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AN INVESTIGATION INTO THE STRESS CONDITIONS OF CRITICAL AND LIFELINE INFRASTRUCTURE IN SOUTH-EASTERN GHANA USING THE MAXIMUM LIKELIHOOD ESTIMATION METHOD

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Abstract

In the face of current seismic hazards that have occurred around the world, investigations have been carried out to estimate the stress condition (b-value) and its impact on critical infrastructure in South-Eastern Ghana. This was done by updating earlier earthquake catalogues of seismic events database from 1615 up to 2018 and harmonizing the units of measurement using descriptive statistics and the MATLAB Programming software. The seismic stress condition (b-value) was evaluated by the Linear Least Square and Maximum Likelihood Estimation Methods. An isoseismal intensity map has been generated out of the unified and harmonized Moment Magnitude Catalogue (using the Geographic Information Systems, GIS) after the evaluation of the b-value. This represents stress accumulated over the period and the relative number of small events $\leq$ 3.5 Mw prevalence over $\geq$ 3.5 Mw. The b-values estimated for 1615-2015, a four-hundred-year period of earthquake in Ghana yielded 0.97 with an error margin of 0.116. The results confirm stress build up around critical infrastructure in and around the Greater Accra Metropolitan Area.

Introduction

The earth is prone to hazards of many dimensions. How to minimize the degree of damage when they do happen is not impossible (Allotey et al., 2010). Situations or occurrences that pose a level of threat to life, property or the environment sometimes do not receive the needed attention. Studies have shown that natural and man-made hazards are usually accompanied with deadly forces or retribution in high vulnerability areas like the Greater Accra Metropolitan Area (GAMA), (Doku et al., 2014). Common disasters such as; earthquakes, epidemics, storm, mass movements, extreme temperature, flood, insect infection (just to mention a few) can be identified easily in the country. Apart from earthquakes which has not received much attention, all other disasters have been fairly mitigated by the National Disaster Management Organization (NADMO) assisted by other agencies. Generally, knowledge about earthquakes in Ghana has not been common before the first records. Documentation on Seismic data, stress level data, epicenters, epicentral and seismic intensity, etc. were all not available. More also, the cause of the seismicity was unknown even after earlier recordings in the region of GAMA (Doku et al., 2014). This has made the understanding and knowledge about this disaster-causing hazard very scanty and may be attributed to the long span in time of occurrence or the assumption that a major one is not imminent (Ennison et al., 2012). According to Danso and Swanzy (2017), Ghana's rainfall pattern is bimodal. At such times, during the peak rainy season many environmental hazards do occur. Some even leading to loss of life and property. The Baby Telescope was developed to make terrestrial observations like this easy (Proven–Adzri et al., 2016).

Seismic hazard evaluations of this nature seek to innovate a way to monitor stress in the ground and make recommendations for mitigation where possible. Measures have always been put in place to mitigate the effect and degree of damage when these occurrences take place (World Health Organisation, 2003). Earthquake has not received the major attention it deserves in Ghana until the consideration of Nuclear Power to boost the country's challenging energy fortunes; the earliest known earthquake in Ghana occurred in the coastal town of Elmina in 1615 (Quartz Africa, 2020). This may be attributed to the long span in time of occurrence or the assumption that a major one is not imminent since that of 1939 (Ennison et al., 2012). Recent works such as Amponsah et al. (2009); Attoh et al. (2004, 2005), have highlighted the fact that areas underlain by unconsolidated sediments experience the greatest shakings. This is clearly evident in the fault map modified from Muff and Efa (2006) for the Greater Accra Metropolitan Area, GAMA (Amponsah et al., 2009). Since Ahulu et al. (2018), that covered earthquake data from 1615 to 2009, no updated catalogue is available for a very current establishment of degree of stability. Lots of the events, currently available as at the end of 2018, after a decade, have not been captured in the Moment Magnitude. Generally, GAMA is low-lying and slightly undulating (Amponsah, 2004; Junner and Bates, 1941). With reference to Nyanyano, the epicenter of the 1939 earthquake, prominent ranges of hills running in the north-east direction from the coast and rising to more than 180 meters above sea level occur. Seismotectonically, 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).
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., 2004). Figure 1 shows the fractured and faulted-soft Phyllite (seismotectonics of the area).

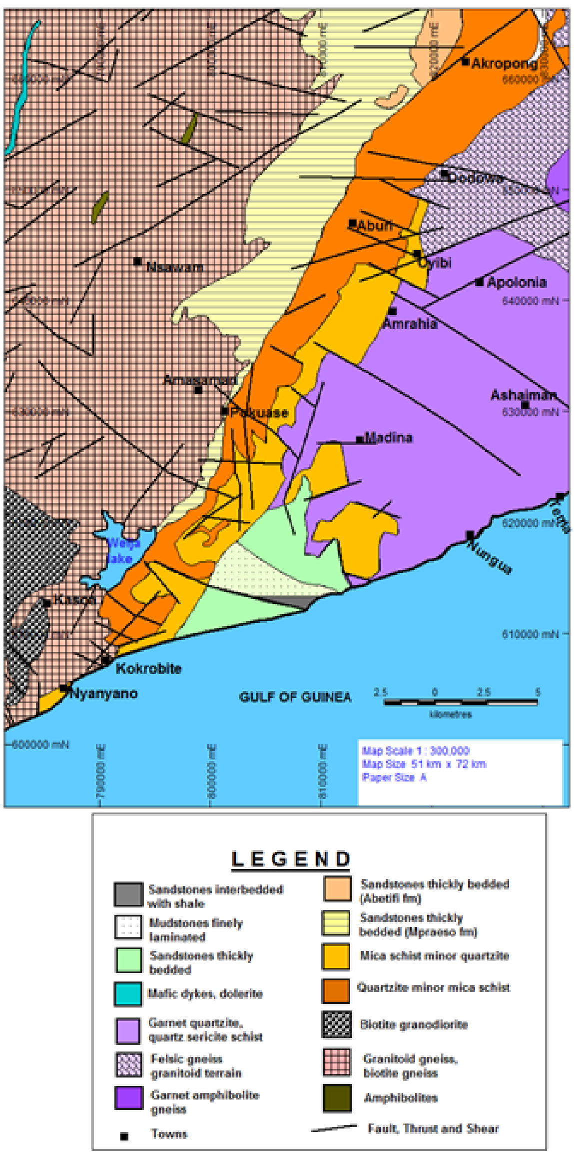

Figure 1. Seismotectonics of the study area (Modified after Doku et al. (2014)

Critical national infrastructure was badly affected by the 1862, 1871, 1872, 1906, and 1939 earthquakes with magnitudes of 6.5, 4,6, 4.9. 5.0 and 6.5 respectively on the Richter Scale (Ahulu et al., 2018; Ambraseys and Adams, 1986; Amponsah, 2004; Doku et al., 2014; Junner and Bates, 1941; Quaah, 1980). The most pronounced being the 1939 earthquake in which seat of government, the castle was badly affected (Junner and Bates, 1941). Brunsdon (2003) observes that low seismicity does not mean that only weak earthquake shaking can be expected, rather strong earthquakes do occur but less frequently Brunsdon (2003).
Critical infrastructure comprises the essential services and facilities on which citizens of a nation depend on day to day basis. They include: utility services (water, sewerage, power, gas and telecommunications), transportation networks (roads, railways, ports), lifeline infrastructure, and Emergency Operation and Control Centres Brunsdon (2003); Prabaharan and Veenendaal (2002). Most of Ghana's critical national infrastructure are located in the Southern Belt especially the Capital, Accra, the Greater Accra Metropolitan Area (GAMA) which is prone to earthquakes (Figure 2). The seismic source

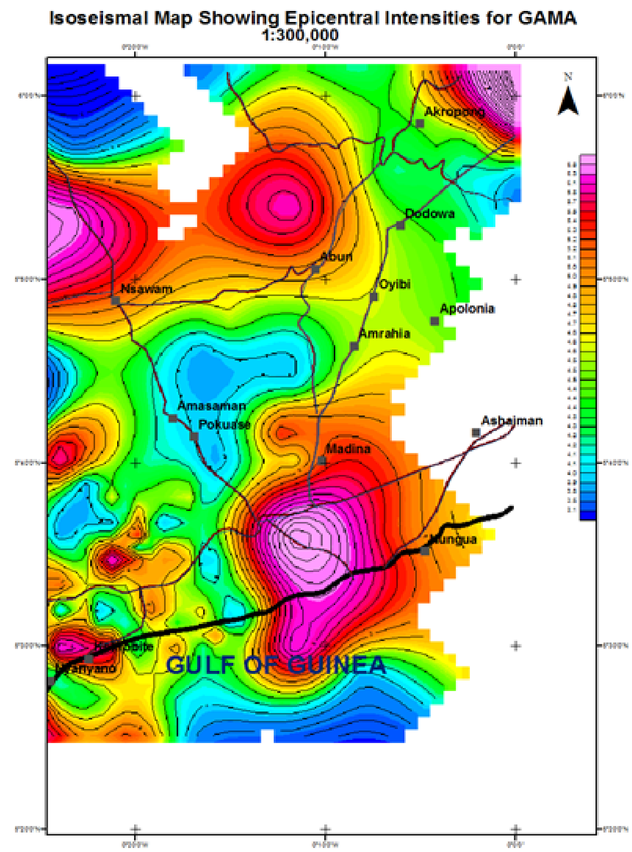

Figure 2. Isoseismal Intensity of the Study Area

zones are the Gulf of Guinea, Accra Region (including Weija, Tema and Koforidua) and the Ho Region (Ahulu et al., 2018). Ghana's critical infrastructure are located in these zones are as follows:

- *Seat of Government*; Flagstaff House (Jubilee House) and Castle
- *Legislature*; Parliament House and Offices of Members

of Parliament

- *Judiciary*; Supreme Court, Court of Appeal, Other High Courts
- *Security*; Emergency Management and Control Centres
- *Lifeline Infrastructure*; Electricity, water supply, sewerage systems, gas, liquid fuels, communications and health.
- *Finance*; Bank of Ghana and other financial institutions
- *Education and Research*; Research and Institutions of higher learning such as the University of Ghana, Ghana Atomic Energy Commission, Environmental Protection Authority, Ghana Geological Survey Authority, University of Environment and Sustainable Development, Council for Scientific and Industrial Research, University of Professional Studies Accra, Ghana Institute of Management and Public Administration, Ghana Telecom University, Accra Technical University, University of Cape Coast, Cape Coast Technical University, Takoradi Technical University, Koforidua Technical University, University of Health and Allied Sciences and Ho Technical University.

The ability of the community to restore the lifeline infrastructure after an earthquake is very important (Brunsdon, 2003; Prabaharan and Veenendaal, 2002). The objectives of the research are:

- Create a unified and harmonized earthquake catalogue
- Use the catalogue to estimate the b-value (Seismic Stress) of the area under study by the Maximum Likelihood Estimation Method
- Generate an Isoseismal map using Geographical Information Systems (GIS)
- Draw conclusions and make recommendations based on the above outcomes

Materials and Methods

The Maximum Likelihood Estimation Method

As a Bayesian inference, the maximum likelihood estimation method (MLE) is a special case of maximum a posteriori estimation (MAP). Here it assumes a uniform prior distribution of the parameters. On the other hand, as a frequentist inference, MLE is a special case of an extremum estimator. In this case it has a key objective function being the likelihood (Lin et al., 2006).

The fundamental idea for the maximum likelihood estimate is to find the value of the parameter(s), here, the earthquakes, for which the data has the highest probability. MLEs behave well under transformations. They are generally asymptotically unbiased. This means the data they process grows. This growing data usually has asymptotically minimal variance. We must not forget that the MLE is itself a random variable since the data is random and the MLE is computed from the data (Orloff and Bloom, 2014).

Doku et al. (2014); Lombardi (2003); Marzocchi and Sandri (2003) were adopted to estimate the degree of stress (b-value) by the maximum likelihood process using the mathematical model:

$$b = \frac{1}{\ln 10(m_{av} - m_c)} \quad (1)$$

where; b is the b-value, stress determinant, m_{av} is the average magnitude from the catalogue and mc represents the cut off magnitude (usually carefully selected from the sharp curve exhibited by chart). The estimation of the threshold magnitude *mc* is very critical. Usually, mc magnitude of data set is evaluated from plotting Log10 N ($\geq$M) against the magnitudes, M. This cut off magnitude m_c, is the level at which the data falls below the line of best fit (Doku et al., 2014; Lin et al., 2008; Wang and Shieh, 2004).

This study applied this estimation to evaluate the stress level of the location over the period of generation of the earthquake catalogue spanning 1615-2015 and 1615-2018. The uncertainty associated with b-value calculation is given by (Aki, 1965)

$$\sigma_b = \frac{b}{\sqrt{4}} \quad (2)$$

Generation of Isoseismal Map

Isoseismal maps were generated using the Geographic Information System software. This was done for the general catalogue generated and then zoomed in to the study area for detailed appreciation of the hazard correlation of the displayed geographically referenced information processed.

Results and Discussion

Results

An isoseismal intensity map has been generated out of the unified and harmonized Moment Magnitude Catalogue after the evaluation of the b-value representing stress accumulated over the period and the relative number of small events $\leq$3.5Mw prevalence over $\geq$3.5Mw as detailed under Present day isoseismals of GAMA.

Present day isoseismals of GAMA

It can be seen that in GAMA the most sensitive areas seismically include regions around Nsawam (Figure 2), In and around Aburi, North East Akropong North West Oyibi, Madina and its environs, Nungua, Tema and South West Ashaiman. Other active areas include Nyanyano and Kokrobite. Areas like North East and Southern Oyibi, Amasaman, Pokuase, North East Kokrobite, Western Amrahia, Apolonia and Dodowa fall within tremors of 4.0 Mw to 4.7 Mw. However, low seismic regions within GAMA include Amasaman, Pokuase and South Western Akropong. These areas have events occurring less than 4.0 Mw. These breakdowns do not however underestimate the general view that the Greater Accra Metropolitan Area and by extension, South Eastern Ghana is seismically active. The average error as estimated from Aki 1965 is 0.123. Table 1 shows that the Maximum Likelihood Estimation Method brings out a better evaluation of the stress condition of the study area.

Table 1. Stress conditions of GAMA

RANGE(YR)	MLE	σ_b
1615 - 2012	0.86	0.126
1615 - 2015	0.97	0.116
1615 – 2018	0.79	0.126
Average	0.87	0.123

Discussion

Present day stress conditions of GAMA

From Table 1, the maximum value of the log of the probability occurs at the same point as the original probability function. This conditionally probabilistic way of properly observing the distribution of the earthquakes over the region has help to disambiguate the density estimation for the various areas within the Greater Accra Metropolitan Area. For example, a distant observation generalizes absolute seismic activism of GAMA. But a closer look of the density distribution puts places like Nyanyano, Kokrobite, Weija and MacCarthy Hill on the high value earthquake occurrence list.

Conclusion

Based on the results available; Catalogue after the evaluation of the b-value (representing stress accumulated over the period and the relative number of small events $\leq$ 3.5 Mw prevalence over $\geq$ 3.5 Mw) and the seismic stress (b-value) evaluated by the Maximum Likelihood Estimation to be 0.97 with an error margin of 0.116, one can conclude that indeed the Tema-Accra-Weija-Nyanyano enclave is very active seismically and the authors will like to call for the following measures to be taken to safeguard the built environment.

1. Critical infrastructure must be spread across the country taking population density and geology into consideration.
2. Re-assessment of critical infrastructure in Ghana especially the capital, Accra must not be an event but a continuous practice.
3. Inculcate earthquake resistant designs in our buildings - retrofit building.
4. District- or regionally-based lifeline infrastructure, control centres, emergency response centres and security control centres must be strategically located within seismically active areas in Ghana taking population density and geology into consideration.
5. All critical infrastructure operators need to have direct relationships with Geoscientists, Seismologists and Earthquake Engineers as advisers in order to have dependable assistance for assessment of their facilities for re-occupancy following an earthquake. On the other hand, these infrastructural units can have regular professional reviews from a centralized agency.
6. Continuous education of the citizenry especially critical infrastructure operators and decision makers on earthquake safety measures.

References

Ahulu, S. T., Danuor, S. K., and Asiedu, D. K. (2018). Probabilistic seismic hazard assessment of southern part of Ghana. *Journal of seismology*, 22:539–557. https://doi.org/10.1007/s10950-017-9721-x.

Aki, K. (1965). Maximum likelihood estimate of b in the formula log n= a-bm and its confidence limits. *Bull. Earthquake Res. Inst., Tokyo Univ.*, 43:237–239.

Allotey, N. K., Arku, G., and Amponsah, P. E. (2010). Earthquake-disaster preparedness: the case of Accra. *International Journal of Disaster Resilience in the Built Environment*, 1(2):140–156.

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

Amponsah, P. (2004). Seismic Activity in Ghana: Past, Present, and Future, Annals of Geophysics.

Amponsah, P., Banoeng-Yakubo, B., Panza, G., and Vaccari, F. (2009). Deterministic seismic ground motion modelling of the greater Accra metropolitan area, southeastern Ghana. *South African Journal of Geology*, 112(3-4):317–328.

Attoh, K., Brown, L., Guo, J., and Heanlein, J. (2004). Seismic stratigraphic record of transpression and uplift on the Romanche transform margin, offshore Ghana. *Tectonophysics*, 378(1-2):1–16.

Attoh, K., Brown, L., and 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(5):549–555.

Brunsdon, D. (2003). Critical infrastructure and earthquakes: Understanding the essential elements of disaster management. *Wellington, New Zealand: National Lifelines Coordinator*, 28:1–7. https://aees.org.au/wp-content/uploads/2013/11/Papers-28-to-33.pdf.

Danso, I. and Swanzy, F. K. M. (2017). Sustainable Oil Palm Production in The Face of Climate Change and Climate

Variability: The Case of Small Holder Former in The Amansie West District of the Ashanti Region of Ghana. *Journal of Ghana Science Association*, 17(2):32–40.

Doku, M., Amponsah, P., and Adomako, D. (2014). b-value estimation for the Greater Accra Metropolitan Area. *Elixir Nucl Radiat Phys*, 73(2014):26218–26224.

Ennison, I., Akiti, T., Amponsah, P., Osae, S., and Gbadago, J. (2012). Determination of Suitable Sites for Nuclear Power Plants in Ghana:-The Issues Involved. *Environmental Research, Engineering & Management*, 62(4).

Junner, N. R. and Bates, D. A. (1941). *The accra earthquake of 22nd June, 1939*. FJ Miller.

Lin, C.-T., Wu, S. J., and Balakrishnan, N. (2006). Monte carlo methods for bayesian inference on the linear hazard rate distribution. *Communications in Statistics-Simulation and Computation*, 35(3):575–590. https://doi.org/10.1080/03610910600716647.

Lin, J.-Y., Sibuet, J.-C., and Hsu, S.-K. (2008). Variations of b-values at the western edge of the Ryukyu Subduction Zone, north-east Taiwan. *Terra Nova*, 20(2):150–153.

Lombardi, A. M. (2003). The maximum likelihood estimator of b-value for mainshocks. *Bulletin of the Seismological Society of America*, 93(5):2082–2088.

Marzocchi, W. and Sandri, L. (2003). A review and new insights on the estimation of the b-valueand its uncertainty. *Annals of geophysics*.

Muff, R. and 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).

Orloff, J. and Bloom, J. (2014). Introduction to probability and statistics (maximum likelihood estimation method). https://ocw.mit.edu/courses/mathematics/18 - 05 - introduction - to - probability - and - \statistics - spring2014 / readings / MIT18_05S14_Reading10b.pdf.

Prabaharan, D. and Veenendaal, B. (2002). Investigation of lifeline interactions using a geographic information system. *Department of Spatial Sciences, Curtin University of Technology*, 29. https://aees.org.au/wpcontent/uploads/2013/11/Papers-28-to-33.pdf.

Proven–Adzri, E., Akoto Danso, A., Koranteng-Acquah, J., Tettey–Madjitey, F., Nsor, J. A. K., Mornoh, E., Azankpo, S., and Ansah Narh, T. (2016). Baby telescope: A tool for inspiring astronomy related research. *Journal of Ghana Science Association*, 17.

Quaah, A. O. (1980). *Microseismicity, past seismic activity, and seismic risk in southern Ghana*. University of London, Chelsea College (United Kingdom).

Quartz Africa (2020). One of Africa's fastest-growing cities is not prepared for the earthquake it knows is coming. https://qz.com/africa/1877188/ghanas-capital-accra-not-ready
-for-earthquake-it-knows-iscoming.

Wang, J.-C. and Shieh, C.-F. (2004). Investigation of seismicity in central taiwan using the accelerating seismic energy release model. *TERRESTRIAL ATMOSPHERIC AND OCEANIC SCIENCES*, 15(1):1–14.

World Health Organisation (2003). Man-made disasters, natural hazards cost Africa $15 billion. https : / / www.afro.who.int / news / man - made - disasters - natural - hazards - cost - africa\-15-billion.