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Factoring Seismic Hazard in Structural Design of Infrastructure in Zambia

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Abstract: *The threat posed by seismicity anywhere in the world is one that can never be completely dismissed. While it is generally accepted that earthquakes will predominantly occur along plate boundaries, devastating earthquakes have been recorded in the interiors of tectonic plates. Zambia, located in the interior of the African plate may generally be assumed to be aseismic. However, the influence of the East Africa Rift System challenges such an assumption.The research aimed at establishing Seismic hazard in Zambia, as regards structural design of infrastructure. The research methodology included literature review of works related to seismicity and geology of Zambia and the sub-region and analysis of raw earthquake data obtained from earthquake monitoring agencies. The research established significant values of peak ground acceleration (PGA) of up to 0.5g and 0.7g for return periods 475 and 950years, respectively, in some seismic source zones. It is recommended that seismic hazard be given due consideration in structural design, especially for lifeline and critical infrastructure.*

Keywords: *Earthquake, Seismicity, Hazard*

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I. INTRODUCTION

By world standards, Seismic hazard in Zambia and the surrounding areas is relatively low, and the general practice has been to neglect seismic hazard in structural design. However, the risk posed by earthquakes in Zambia and the surrounding areas is not to be neglected as historical records of earthquakes prove that destructive earthquakes have occurred in relatively aseismic regions around the world as well as Eastern and Southern Africa.

Seismic activity in Eastern and Southern Africa is controlled by the East Africa Rift System, an intraplate fault line on the Africa plate. The East Africa Rift System forms two main lines, the Eastern and Western Branches. The Eastern Branch extends from the Afar triangle in the north to Northern Tanzania in the south. The western branch extends from Lake Albert in the north to the south of Lake Malawi in the south, encompassing lakes Edward and Tanganyika. Zambia's seismic activity is mainly influenced by the Western branch which passes close to the northern and eastern region of the country.

Given the remoteness of the region from the African plate boundaries, seismicity in southern Africa is largely attributed to intraplate tectonics that globally account for a very small percentage of annually recorded earthquakes. In spite of the very low frequency of occurrence, seismicity associated with intraplate tectonics is complex and will occasionally reach critical values. In Malawi, the Salima earthquake (Ms=6.1) of 10 May 1989 killed 9 people. In Tanzania, the Kasanga earthquake (Ms=7.3) of 13 December 1910 caused significant damage in southern Tanzania (Midzi et al; 1999).

II. GEOLOGY OF ZAMBIA

Zambia lies between the Kasai, Zimbabwe, Kaapvaal and Tanzania cratons. Differential movements between these stable blocks, together with their buttressing effects, have played an important role in the geological evolution of the country and hence in the genesis of the country's mineral and energy resources (Ministry of mines and Mineral Development, 1999; Scholtz, 2010). Figure 1 shows the tectonic setting of Zambia.

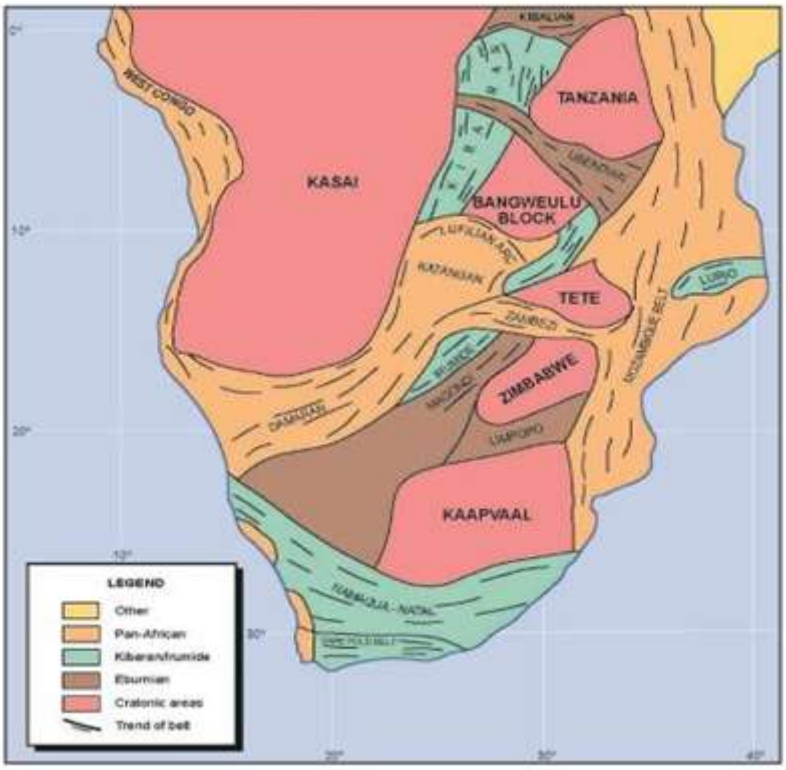

Figure 1: Tectonic setting of Zambia (Source: Ministry of Mines and Mineral Development, 1999)

The main structural provinces of Zambia are the Bangweulu Block, the Ubendian Belt, the Irumide Belt, the Kibaran Belt, the Mozambique Belt and the Zambezi Belt, the Lufilian Arc and the Mwembeshi Shear Zone (Schlüter, 2006). The Bangweulu Block, a craton of Proterozoic age, covers a large portion of northern Zambia. The Ubendian Belt has a NW-SE orientation and is probably of Paleoproterozoic age. The Irumide and Kibaran Belts have a NE-SW orientation and are dated 1.1Ga. The Irumide orogeny affected pre-Katanga rocks, especially those of the Muva Supergroup. The Neoproterozoic Mozambique Belt forms the southern part of an orogenic belt extending from Ethiopia and cutting across the Irumide Belt in southern Zambia. The Zambezi Belt is probably a southern extension of the Mozambique Belt. The Lufilian Arc is an arcuate belt that stretches from Angola through the Democratic Republic of Congo and Zambia, giving NE-SW and NW-SE structures, being formed by a northward movement between 840 and 465 Ma. The about 550 Ma old Mwembeshi Shear Zone is a ductile shear zone associated with a sinistral strike slip movement. Karoo rifting formed the Luangwa, Zambezi and Luano-Lukasashi Valleys (Schlüter, 2006). Figure 2 shows the main structural provinces of Zambia.

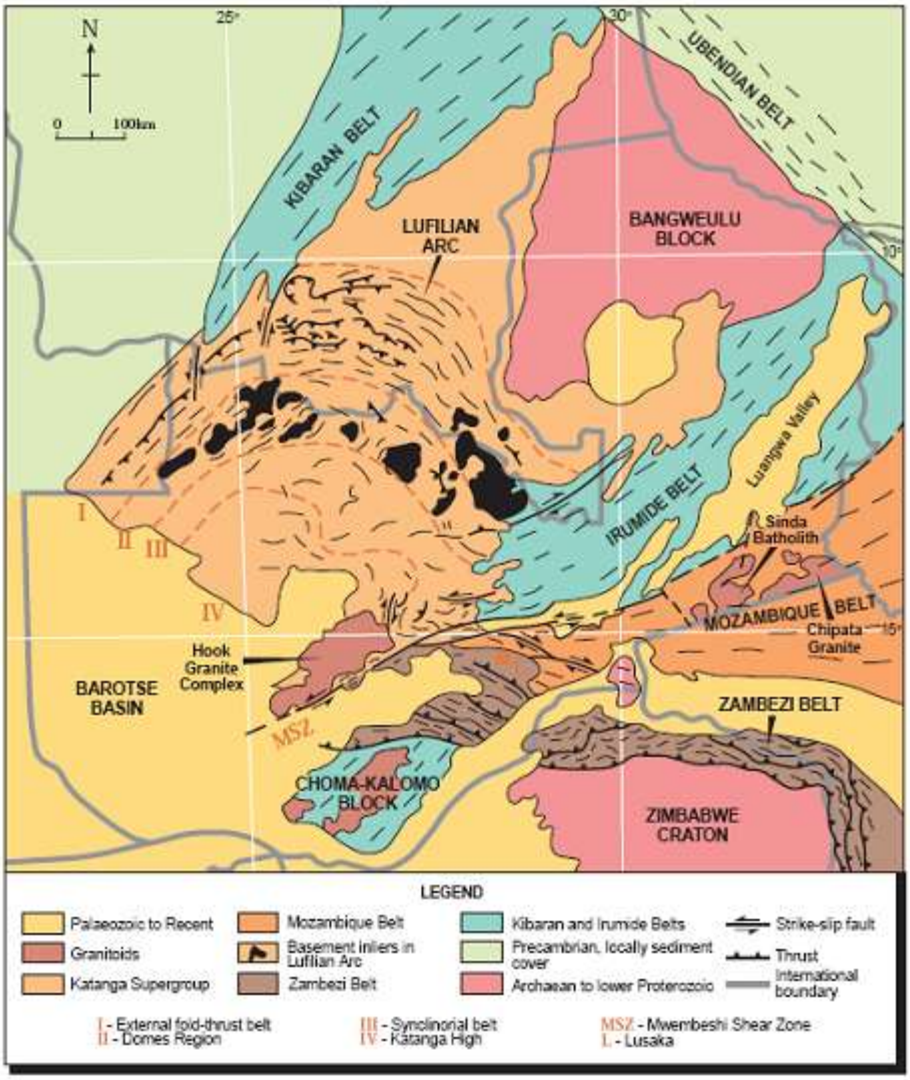

Figure 2: Main structural provinces of Zambia (Source: Ministry of Mines and Mineral Development, 1999)

III. REGIONAL SEISMICITY

According to Midzi, et al., (1999), Earthquake activity in the eastern and southern Africa region is characterised by the occurrence of destructive earthquakes which are controlled by the well-known regional tectonic feature, the East Africa Rift system. The East African Rift System (EARS) is a 3,000-km-long Cenozoic age continental rift extending from the Afar triple junction, between the horn of Africa and the Middle East, to western Mozambique. Sectors of active extension occur from the Indian Ocean, west to Botswana and the Democratic Republic of the Congo (DRC). It is the only rift system in the world that is active on a continent-wide scale, providing geologists with a view of how continental rifts develop over time into oceanic spreading centers like the Mid-Atlantic Ridge (Hayes, et al., 2014). Figure 3 illustrates the East African Rift System.

Traditionally, an Eastern (including the Ethiopian Rift) and a Western Branch are distinguished (Ring, 2014). The eastern branch runs over a distance of 2200 km, from the Afar triangle in the north, through the main Ethiopian rift, the Omo-Turkana lows, the Kenyan (Gregory) rifts, and ends in the basins of the North-Tanzanian divergence in the south (Chorowicz, 2005).

The western branch runs over a distance of 2100 km from Lake Albert in the north, to Lake Malawi in the south. It comprises several segments: the northern segment includes Lake Albert, Lake Edward and Lake Kivu basins, turning progressively in trend from NNE to N–S; the central segment trends NW–SE and includes the basins of lakes Tanganyika and Rukwa; the southern segment mainly corresponds to Lake Malawi (Nyasa) and small basins more to the south (Chorowicz, 2005). A third, south-eastern branch is in the Mozambique Channel. The south-eastern branch comprises N-striking undersea basins located west of the Davie ridge (Chorowicz, 2005).

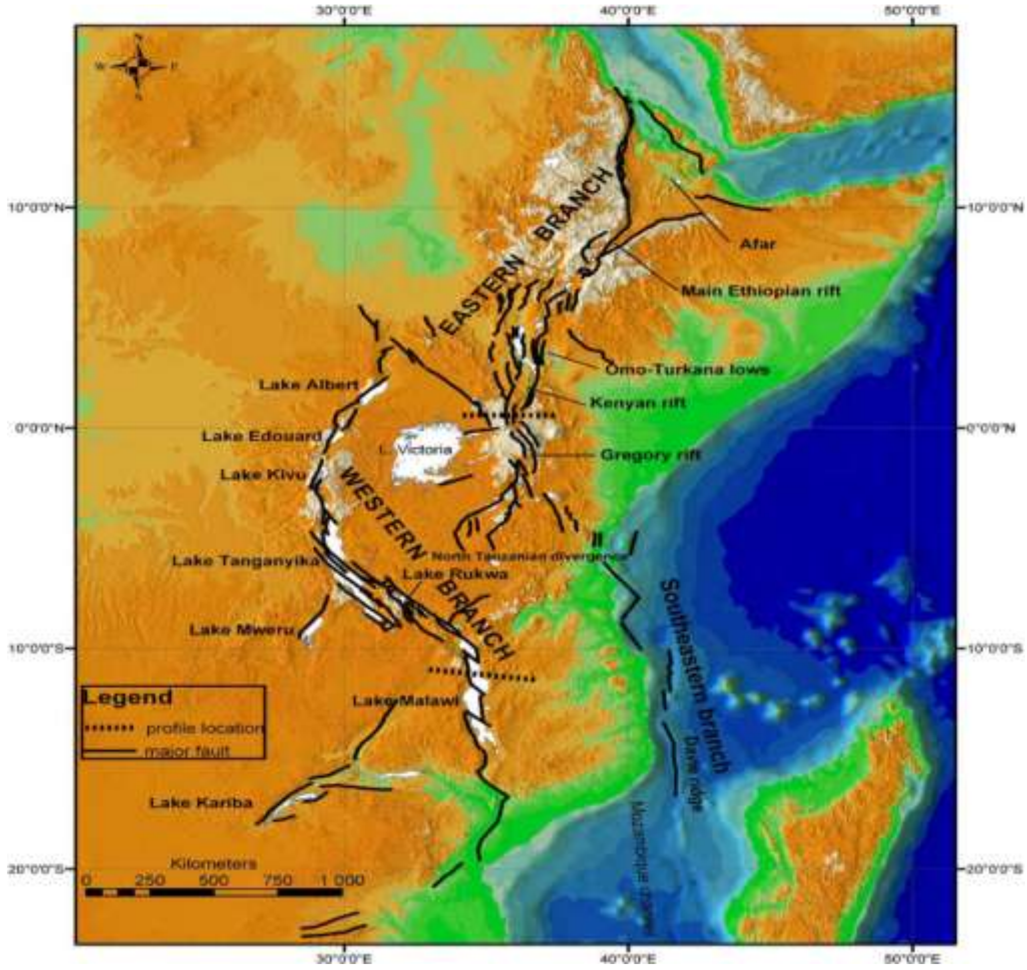

Figure III: Illustration of the East African rift system (Source: Chorowicz, 2005)

Seismicity in the East African Rift is widespread, but displays a distinct pattern. It is characterized by mainly shallow (<40 km) normal faults (earthquakes rupturing as a direct result of extension of the crust), and volcano-tectonic earthquakes. The majority of events occur in the 10–25-km depth range. This pattern is widespread throughout the EARS, and provides insight into the relationship between depth of earthquakes, the deformation of continental lithosphere, and magmatic processes in many sectors of the rift (Hayes, et al., 2014).

IV. OVERVIEW OF SEISMIC HAZARD ASSESSMENT

Given the challenges in earthquake prediction, seismic hazard analysis is considered one of the practical solutions to cope with the complicated, random earthquake process (Geller et al. 1997). Seismic hazard assessment has a number of applications, among them, seismic micro-zonation studies, which are important for decision-making on land use, evaluation of the level of earthquake preparedness, economical consideration of earthquake-resistant design, retrofit strategy, economic loss estimation in the event of future earthquakes, and also for the design of ordinary structures where site-specific studies are not warranted (Samam Yangmaei-Sabegh et al., 2010).

Two basic methods are widely used to carry out seismic hazard analysis, Deterministic Seismic Hazard Analysis **(DSHA)** and Probabilistic Seismic Hazard Analysis **(PSHA**). The strength of one over the other depends on the earthquake mitigation decisions to be made, on the seismic environment, and on the scope of the project. In general, more complex decisions and subtler, detailed seismic environments strongly suggest the probabilistic analysis, whereas simpler decisions and well understood seismicity and tectonics point toward deterministic representations (McGuire, 2001).

In the deterministic approach, the strong-motion parameters are estimated for the maximum credible earthquake, assumed to occur at the closest possible distance from the site of interest, without considering the likelihood of its occurrence during a specified exposure period (Gupta, 2002). Probabilistic seismic hazard analysis (PSHA) estimates the likelihood that various levels of earthquake caused ground motion will be exceeded at a given location in a given future time period, given all possible earthquake scenarios. The probabilistic approach integrates the effects of all the earthquakes expected to occur at different locations during a specified life period, with the associated uncertainties and randomness taken into account (Gupta, 2002). The most commonly used procedure for PSHA is referred to as the classic Cornell-McGuire approach (Cornell, 1968; McGuire, 1976).

4.1 Probabilistic Seismic Hazard Analysis

Probabilistic Seismic Hazard Analysis (PSHA) estimates the likelihood that various levels of earthquake caused ground motion will be exceeded at a given location in a given future time period, given all possible earthquake scenarios. The probabilistic approach integrates the effects of all the earthquakes expected to occur at different locations during a specified life period, with the associated uncertainties and randomness taken into account (Gupta, 2002).

The most commonly used procedure for PSHA is referred to at the classic Cornell-McGuire approach (Cornell, 1968; McGuire, 1976). The procedure is based on four basic assumptions;

1. That the occurrence of earthquakes is random and follows the Poisson distribution (the events are independent and constant over time)
2. That Probability of exceedance $P(Z>z)$ of a specified ground motion level z, in an exposure time or design time period t at a site, is related to the annual activity rate of ground motion exceedance (γ)
3. That earthquake attenuation with distance follows a selected law
4. That seismicity is uniformly distributed in each seismic regionPSHA is carried out in four steps illustrated in the Figure 4. The steps are briefly described in the following subsections.

Step 1: Identification of seismic Sources

The first step is to identify and demarcate the boundaries of the various seismic sources. Normally, the sources

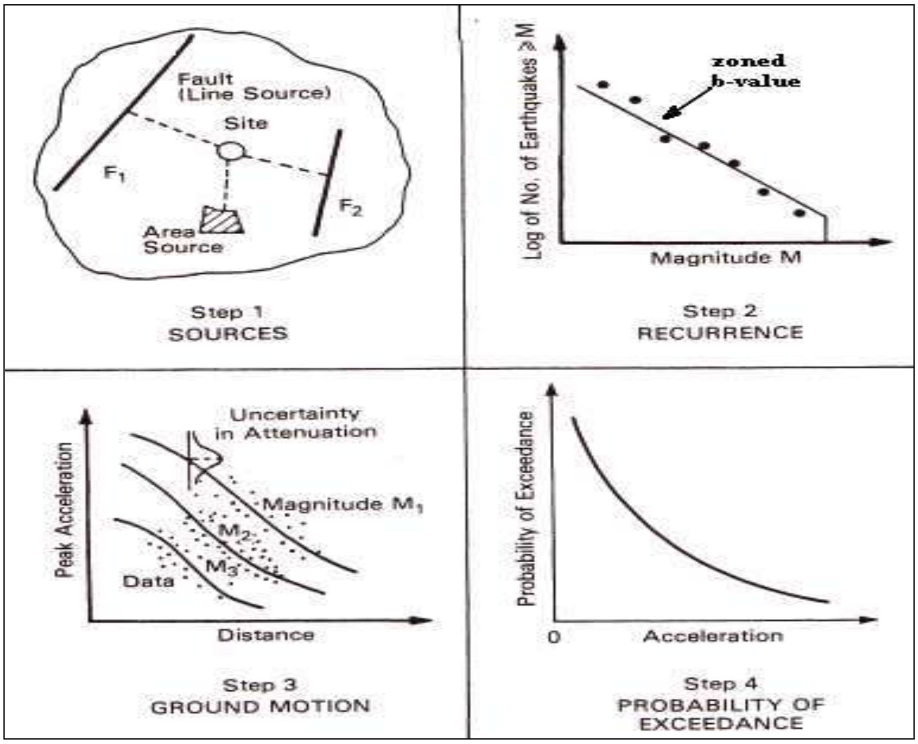

Figure IV.1: Basic procedure for PSHA seismic hazard assessment (Source: Chen et al., 1998; Reiter, 1990).

within about 300 to 400 km (depending on the tectonic region) of the site are sufficient for this purpose. Each of the sources is divided into a large number of small-size elements, and the expected seismicity in a source is distributed suitably among all the elements. The epicentres of all the earthquakes in an element are assumed to occur at the geometric center of the element (Gupta, 2007). It is assumed that earthquakes are equally likely to occur at any point with a seismic source Zone.

Gupta identifies four types of seismic source zones; **Point sources** where seismicity is concentrated in a small area at a very long distance from the site, **line sources** where seismicity is related to a long fault,**dipping plane sources** associated with a dipping fault planes sources and **Area sources** demarcated with polygons. Due to limited knowledge of faults, area sources are most commonly used in PSHA procedures.

Step 2: Determination of seismic parameters for each source

The second step involves determination of the seismic source parameters of each seismic source zone identified in the first step. These parameters include an annual occurrence rate, b-value, and a lower and upper bound magnitude ($m_{min}$and m_{max}) for the Gutenberg-Richter (G-R) relation defined in Equation 4.

$Log\ (N) = a - bM$ Equation 1

N is the number of events with magnitude greater than or equal to M. The parameter a, is the measure of the level of seismicity, while b describes the ratio between the number of small and large events. It is further assumed that the magnitude M lies within the range (m_{min},m_{max}) where m_{min} denotes level of completeness of the earthquake catalogue and m_{max} is the area characteristic maximum possible seismic event magnitude (Mapuranga 2014).

Step 3: Estimation of earthquake effects using GMPEs

The third step involves estimation of earthquake effects using ground motion prediction equations (GMPEs). For quantifying the seismic hazard at a site or to prepare a seismic zoning map, one needs to know the attenuation and scaling characteristics of the various strong motion parameters with distance, earthquake size and the geological conditions (Gupta, 2002). Attenuation is the reduction in amplitude or energy of seismic waves caused by the physical characteristics of the transmitting media or system.

Step 4 Integration seismic effects contributed by each zone

The final step involves the integration of seismic effects contributed by the individual source zones into one hazard curve that shows the probability of exceeding different levels of ground motion (such as PGA) at certain probabilities of exceedance for a specified period of time at the site of interest.

4.2 Ground motion prediction equations

Weather deterministic or probabilistic, seismic hazard analysis requires the use of ground motion prediction equations (GMPEs) to estimate the effects of earthquakes. A typical form of a GMPE is presented in Equation 5:

$\ln(Z) = c_1 - c_2M - c_3 \ln(R) - c_4R + c_5F + c_6S + \varepsilon$ Equation 2

where Z is a ground motion parameter (e.g. PGA), M is the earthquake magnitude, R is the distance from the source to site F refers to the faulting mechanism, S describes the site effects and ε is the random error. The coefficients C_1 to C_6 are dependent on a particular tectonic setting of the site (Mapuranga, 2004).

V. EARTHQUAKE DISTRIBUTIONIN STUDY REGION

For the study, earthquakes occurring within the area bounded by **latitudes -7º to 19º** and **longitudes 21º to 35º** were considered. The study region extends beyond the boundaries of Zambia into the neighboring countries to account for seismic effects that extend beyond the vicinity of the epicenter. Figure 5showsthe distribution of earthquakes for the period **1910-2018** in the study area, based on data obtained from the International Seismological Center **(ISC)** database.

A total of 5270 events where obtained from the ISC database to form an earthquake catalogue for the study region representing all available magnitudes. However, magnitudes less than 4 are generally considered to have less significance to structures. 851 events in the catalogue had a magnitude greater or equal 4, as shown in Figure 6. Due to lack of or limited instrumentation prior to 1963, only 50 events were documented prior to 1963. The largest earthquake in the data set is a magnitude Mw 7.3 which occurred on December 13, 1910 in the Lake Tanganyika Region, about 250km from the border with Zambia. This is reported to have caused significant damage in that region. An Mw 7.2 earthquake occurred in Tanganyika region on July 8, 1919 at a depth of 15km. This was within 48km of the border with Zambia. The largest earthquake recorded within Zambia was a magnitude Mw 6.7 at location 33.116º E 11.421º S south of Chama District on May 1, 1919. Table 1 presents statistics on occurrence of earthquakes in the study region derived from ISC events catalogue.

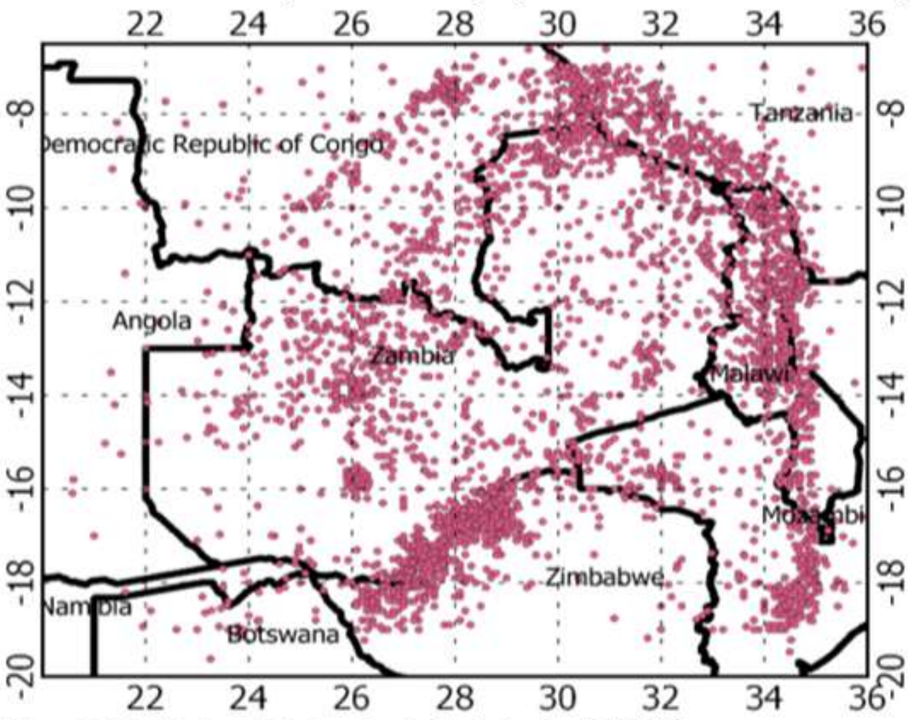

Figure 5: Distribution of Earthquakes in Study Region 1910-2018

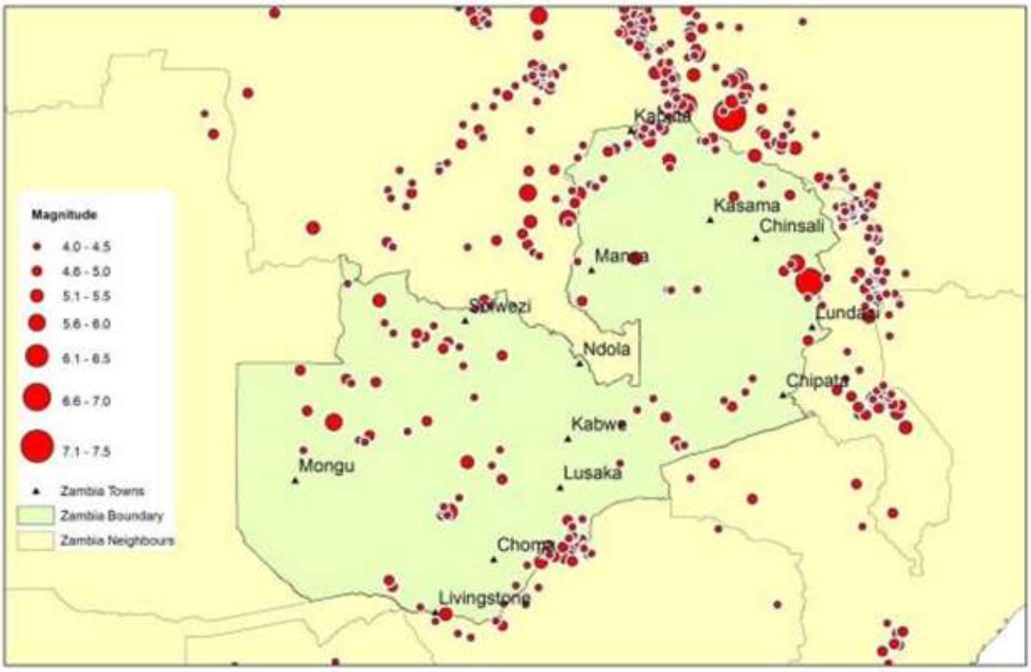

Figure 6 Distribution of earthquakes with magnitude greater than M_w 4 from 1910-2018

Table 1: Earthquake Statistics in Study Area

Recorded events 1910-2018	5270
Recorded events 1910-1963	50
Recorded events 1963-2018	5220
Recorded events with magnitude > 4	851

Largest recorded event in study region	7.3Mw
Largest recorded event in within Zambia	6.7Mw

1. Seismic Hazard Assessment for Zambia

A probabilistic seismic hazard assessment (PSHA) was carried out using the Cornell-McGuire approach. The procedure included Catalogue clean up, Homogenization of catalogue, Catalogue de-clustering,Seismic source zone identification, Definition of earthquake parameters, Determination of ground motion prediction equations and Estimation of earthquake effects.

1.1 Catalogue clean up

The catalogue clean-up involved elimination of events with limited information such as events with no recorded magnitude. The result of the cleanup was a catalogue with 4409 events. The data was then homogenized before conducting a De-clustering procedure on the catalogue.

1.2 Homogenization of catalogue

The catalogue homogenization involved the conversion of all earthquake magnitudes into a single magnitude. In this study, all magnitudes were converted to Moment magnitude (M_w). ISC database is composed of events recorded by different agencies. Therefore, in converting the magnitudes to Mw, priority was given to events initially recorded in that magnitude scale by one of the agencies that captured the particular event. In cases where moment magnitude was not recorded, the Local Magnitude (M_L) was given priority. The following relations derived by Strasser and Mangongolo (2013) were used to convert M_L to M_w.

$$Mw = 0.5631 M_L + 0.9265 \qquad for M_L \leq 2.5$$

$$Mw = 0.1942\, M_L^2 - 0.1518 M_L + 1.5 \qquad for\ 2.5 \leq M_L \leq 4.0$$

$$M_w = M_L \qquad for M_L \geq 4.0$$

1.3 Catalogue de-clustering

To remove dependent events such as aftershocks and foreshocks,the catalogue was de-clustered using ZMAP Catalogue analysis software package (Wiemer, 2001). ZMAP, a MATLAB code which was first published in 1994, is a set of tools driven by graphical user interface designed to analyse earthquake catalogues (Wiemer, 2001). The software uses the windows-based method of Gardner and Knopoff (1974). De-clustering resulted in 4124 events from an initial 4409 events.

1.4 Seismic source zone identification

A source zone is a configuration within which earthquakes are observed to occur at the same rate with respect to magnitude, irrespective of their location (Reiter, 1990). Nine seismic source zones where identified. The zones where delineated using QGIS software and saved as shapefiles. Only area source zones were considered in the delineation of source zone. Figure 7shows these zones.

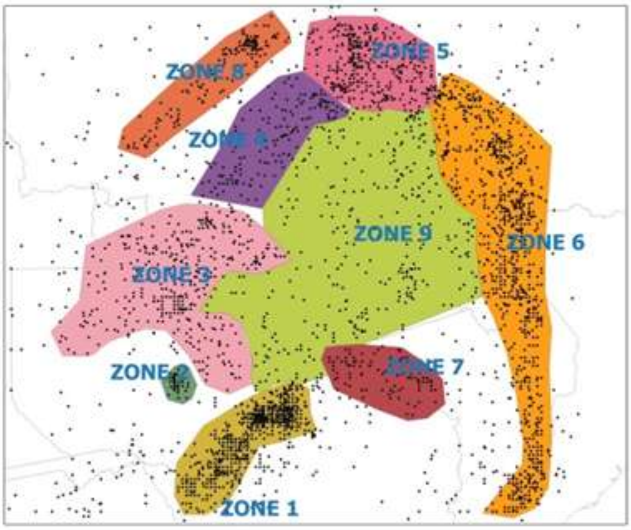

Figure 7: Seismic zone delineation

1.5 Definition of earthquake parameters

Recurrence parameters for each source zone were determined using ZMAP Catalogue analysis software package (Wiemer, 2001). These parameters described in Section 4 of this paper and shown in Table 2 are:

i. a and b values of the Gutenberg-Richter (G-R) relation
ii. Mean seismic activity rate (γ),
iii. The upper and lower bound magnitudes, M_{min} and M_{max}
iv. The β value calculated using the expression β =bIn(10), with be *b* being the value of Gutenberg-Richter (G-R) relation.

Table 2 Seismic zone parameters

Zone	**a**	**b**	γ	M_{min}	M_{max}	β
1	5.628	0.94	3.904	3	6.5	2.164
2	3.621	0.76	1.925	3.2	5	1.750
3	4.711	0.75	2.946	3.3	5.8	1.727
4	5.107	0.87	3.343	3.8	5.6	2.003
5	5.459	0.85	3.466	3.7	7.1	1.957
6	5.284	0.76	3.289	3.5	6.8	1.750
7	4.46	0.88	2.694	2.8	6.1	2.026
8	5.205	0.89	3.428	3.6	6.1	2.049
9	4.717	0.8	2.831	3.1	6	1.842

1.6 Estimation of earthquake effects

Seismic hazard computations were carried out using R-Crisis software. The main input parameters for the software included Seismic source geometry, Source seismic parameters and Attenuation data. Atkinson and Boore (2006) attenuation model was selected. This model was created for stable continental regions similar to the study region.

The hazard computations resulted in seismic hazard maps of different return periods. Figures 8and 9show the hazard maps for return periods of 475 years and 950 years, respectively. According to EN 1998-1, the design seismic action is generally expressed in terms of the seismic action associated with a 10% probability of exceedance in 50 years or a reference return period of 475 years.

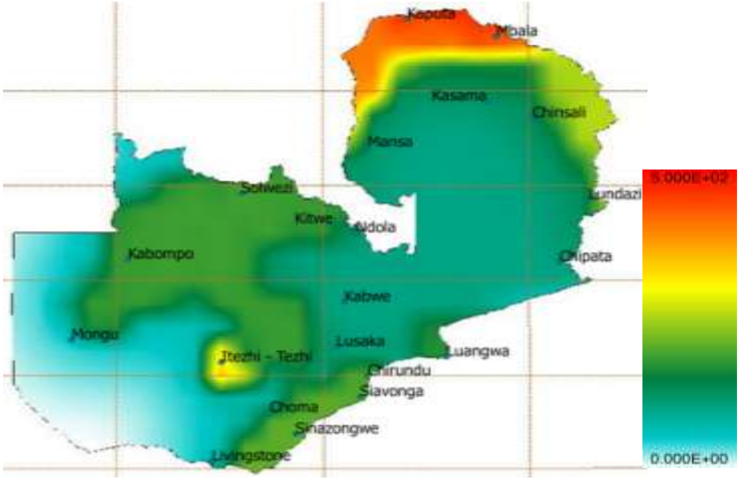

Figure 8: PGA map in cm/s^2 for 475 year return period

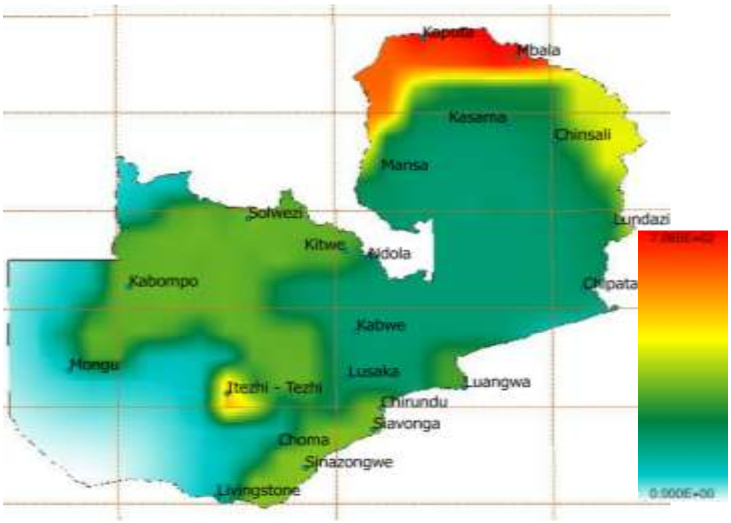

Figure 9: PGA map in cm/s^2 for 950 year return period

Table 3 shows PGA values for selected towns in Zambia. It was noted that the highest PGA values wererecorded in seismic zone 5 of up to 0.5g and 0.7g for return periods 475 and 950years, respectively. Of the selected towns, Kaputa recorded the highest PGA values of 0.45g and 0.63g for return periods 475 and 950years, respectively. It was noted that most urban centres were on the periphery of major seismic source Zones identified in this study. However, it is noted that only Mongu town has a PGA value less than 0.1g for both the 475 and 950 year return period. For a return period of 475 years, Lusaka had a PGA value of 0.11 g, while Ndola, Kitwe and Solwezi had PGA values of 0.12, 0.15 and 0.19 g, respectively.

An earlier study carried out by Mapuranga (2016) shows similar results. The study was centred on Zimbabwe but extended into the southern part of Zambia. Using Cornell-McGuire approach for PSHA, the study found values of PGA up to 0.3 g around Itezhi-Tezhi and 0.2 g around Chirundu and Siavonga towns, for a return period of 475 years. The present study showed a PGA value of 0.316 g in Itezhi-Tezhi and 0.2 g for both Chirundu and Siavonga, for the same return period.

Table 3 PGA values for selected towns in Zambia

Town	**Province**	**PGA (cm/s^2)**		**PGA (g)**	
		475 Years Return	**950 Years Return**	**475 Years Return**	**950 Years Return**
Chinsali	Muchinga	140	193	0.140	0.193
Chipata	Eastern	107	148	0.107	0.148
Chirundu	Southern	198	288	0.198	0.288
Choma	Southern	166	261	0.166	0.261
Itezhi-Tezhi	Southern	316	431	0.316	0.431
Kabompo	North-Western	183	270	0.183	0.270
Kabwe	Central	103	149	0.103	0.149
Kaputa	Luapula	449	627	0.449	0.627
Kasama	Northern	126	175	0.126	0.175
Kitwe	Copperbelt	154	239	0.154	0.239
Livingstone	Southern	94	120	0.094	0.120
Luangwa	Eastern	167	248	0.167	0.248
Lundazi	Eastern	183	267	0.183	0.267
Lusaka	Lusaka	112	164	0.112	0.164
Mansa	Luapula	140	200	0.140	0.200
Mbala	Northern	434	620	0.434	0.620

Mongu	Western	62	90	0.062	0.090
Ndola	Copperbelt	123	177	0.123	0.177
Siavonga	Southern	200	289	0.200	0.289
Sinazongwe	Southern	205	295	0.205	0.295
Solwezi	Norrthwestern	190	280	0.190	0.280

VI. CONCLUSION AND RECOMMENDATIONS

The study highlighted seismic hazard in Zambia. Zambia lies in the interior of the African plate that is considered relatively aseismic. However, the presence of the East Africa Rift System with its various sectors influences seismic activity in the region.

It is evident from the study that there is sufficient level of earthquake activity to warrant consideration of earthquake effects in the design of structures in Zambia. Even with the limited history of earthquake event documentation, there are a number of events that should compel engineers to consider seismic loading in the design of structures. According to EN 1998-1, the design seismic action is generally expressed in terms of the seismic action associated with a 10% probability of excedance in 50 years or a reference return period of 475 years. The existing records of only around 100 years in Zambia cannot be relied upon to dismiss the occurrence of destructive earthquakes anywhere within Zambia.

The periodicities of large earthquakes can be in the hundreds of years. Investigations into the 1966 Koynanagan earthquake of magnitude 7.0 in the Deccan Plateau of India revealed periodicities of about 200 years for such earthquakes (Brandit, 2011). The particular earthquake occurred in an intraplate region similar to the study region in this study.

The results of the probabilistic seismic hazard analysis showed significant values of peak ground acceleration (PGA) in various zones in Zambia, as observedin the presented maps. The results showed PGA values of up to 0.5g for a return period of 475years associated with a 10% probability of excedance in 50 years and up to 0.7g for a return period of 950 years associated with a 10% probability of excedance in 100 years. According to Wium (2008), it is accepted practice internationally to design structures for seismic loads when the nominal peak ground acceleration values (1:475 years) exceed a value of 0.1g. The results of hazard analysis showed values of peak ground acceleration greater than 0.1g for a return period of 475 years in many zones around Zambia.

It is recommended that seismic hazard be given due consideration in the design of structures in Zambia, especially in regions which the study has identified as high earthquake risk regions. The study particularly recommends that all lifeline and critical installations and infrastructure such as hospitals, bridges, dams and electrical power plants should be designed and built to withstand significant levels of seismic action.

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