthquakes and tremors in the recent past.

The catalogue produced contained various magnitude units. These include the Local Magnitude, M_L, the Body-wave Magnitude, M_b, the Duration Magnitude, M_D and the Surface-Wave Magnitude for macroseismal data, MM. The different magnitude scales used in describing the size of the earthquakes in the catalogue calls for unification and harmonization. All the units must be converted to one single unit where possible, since the earthquake magnitude scale is one of the most fundamental earthquake source parameters used for catalogues. Drawing a unified relationship between these scales would help in a better hazard and risk assessment by improving on uniformity and continuity of the data. The moment magnitude was used because it is a direct indicator of the seismic moment of an event and also this magnitude relates to some physical parameters of the fault such as the amount of slip (Hanks and Kanamori, 1979; Mavonga and Durrheim, 2009).

The following relations were used to convert the various magnitude units to the Moment Magnitude, M_w. However, for small events, magnitudes M_L and M_b were considered to give reliable measure of events (Hanks and Kanamori, 1979; Mavonga and Durrheim, 2009). Events spanning 1615 to 2003 were recorded in M_D, MM and M_L. M_D was converted to M_L according to Brumbaugh (1987) as:

$M_L = 0.936\ M_D – 0.16±22$……………………………3.1

where;

M_L is the Local magnitude and M_D is the Duration magnitude

This linear regression relation (equation 3.1) has been used for evaluating magnitudes in local and regional seismic networks. One advantage of the duration magnitude however, is that it allows rapid estimates for large number of local events (Brumbaugh, 1987).

The rest of the relations relied on during the harmonization include the following; according to Hanks and Kanamori (1979) and Mavonga and Durrheim, (2009):

$M_s = 2.08M_b – 5.65$………………………………3.2

$M_b = 0.481M_s + 2.716$…………………………… 3.3

$M_b = 1.7 + 0.8M_L – 0.01M_L^2$ ……………………….3.4

$Log_{10}{}^{Mo} = 1.5Ms + 16.1± 0.1\quad 5 ≤ Ms ≤ 7.5$…………3.5

$Log_{10}{}^{Mo} = 1.5M_L + 16.0 \quad 3 ≤ M_L ≤ 7$...........3.6

$M_s = 1.45M_L – 3.2$…………………………………3.7

$M_{b,\ ISC} = 0.46M_s + 2.74$…………………………...3.8

$M_w = 2/3\ Log_{10}{}^{Mo}\ 10.7$…………………………...….3.9

where;

M_s is the Seismic-wave magnitude

M_b is the Body-wave magnitude

M_o is the Seismic moment

M_L is the Local magnitude

$M_{b,\ ISC}$ is the Body-wave magnitude according to the ISC standards

M_w is the moment magnitude

The National Data Centre records captured in M_L and M_b were maintained where the conversion leads to a reduction in magnitude. This would help consider extreme scenarios of earthquakes occurring instead of maintaining lesser earthquake magnitudes that can only be used to evaluate less effect.

Epicentral Intensity Map

The epicentral intensity map was generated according to Herak (2012) equation defined as:

$I = M + 2$ ………..……… ……………………….3.10

where;

I is the epicentral intensity whilst M is the magnitude,

Equation 3.10 was used to convert the magnitudes to epicentral intensities. The coordinates, thus latitude and longitudes were also converted to metres using Franson CoordTrans software (version 2.3). The conversion helps to arrive at a more accurate location of the epicenters as compared to the latitude-longitude approach. The epicentral intensity was plotted using the Geographical Information System, GIS. The plot also indicates the distribution of earthquakes in space in the Greater Accra Metropolitan Area as shown in Figure 4.1

b-value Evaluation

Two approaches were adopted to evaluate the b-value. These are the;

i. Linear least square fit
ii. Maximum likelihood estimation

The linear least square fit is the Guttenberg-Richter approach which uses the Guttenberg-Richter magnitude frequency relationship (Guttenberg and Richter, 1942). This empirical relation expresses the relationship between magnitude and the total number of earthquakes in a given area and the time period of at least that magnitude. The relation is given as:

$Log_{10}\ N\ (≥ M) = a – bM$……………...................................3.11

where,

N is no. of events with magnitude ≥ M,

M is the magnitude of the events,

a and b are constants, thus a describes the seismic activity (log number of events with M=0). It is determined by the event rate and for certain region depends upon the volume and time window considered. b, which is typically close to 1, is a tectonic parameter describing the relative abundance of large to smaller shocks. It seems to represent properties of the seismic medium in some respect, like stress and/or material conditions in the focal region (Kulhanek, 2005).

Comparing equation 3.11 to the equation of a straight line (equation 3.12),

$y=c+mx$……………...3.12

where;

y represents plots on the vertical coordinate

x represents plots on the horizontal coordinate

c represents the y-intercept

m represents the gradient of the plot of y against x

Then equation 4.11 can be re-written as:

$y = Log_{10}\ N\ (≥ M)$………………………………………...3.13

$x = M$……………………………………….……………...3.14

and the gradient

$m = -b$…………………………………………..……..….3.15

$Log_{10}\ N\ (≥ M)$ was evaluated from the catalogue with the corresponding cumulative magnitude M as shown in Table 5.1,

The result obtained from the plot of equation 3.13 against equation 4.14 was used to evaluate the b-value (the slope of the graph) according to the equations 3.11, 3.12, 3.13, 3.14 and 3.15. One interesting feature of this method is that all the $Log_{10}\ N\ (≥M)$ values evaluated take part in the calculation (Chen *et al.*, 2003).

Marzorcchi and Sandri (2003), Lombardi (2003) and Felzer (2006) approaches were adopted to estimate the b-value by the maximum likelihood process using the equation 3.16 given below

$b=1/\ [ln10\ (m_{av}- m_c)]$………………………………..….3.16

where;

b represents the b-value

m_{av} represents the average magnitude from the catalogue and

m_c represents the threshold or cut off magnitude (usually carefully selected from the sharp curve exhibited by chart). The completeness of the earthquake catalogue, i.e. the estimation of the so-called threshold magnitude m_c is critical. In general, m_c magnitude of data set is obtained from the Guttenberg-Richter relation plot (plotting $Log_{10}\ N\ (≥ M)$ against the magnitudes, M). m_c is the level at which the data falls below the line of best fit (Lin *et al*., 2008; Wang and Shieh, 2004)

Marzorcchi and Sandri (2003) reviewed and gave new insights on the estimation of b-value and its corresponding uncertainty. The new insights given involved the introduction of the maximum likelihood estimation method and further went on to calculate the uncertainties associated. Lombardi (2003), on the other hand, used the maximum likelihood estimator to calculate the b-value of mainshocks and compared the results to the Guttenberg-Richter method of least square fit. Felzer (2006), in calculating Californian seismicity rates from the earthquake catalogue for time-independent hazard analysis adopted the maximum likelihood estimation method.

According to Aki (1965), the uncertainty associated with b-value calculation is given by

$\sigma_{b} = b/\sqrt{N}$……………………………………………………..…3.17

where σb represents the uncertainty, b represents the b-value and N represents the number of earthquakes under consideration

Results and Discussion

(α) Results

Earthquake Catalogue

An earthquake catalogue has been created, and this is an improvement on the one generated by Amponsah *et al.* (2012). In all, 554 events from 1615 to 2012 from Ghana and its neigbouring countries were used in this study. The interpolated earthquake magnitudes were computed using Matlab software which generated the earthquake magnitudes between 2.9M_w and 6.6M_w.

Epicentral Intensity

The epicentral intensity map clearly defines the epicentral intensities evaluated. The range of the epicentral intensity computed for the study area is from 3.6 to 8.2 whilst earthquake magnitudes between 4 and 5 are highly present in GAMA. The plot shows areas of high intensities to be western, south western (around Weija) and north eastern Accra (6.02 to 8.6). Other areas include Kokrobitey, Kasoa and Nyanyano. South eastern Kasoa and south western Amasaman, however, have low seismic intensities (3.6 to 5.97). The plot of the epicentral intensities is shown in Fig. 4.1

b-value Evaluation

Linear Least Square Fit Approach

A cumulative frequency table of events and their corresponding number of occurrence is shown in Table 4.1. This is the linear least square fit approach.

Table 4.1: Magnitudes and Cumulative Number of Events

M	N≥ M	Log(N≥ M)
2	553	2.742725131
2.5	447	2.650307523
3	405	2.607455023
3.5	381	2.580924976
4	311	2.492760389
4.5	47	1.672097858
5	16	1.204119983
5.5	11	1.041392685
6	8	0.903089987
6.5	3	0.477121255

The plot of graph showing the relationship between Log (N≥ M) and M is shown in Figure 4.2.

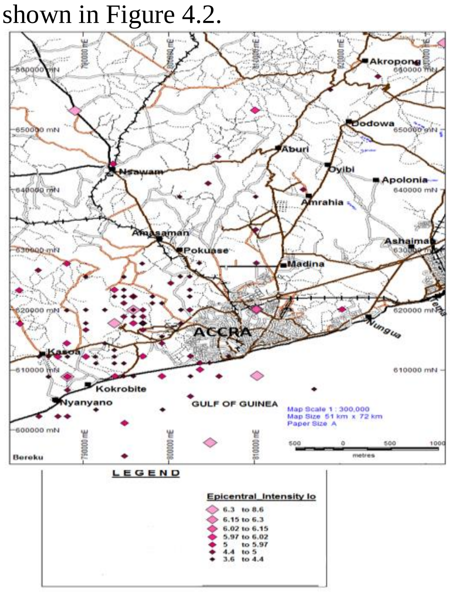

Fig. 4.1: A Plot of the Epicentral Intensity Map of the Study Area

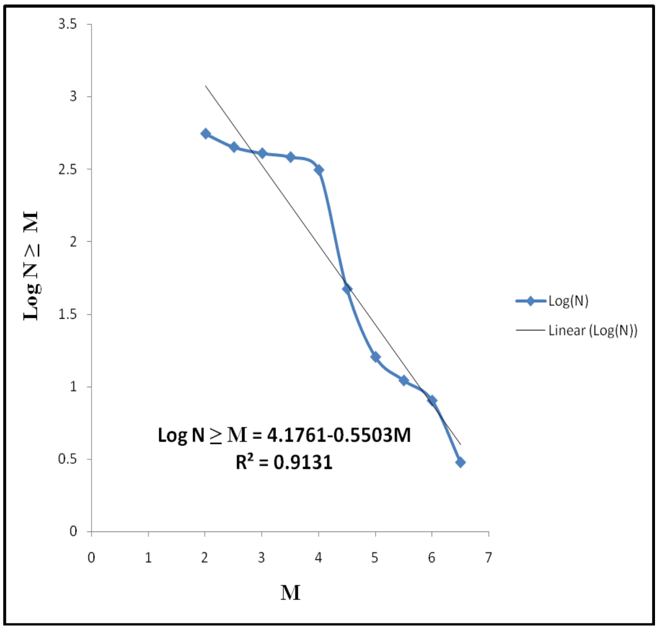

Fig. 4.2: Graph Indicating the Plot of Cumulative Number of Events against Magnitude

The b-value has been evaluated from the graph (Fig 4.2) employing the equation below:

Log (N≥ M) = a-bM…….……..……..……...4.1

where,

N is no. of events with magnitude ≥ M,

M is the magnitude of the events,

a and b are constants, thus a describes the seismic activity (log number of events with M = 0). It is determined by the event rate and for certain region depends upon the volume and time window considered.

Thus comparing equation 4.1 and Figure 4.3, the b-value was computed as 0.6. The Regression coefficient, R^2, is 0.9131. Thus, the variation in the regression is 91.31% explained by the independent variable M, the magnitude of events.

Maximum Likelihood Estimation

The maximum likelihood estimation method was used to evaluate the b-value according to Aki (1965), Marzorcchi and Sandri (2003), Lombardi (2003) and Felzer (2006)

b=1/ [ln10 (m_{av}- m_c)]……………………….4.2

where,

b represents the b-value

m_{av} represents the average magnitude from the catalogue and

m_c represents the threshold or cut off magnitude (usually carefully selected from the sharp curve exhibited by chart). The completeness of the earthquake catalogue, i.e. the estimation of the so-called threshold magnitude m_c is critical. In general, m_c magnitude of data set is obtained from the Guttenberg-Richter relation plot (plotting Log_{10} N (≥ M) against the magnitudes, M). m_c is the level at which the data falls below the line of best fit.

From Fig. 4.2 the threshold magnitude also known as the cut off magnitude, $m_{c,}$ was evaluated as 4.5. The average magnitude was subsequently calculated from the catalogue after applying the cut off magnitude. In calculating the average magnitude, m_{av}, forty seven (47) events were used. These include magnitudes 4.5 to 6.6. An average magnitude of 5.0 was obtained.

The b-value was then calculated using equation 5.2 as

b=1/ [ln10 (5.0-4.5)] =0.864 ≈ 0.9,

The uncertainty associated with the analysis of the data was also calculated using the equation below:

$\sigma_b = b/\sqrt{N}$……………………………………….…………4.3

where;

σ_b represents the uncertainty,

b represents the b-value and

N represents the number of earthquakes under consideration

$\sigma_b = 0.864/\sqrt{47} = 0.126$

(β) Discussion

The research work was aimed at investigating earthquake hazard in the Greater Accra Metropolitan Area using seismological means by employing mathematical models. The seismological method involved establishing a comprehensive earthquake catalogue in order to study the history of earthquakes and earth tremors in the study area. The catalogue is an update of the one produced by Amponsah *et al*. (2012) which involved the relocation of some epicenters to reflect the current situation. There was also the interpolation of earthquake magnitude for events without magnitudes (resulting in magnitudes between 2.9 M_w and 6.6 M_w). A completely homogenized earthquake catalogue was generated with most seismic events occurring in and around Western Accra.

The epicentral intensity map generated from the catalogue clearly shows the earthquake prone zones in the metropolis are mostly around Western Accra, Nyanyano, Kasoa, Weija, Amasaman and Pokuase. It is also evident that major events are occurring off the coast of Ghana (GAMA). This can be associated with the well-defined unconsolidated and poorly consolidated sediments and soils which are prone to liquefaction and the formation of sand vents and mud volcanoes as described by Muff and Efa (2006). Events here can also be attributed to faults along the coast, some of which cause major displacements (Muff and Efa, 2006). The fact that these events have not been felt on-shore maybe indicative of silent and/or slow earthquakes (Singh *et al*., 2009). These events may be as a result of the Coastal boundary faults as observed by Sykes (1978) that the Cameroon line and the Ngaourandéré fault zone are situated near the boundary between the Congo and a belt of Pan-African deformation that extends as far as West of Accra, Ghana and captured in the fault map of GAMA as modified from Muff and Efa (2006) (Ennison *et al.*, 2012).

To investigate the earthquake hazard in the Greater Accra Metropolitan Area, one key objective was to calculate the b-value of GAMA from the earthquake catalogue that was compiled. The linear least square fit method resulted in a b-value of 0.6 and the maximum likelihood estimation of 0.9 approximately. The linear least square is disproportionately influenced by the largest earthquakes whilst the maximum likelihood estimation method weighs each earthquake equally. In fact, a b-value approximately 1 is indicative of the fact that there are relatively smaller shocks to larger ones in an earthquake catalogue. The b-value of 0.9, just like the earlier one (0.6) is in line with the globally accepted b-value of approximately 1.0 (Chen *et al*., 2003; Lombardi, 2003; Marzocchi and Sandri, 2003; Felzer, 2006; Kulhanek, 2005). According to Talwani (1998), earthquake generation is influenced by several factors including the nature of the fault zone and the stress conditions. The b-value obtained confirms the relative abundance of small shocks to large ones and is representative of stress and/or material conditions in the study area (Kulhanek, 2005). The uncertainty calculated from the maximum likelihood estimation of the b-value was 0.126 as compared to the coefficient of determination of 0.9131 obtained from the linear least square fit. The errors 0.126 and 0.0869 respectively may be due to the incompleteness of the catalogue or variations in scaling of magnitudes.

The delimitation of the study area has lead to the generation of enough data for the seismic stress evaluation (b-value calculation). The 554 events used in this research would have been unattainable. The two methods used to evaluate the b-value were to test whether the best approach in terms of calculating the b-value. True to some schools of thought enumerated earlier the maximum likelihood estimation method gave an improved b-value of 0.9.

The thematic epicentral intensity map further revealed the accumulation of events around the Weija Lake and the numerous faults, thrusts and shear zones around its vicinity. South western GAMA is very active and, therefore has recorded a lot of the events captured in the study area. These areas include Nyanyano, Kokrobite, Pokuase, Weija, Atomic, Kwabenya, Legon and the city centre Accra. Some events are also recorded offshore. They are also significant events (they have epicentral intensities as high as 8.6 and magnitudes to the tune of 6.6 M_w). The coast of Accra records events of epicentral intensities as high as 6.02 to 6.15 of magnitudes ranging between 4.02 and 4.15 whereas the offshore has epicentral intensities ranging from 3.6 to 8.6. It can be seen that all units of the Accraian sandstones have major faulting and jointing and are prone to earthquakes. Seismological activity is greatest in the unconsolidated sand and clay deposits around Sakumono, Densu Delta and South of Weija, Nyanyano, along the Togo Series alluvium boundary and in the area underlain by the Accraian rocks.

The faults, thrusts and shear zones (also confirmed by Junner, 1941; Amponsah, 2002; Amponsah, 2004; Amponsah, *et al.*, 2009; Allotey *et al*., 2010; Muff and Efa, 2006 and Ennison *et al.*, 2012) cannot be left out when discussing the possible contributions to seismic activity in the study area. The blend of seismological and geological observations (the completely homogenized earthquake catalogue, the b-value calculated and the epicentral intensity map generated) from the investigations agrees to the observation that key areas of the Greater Accra Metropolitan Area are earthquake prone.

Conclusion

After the compilation of an earthquake catalogue for Ghana and its immediate neighbours spanning the period 1615 to 2012, the epicentral intensity map generated is just supplementary. Reconciling the epicentral intensities observed with the geology of the study area, the relationship between the seismic events and the geology has been established. The epicentral intensity map developed from the comprehensively harmonized earthquake catalogue generated has brought out the earthquake prone areas in the Greater Accra Metropolitan Area. Some of these areas are Weija, Kasoa, Nyanyano, Kokrobite, Southern Pokuase, Accra and offshore Accra. Nsawam, Madina Nungua, Tema, Ashaiman, Amrahia, Oyibi, Dodowa, Aburi and Apolonia on the other hand have not recorded very significant number of events. These areas may be said to be seismically stable. Further studies may be required to confirm this assertion though. Policy makers have no option but to rely on credible information on the seismicity (Earthquake catalogue, b-values calculated and the epicentral intensity map developed) of GAMA and update existing building codes and lay down clear guidelines for settlement.

The calculated b-value (0.6 and 0.9), indicative of the prevalence of small shocks over large ones, must be taken into consideration in order to locate more settlements at stress/fault free areas such as those mentioned earlier.

Acknowledgements

We appreciate all bodies that have allowed the use of their data for the research. We also want to single out Pof. Samuel Dampare and Dr. Thomas Tetteh Akiti for their immense contribution towards this research. They have been very inspiring and insightful.

Our sincere gratitude goes to some staff of the School of Nuclear and Allied Sciences; Earth Sciences Department, University of Ghana and the Ghana Atomic Energy Commission (National Data Centre).

References

Aki, K., 1965. Maximum Likelihood Estimate of b in the formula Log (N) =a –bM and its Confidence Limits, Bull. Earthq. Res. Inst. Tokyo Univ., 43, 237-239.

Allotey, N. K., Arku, G., Amponsah, P. E., 2010. Earthquake Disaster Preparedness: the Case of Accra, International Journal of Disaster Resilience in the Built Environment, Vol. 1, No. 2

Ambraseys, N.N., Adams, R.D., 1986. Seismicity of West Africa. Annales Geophysicae 4 (B6), 679–702

Amponsah, P. E., Banoeng-Yakubo, B. K., Panza, G. F., Vaccari, F., 2009. Deterministic Seismic Ground Motion Modeling Of The Greater Accra Metropolitan Area, South Eastern Ghana, South African Journal Of Geology, Vol. 112, No. 3-4, pp. 317-328

Amponsah, P. E., Leydecker, G., Muff, R., 2012. Earthquake Catalogue Of Ghana for the Time Period 1615-2003 With Special Reference to the Tectono-Structural Evolution of South-East Ghana, Journal of African Earth Sciences, Vol. 75, pp. 1-13

Amponsah, P. E., 2002. Seismic Activity in Relation to Fault Systems in Southern Ghana, Journal of African Earth Sciences, Vol. 35, pp. 227-234

Amponsah, P. E., 2004. Seismic Activity in Ghana: Past, Present, and Future, Annals of Geophysics, Vol. 47, pp. 239-243

Attoh K., Brown L., Guo J., Heanlein J., 2003. Seismic stratigraphic record of transpression and uplift on the Romanche transform margin, offshore Ghana. Tectonophysics 378 (2004) 1 –16

Attoh K., Brown L., Guo J., Haenlein J., 2005. The role of Pan-African structures in intraplate seismicity near the termination of the Romanche fracture zone, West Africa. Journal of African Earth Sciences 43 (2005) 549–555

Brumbaugh, D. S., 1987. A comparison of Duration Magnitude to Local Magnitude for Seismic Events Recorded in Northern Arizona, Journal of the Arizona-Navada Academy of Sci., Vol. 23, No. 1, pp. 29-31

Chen, P., Bai, T., Li, B., 2003. The B-value and Earthquake Occurrence Period, Chinese Journal of Geophysics, Vol. 46, No. 4, pp. 736~749.

Ennison, I., Akiti, T., Amponsah, P., Osae, S., Gbadago, J., 2012. Determination of Suitable Sites for Nuclear Power Plants in Ghana: - The Issues Involved, Environmental Research, Engineering and Management, No. 4 (62), pp. 30-38

Felzer, K., 2006. Calculating California Seismicity Rates from the Earthquake Catalogue for Time-Independent Hazard Analysis, Pages 1-32

Geological Map of Ghana, 2009. Geological Survey Department of Ghana, Ghana Building Code, February 1988. Building and Road Research Institute of the Council for Scientific and Industrial Research

Hanks, T. C., Kanamori, H., 1979. A Moment Magnitude Scale, Journal of Geophysical Research, Vol. 84, No. B5, pp. 2348-2350

Herak, M., Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia, www.uic.edu/classes/geol/eaes102/Lecture%2021-22.ppt, Accessed December, 2012

International Seismological Centre, Reference Event Bulletin, http://www.isc.ac.uk, Internatl. Seis. Cent., Thatcham, United Kingdom, 2010, Accessed March, 2013

Junner, N. R., 1941. The Accra Earthquake of 22nd June 1939, Gold Coast Geological Survey (Bulletin No. 13), pp. 1-70

Kulhanek, O., 2005. Seminar on b-value, Department of Geophysics, Charles University, Prague, December 10-19, 2005.

Lin, J., Sibuet, J., Hsu, S., 2008. Variations in b-value at the Western Edge of the Ryukyu Subduction Zone, North-East Taiwan, Terra Nova, Vol. 20, Issue 2, pp. 150-153.

Lombardi, A. M., 2003. The Maximum Likelihood Estimator of b-value for Main Shocks, Bulletin of the Seismological Society of America, Vol. 93, No. 5, pp. 2082-2088

Marzocchi, W., Sandri, L., 2003. A Review And New Insights On The Estimation Of The B-Value And Its Uncertainty, Annals Of Geophysics, Vol. 46, No. 6, pp.1271-1282

Mavonga, T., Durrheim, R. J., 2009. Probabilistic Seismic Hazard Assessment Of The Republic Of Congo And Surrounding Areas, South African Journal Of Geology,Vol. 112, No. 3-4, pp. 329-342

McConnell, R. B., 1969. Fundamental Fault Zones In The Guiana And West African Shields In Relation To Presumed Axes Of Atlantic Spreading, Geol. Soc. Of Amer., Bull., 80, pp. 1775-1782

Microsoft Encarta Premium, 2009. One Microsoft Way, Redmond, WA 98052-6399, USA, encwish@microsoft.com

Muff, R., Efa, E., 2006. Explanatory Notes for the Geological Map for Urban Planning 1:50,000 of Greater Accra Metropolitan Area, Ghana Geological Survey, Accra, Ghana (GSD) and Federal Institute for Geosciences and Natural Resources, Hannover, Germany (BGR)

Opoku, N., 2012. CTBTO-S & T 2011 Conference, The Recently Acquired Broadband And Strong Motion Sensors Network In Ghana And The Access To CTBTO's Data And Products, The Way Forward For The Update Of Ghana's National Seismic Hazard Assessment For Sustainable Infrastructure Development

Rajendran, C. P., 2000. Using Geological Data for Earthquake Studies: A Perspective from Peninsular India, Current Science, vol. 79, No. 9, pp. 1251-1257

Singh, M., Kijko, A., Durrheim, R., 2009. Seismotectonic Models For South Africa: Syntesis of Geoscientific Information, Problems and The Way Forward, Seismological Research Letters, Vol. 80, No. 1, pp. 71-80

Sykes, L. R., 1978. Intraplate Seismicity, Reactivation Of Preexisting Zones Of Weakness, Alkaline Magmatism, And Other Tectonism Postdating Continental Fragmentation, Reviews Of Geophysics And Space Physics, Vol. 16, No. 4, pp. 621-688

Talwani, P., 1998. Fault Geometry and Earthquakes in Continental Interiors, Tectonophysics 305, pp. 371-379

Wang, J., Shieh, C., 2004. Investigation of Seismicity In Central Taiwan Using the Accelerating Seismic Energy Release Model, TAO, Vol. 15, No. 1, pp 1-13.

Wereko, C., 2012. http://www.ghana.gov.gh/index.php/news/general-news/18776-ghanas-digital-seismic-network-commissioned