Probabilistic assessment of seismic hazard in Lake Tanganyika Rift accounting for local geologies conditions.

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Abstract: ***In this study, we applied a probabilistic methodology to seismic hazard assessment in the lake Tanganyika Rift and accounting the local geological condition. We had proposed to create a phantom stations across the affected region with spacing each grid point 1° x 1° kept constant at 0,1° by 0,1° and computing return periods of ground motion exceedances to obtaining a very small value of Maximum distance, like 4 to 94 km, to get a report of this probability. We had obtained 0,01520016 km/s^2 and 2,04414004 km/s^2 respectively for an epicentral distance of 4 km and 94 km. The return period of 3028 years (4km) and 27 year (94 km) corresponding at the annual probability exceedance of 0,03% and 3,73% respectively. Accounting for local geologies conditions the average value of PGA in the lake Tanganyika region is less than 1,6 however, this region is mainly dominated by the soft rock/hard rock ratio.***

Keywords: Probabilistic assessment, Seismic hazard, Lake Tanganyika Rift, Peak ground acceleration (PGA), Probability exceedance, Return period..

1. Introduction

The advanced seismic zoning map of Western Branch of the East African Rifts system, shows that the seismic activity is mainly confined to the following zones: the south, central and northern part of the Lake Tanganyika, the western border of Lake Kivu and Ruzizi Valley, the Lake Edouard trough, and the Mount Ruwenzori area [1].

The seismic hazard in the Democratic Republic of Congo and areas adjacent to the Western Rift Valley of Africa has been previously assessed by Zana et al. (1992 a), Mavonga et al. (2009) and Manyele et al. (2014).

- The estimation of earthquake hazard in Zaire (former name of DRC) [2] was based only on combining the pattern of spatial distribution of epicenters, the equivalent earthquake magnitude distribution and trends of a and b in the Gutenberg Richter formula, but they did not take the attenuation of ground acceleration into account.
- Probabilistic seismic hazard assessment for Democratic Republic of Congo and surrounding areas, Western Rift Valley of Africa [3] was based only on the presentation a seismic hazard map covering a large scale and considering that, the highest level of seismic hazard were found in the Lake Tanganyika seismic zone, but they did not take in account the geological condition and that for each main basin zone, the seismic hazard is constant.
- Correlation Between the Reported Earthquakes Damages from the Magnitude 6.5 Lake Tanganyika earthquake of October 2, 2000 and the Simulated PGA Shaking Maps [4] was based only to purpose the predictive PGA shaking maps for initiating earthquake early warnings and emergency responses but did not take into account probabilistic assessment and return periods of ground motion exceedances in lake Tanganyika zone.

The choice of distance metric and the geological conditions are very important in probability assessments of seismic hazard. Thus, to know the probability that a nearby dipping fault may

rupture in the next few years, it needs to could input a very small value of Maximum distance, like 1 or 2 km, to get a report of this probability.
Therefore, in this study, we propose to create a phantom stations across the affected region with spacing each grid point 1° x 1° kept constant at 0,1° by 0,1° and computing return periods of ground motion exceedances.

In this paper, we briefly introduce the seismic activity in the Western Branch of the East African Rifts Systems.
Explain the probability approach method (Poisson model) of earthquakes occurrence and its application in the case of this study and discuss the result.

2. DATA PRESENTATION AND METHOD

Data
All seismic data used in this study covering the region between 08°48'S to 1°34' S of latitude and 28°50' E to 31°12'E of longitude. The data were compiled from various sources (United States Geological Survey (USGS- http://www.usgs.gov), Centre de Recherche en Sciences Naturelles de Lwiro (CRSN)) for the period 1954 to 2010. All available catalogues and seismological bulletins were carefully searched. A catalogue was compiled, listing the source of the data, the origin time, coordinates of the earthquake, and a magnitude homogenized according to the a body-wave magnitude scale (M_b).

3. Method

In this study, the probabilistic approach to seismic hazard analysis as formulated by Cornell (1968) and McGuire (1976, 1993) was employed. Application of the procedure includes several steps [5]:

- Potential seismic source zones are defined, over which all available information may be averaged. These zones are usually associated with geological or tectonic features.
- Seismicity parameters will be determined for each seismic source zone. Assessment of the above parameters requires a seismic event catalogue containing origin times, size of seismic events and spatial locations. Site-specific analysis of seismic hazard requires knowledge of the attenuation of the selected ground motion parameter, usually PGA, as a function of earthquake magnitude and distance.
- The final step requires the integration of individual contributions from each seismic source zone into a site.

A Poisson model of earthquake occurrence, which assumes that events are independent, was adopted (Bender and Perkins, 1987). $M_b = 3{,}6$ was selected as the lower magnitude bound (Mmin) because smaller earthquakes are considered unlikely to cause damage, even to houses that are poorly designed and built.

Seismic parameters of seismic source zone

Following typical assumptions made in engineering seismology, the seismic characteristics of each seismic source zone were modeled as a Poisson process. The most widely used model of magnitude distribution has its source in the classical Gutenberg-Richter relation as:

$$logN = a - bM_b \qquad (1)$$

Where N is an annual earthquake frequency, M_b is a body – wave magnitude, a is a logarithm number when $M_b = 0$ and b is a regression coefficient (b-value).

In order to ensure a finite seismic energy release [Knopoff and Kagan, 1977], the Gutenberg-Richter relation is often combined with an assumption on the existence of a physical upper limit of the magnitude Mmax.. The respective probability density function (PDF) of earth-
quake magnitude for the exponential distribution is given as [6] :

$$P(m_1 \leq m \leq m_2) = \frac{e^{\beta M_{min}}(e^{-\beta m_1} - e^{-\beta m_2})}{1 - e^{-\beta(M_{max} - M_{min})}} \qquad (2)$$

for Mmin ≤ m≤ Mmax

The characteristic parameters defined for each seismic source zone are:

- Average rate of occurrence or mean seismic activity rate λ (which is the parameter of the Poisson distribution),
- Level of completeness of the earthquake catalogue M_{min} ;
- Maximum possible earthquake magnitude $M_{max;}$
- Gutenberg – Richter parameter b (which indicate the relative number of large and small earthquakes, , β= b ln10);
- Focal depth; and
- Regional attenuation relationship for the strong ground motion.

The b-value is expected to be regionally stable with variations less than the uncertainty limits, while the activity rate λ (annual number of earthquakes above the lower bound magnitude) is liable to vary substantially from one seismic source zone to another.

$$\lambda_{M_s} = e^{\alpha - \beta M_b} \qquad (3)$$

Where $\alpha = axln10$

SEISMICITY OF THE WESTERN BRANCH OF THE EAST – AFRICAN RIFTS SYSTEM

The Western Branch, which is a part of the East African Rifts System, is cutting into uplifted structures of the Precambrian basement and has deep lakes such as, from South to North, Malawi (472 m above sea level), Rukwa (782 m), Tanganyika (771 m), Kivu (1,463 m), Edward (912 m) and Albert (619m). The Lake Kivu is the highest lake in the Western Branch, implying that the center of doming accompanying the rift formation must be located around this lake [7].

Four main seismic sud – zones were identified in the western Rift Valley of Africa based on local seismicity and geological structure (fig.1):

a) Southern Sudan, Ruwenzori area, and Lake Edouard trough. Southern Sudan is dominated by relatively strong earthquakes with poor tectonic control, however Ruwenzori area experienced large earthquakes on 20 March 1966 $(M_w\ 6{,}8)$ and 5 February 1994 $(M_w\ 6{,}2)$ [3];

b) Virunga volcanic complex, Rutsuru basin and Masisi area. The Virunga volcanic complex is the largest of the Cenozoic volcanic complexes in the Kivu Province and the only one that is presently active. Earthquakes in the volcanic area generally have low magnitudes $(M_w \leq 4)$ [3];

c) Lake Kivu basin, Ngweshe area and Ruzizi plain. The Lake Kivu basin consists of two subsiding half – grabens separated by the 700 m high Idjwi horst structure. The central part of the Lake Kivu experienced a large earthquake $(M_w\ 6{,}2)$ on 24 October 2002 in the Kalehe area, which was felt strongly at Goma, Bukavu and Kigali [8]. On 3 February 2008 an $(M_w\ 6{,}0)$ earthquake occurred 20 km North of Bukavu City [3].

d) Lake Tanganyika Rift. Many larger magnitude earthquakes have occurred in the Tanganyika Rift. The best known are the events which occurred on 13 December 1910 at the southern end of Lake Tanganyika $(M_w\ 7)$, 22 September 1960 at the northern end of Lake Tanganyika $(M_w\ 6{,}5)$ [9], and 5 December 2005 $(M_S\ 6{,}8)$ in the central part of Lake Tanganyika (Table 1).

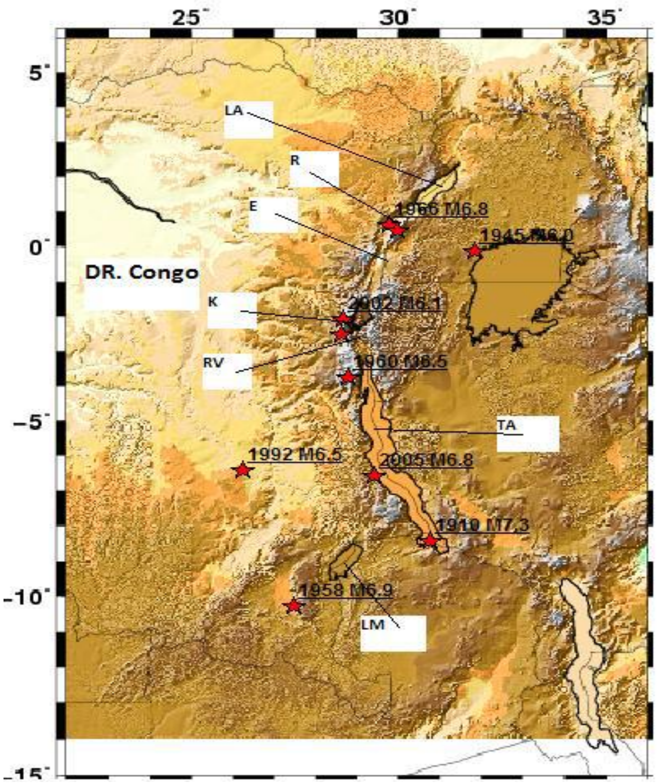

Fig.1: Large earthquakes with magnitude M≥6 observed in the Western Branch since 1910. The coordinates of the 1910 M7.3 were obtained by combining those obtained from instrument with local macro seismic record as published in Ambraseys and Adams [1992]

LA= Lake Albert, R= Ruwenzori Mountain, E= Lake Edouard, K=Lake Kivu, TA= Lake Tanganyika, LM= Lake Moero and RV= Ruzizi Valley [3].

Table 1. Statistical data of the seismicity of Lake Tanganyika for the period 1954 to 2010 [1]

Sous-zone T_{NO}			Sous-zone T_{NE}			Sous-zone T_{CO}			Sous-zone T_{CE}			Sous-zone T_{SO}			Sous-zone T_{SE}		
$m_b \geq$	logN	N	$m_b \geq$	logN	N	$m_b \geq$	logN	N	$m_b \geq$	logN	N	$m_b \geq$	logN	N	$m_b \geq$	logN	N
3,8	2,08278537	121	4	1,176091259	15	3,6	1,949390007	89	3,8	1,740362689	55	3,7	1,342422681	22	3,5	1,897627091	79
3,9	2,079181246	120	4,1	1,146128036	14	3,7	1,944482672	88	3,9	1,716003344	52	3,8	1,322219295	21	3,6	1,892094603	78
4	2,075546961	119	4,2	1,041392685	11	3,8	1,944482672	88	4	1,716003344	52	3,9	1,301029996	20	3,7	1,892094603	78
4,1	1,949390007	89	4,3	0,954242509	9	3,9	1,929418926	85	4,1	1,591064607	39	4	1,255272505	18	3,8	1,880813592	76
4,2	1,84509804	70	4,4	0,77815125	6	4	1,924279286	84	4,2	1,491361694	31	4,1	1,176091259	15	3,9	1,86923172	74
4,3	1,716003344	52	4,5	0,602059991	4	4,1	1,86923172	74	4,3	1,380211242	24	4,2	1,146128036	14	4	1,86923172	74
4,4	1,633468456	43	4,6	0,477121255	3	4,2	1,799340549	63	4,4	1,301029996	20	4,3	1,079181246	12	4,1	1,819543936	66
4,5	1,568201724	37	4,7	0,301029996	2	4,3	1,707570176	51	4,5	1,255272505	18	4,4	1,041392685	11	4,2	1,698970004	50
4,6	1,447158031	28	4,8	0	1	4,4	1,672097858	47	4,6	1,146128036	14	4,5	0,903089987	8	4,3	1,568201724	37
4,7	1,361727836	23	4,9	0	1	4,5	1,602059991	40	4,7	0,903089987	8	4,6	0,84509804	7	4,4	1,505149978	32
4,8	1,176091259	15	5	0	1	4,6	1,505149978	32	4,8	0,698970004	5	4,7	0,77815125	6	4,5	1,431363764	27
4,9	1	10				4,7	1,477121255	30	4,9	0,477121255	3	4,8	0,698970004	5	4,6	1,397940009	25
5	0,954242509	9				4,8	1,397940009	25	5	0,477121255	3	4,9	0,602059991	4	4,7	1,342422681	22
5,1	0,903089987	8				4,9	1,342422681	22	5,1	0,477121255	3	5	0,602059991	4	4,8	1,255272505	18
5,2	0,84509804	7				5	1,301029996	20	5,2	0,301029996	2	5,1	0,602059991	4	4,9	1,041392685	11
5,3	0,602059991	4				5,1	1,146128036	14	5,3	0,301029996	2	5,2	0,301029996	2	5	0,903089987	8
5,4	0,477121255	3				5,2	1,041392685	11	5,4	0,301029996	2				5,1	0,84509804	7

5,5	0,477121255	3				5,3	1,041392685	11	5,5	0,301029996	2				5,2	0,84509804	7
5,6	0,301029996	2				5,4	0,77815125	6	5,6	0	1				5,3	0,698970004	5
5,7	0,301029996	2				5,5	0,602059991	4	5,7	0	1				5,4	0,698970004	5
5,8	0	1				5,6	0,477121255	3							5,5	0,698970004	5
5,9	0	1				5,7	0,477121255	3							5,6	0,698970004	5
6	0	1				5,8	0,477121255	3							5,7	0,698970004	5
6,1	0	1				5,9	0	1							5,8	0,602059991	4
6,2	0	1				6	0	1							5,9	0,602059991	4
6,3	0	1				6,1	0	1							6	0,301029996	2
6,4	0	1				6,2	0	1							6,1	0,477121255	3
6,5	0	1				6,3	0	1							6,2	0,301029996	2
						6,4	0	1							6,3	0,301029996	2
															6,4	0,301029996	2
															6,5	0,301029996	2
															6,6	0	1
															6,7	0	1

Table 2. The characteristics of the seismicity of Tanganyika source zones

ZONE	LONG. (°E)	LAT. (°S)	M_{min}	M_{max}	Beta (β)	Lambda (λ)
N - W	29 – 30,15	5,1 – 3	3,8	6,5	2,1222927	703,16903
N - E	30,16– 31,3	5,1 – 3	4	5	3,18102131	67,7408093
C - W	29 – 30,15	7,1– 5	3,6	6,4	1,92473088	1019,00428
C - E	30,16– 31,3	7,1– 5	3,8	5,7	2,3357423	330,67766
S - W	29– 30,15	9– 7	3,7	5,2	1,5093445	174,40769
S - E	30,16– 31,3	9 – 7	3,5	6,7	1,466517	794,2727

With:
N – W: Tanganyika North – West
N – E: Tanganyika North – East
C – W: Tanganyika Center – West
C – E: Tanganyika Center – East
S – W: Tanganyika South – West
S – E: Tanganyika South - East

Mmin: lower bound magnitude;
Mmax: maximum expected upper bound magnitude;
b-value: slope of magnitude-frequency relation;
Beta (β): ln(10)x b-value,
Lambda (λ): annual number of earthquakes above the lower bound magnitude.

The high magnitude recorded in the West Branch of the Lake Tanganyika zone is 6,5 and our study is focused in this earthquake (22 September 1960, $(M = 6,5)$, longitude 29,08 E, latitude 3,5 sud) and in the eastern branch 6,7 (table 1 and 2).

A. Determining PGA at Target sites

The goal is to produce PGA predictions and its spatial distribution paying special attention to maximum values that will indicate the potential damaged zones. Knowing earthquake magnitude and its epicenter location, first uniformly spaced grid of phantom stations are created across the affected region with spacing for each grid point kept constant at 0.1° by 0.1 °. Using the estimated event geographical location, the epicentral distance between each grid point and event location are estimated using Equation [4].

$$R = 111,19\sqrt{\cos(latG) * (longG - longE)^2 + (latG - latE)^2}$$

(4)

Where R is distance between grid point and event epicenter in kilometer, lat G and long G are latitude and longitude coordinate of grid point, and lat E and long E are latitude and longitude coordinate of event.

Then, the peak ground acceleration (PGA) value at each target is predicted using an empirical attenuation relation of Smit (1998) based on base rock as shown in the equation [6]:

$$\log_{10} PGA = -3,93 + 0,78 * M - 1,5 * \log_{10} R \qquad (5)$$

Where M is the earthquake estimated magnitude, R is the distance from the event epicenter to the grid point center.

For M=6,5, we obtain (table 3): the results given in the table (3)

Table 3. Peak ground acceleration (PGA) function of grid point and distance

G (°)	R(km)	PGA (km/s^2)
0,1	4	2,04414004
0,2	9	0,54098819
0,3	15	0,23177137
0,4	23	0,12286214
0,5	33	0,07375715
0,6	44	0,048114
0,7	56	0,03332295
0,8	67	0,02415945
0,9	83	0,01816119
1	100	0,01520016

B. PGA and geological conditions

Local geological conditions are known to significantly affect ground motion. Because the attenuation law is established for stiff bedrock, we consider that taking geological conditions into account is essential to present results that are not globally minimized.

Using the geological map of Lake Tanganyika region [11] we classified surface geology in terms of "hard rock," "soft rock," and "firm soil [12]:

- Hard rock: primarily Cretaceous and older sedimentary deposits, metamorphic and crystalline rock, and hard volcanic deposits (basalt);
- Soft rock: primarily Tertiary sedimentary deposits and soft volcanic deposits (ashes deposits);
- Firm soil: firm or stiff Quaternary deposits (alluvium especially) with depth greater than 10 m.

Finally, the mean amplification factors used for peak horizontal ground acceleration are:

- 2.2 for the ratio firm soil / hard rock and;
- 1.6 for the ratio soft rock / hard rock.

So geological conditions are important parameters for the assessment of seismic hazard at the regional scale, even if they only represent mean amplification factors.

C. Probability exceedences

For each magnitude m, the probability that m-magnitude earthquake in R hypocentral distance (km) to the site cause greater acceleration at $A_{seuil}*$ (km/s^2) are obtained from the relationship [5]:

$$P(A > A^*\backslash m,r) = 1 - \Phi\left[\frac{\ln A^* - \overline{\ln A}}{\sigma_{\ln A}}\right] \qquad (6)$$

with Φ a normal standard cumulated probability distribution.

Since earthquakes are expected to occur in time according to a Poisson process; then, for a Poisson phenomenon that occurs with an average annual rate τ, the probability P that the phenomenon occurs at least once during the time t is:

$$P = 1 - e^{-\tau t} \qquad (7)$$

If the annual rate exceeded of A^* is λ_{A^*}, then the probability P becomes:

$$P = 1 - e^{-\lambda t} = 1 - e^{-\frac{t}{T}}$$

(8)

With $T = \frac{1}{\lambda}$; return period

Then :

$$\lambda = -\frac{\ln(1-P)}{t} \qquad (9)$$

D. Results and discussion

Predict future ground motion using an appropriate regional attenuation relationship for the strong motion for the Lake Tanganyika region between magnitude, distance and site conditions was done. The probability that a specified ground motion level at a site will be exceeded during a particular time period is ranged between 0,03% and 3,73%. This result show that the earthquake occurrence probability in the Lake Tanganyika region is very low but not null.

The results obtained in this study are based on a period of about 56 years duration, and assumed to be complete for events of magnitude M >3,5.

The results obtained in this study (table 4 and fig.3) were compared with previous work in the Lake Tanganyika region:

- Correlation Between the Reported Earthquakes Damages from the Magnitude 6.5 Lake Tanganyika earthquake of October 2, 2000 and the Simulated PGA Shaking Maps [4] the great value of PGA were 0,42 for the hypocenter distance of 123,03 km and 1,24 for the hypocenter distance of 53,84 km;
- The assessment of the probabilistic seismic hazard for Democratic Republic of Congo and its surrounding areas, Western Rift Valley of Africa [3], in his study, the city situated in the lake Tanganyika region were Kalemi the value of PGA 2,416 g (0,02367 kms^{-2}) and the return period of 250.000 years.

The results obtained in this study are in general accord with the earlier studies, but were the main difference is located at return period of 250.000 years in Kalemi city obtained by Mavonga et al. (2009) than our return period of 3028 years in this study, which correlated high value in the entire sub-region.

Table 4. The results obtained in this study are summarize in the table and figure (3)

R (km)	PGA (km/s^2)	$P(A > A^*\backslash m,r)$	Annual rate exceedences λ_{A^*}	Return period T (year)
4	2,04414004	0,01832599	0,0003	3028
9	0,54098819	0,11319878	0,0021	466
15	0,23177137	0,25829617	0,0053	187
23	0,12286214	0,40963391	0,0094	106
33	0,07375715	0,54351255	0,0140	71
44	0,048114	0,65249574	0,0189	53
56	0,03332295	0,73735508	0,0239	42
69	0,02415945	0,80180059	0,0289	35
83	0,01816119	0,85012697	0,0339	30
94	0,01520016	0,87591164	0,0373	27

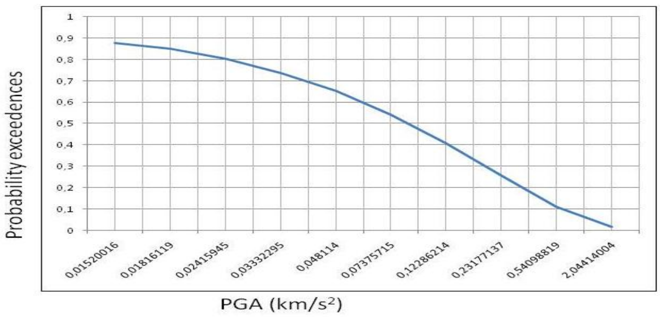

Fig. 3. Distribution of probability exceedances

Accounting for local geologies conditions

The Lake Tanganyika region comprises two geological domains. The first contains Cenozoic to recent deposits of the alluvial fans along the Tanganyika Lake coast and the fans and underlying detritic fluvial–lacustrine deposits in the Rusizi Plain. The second forms the rift shoulder and includes the Proterozoic metamorphic and intrusive rocks of the Mitumba rift shoulder, displaying the SSE-NNW 'Ubende' lineament direction. This folded and faulted massive is composed of alternating bands of quartzite, schist and intermediate lithology, with some granite intrusions and gneisses, amphibolites, dolerites and quartz veins [11].
According in the result obtained (table 4), the average value of PGA in the lake Tanganyika region is less than 1,6 however, this region is mainly dominated by the soft rock/hard rock ratio.

4. Conclusion

The prediction of ground motion is the first step of earthquake damage assessment. In this study, we had proposed to create a phantoms stations across the affected region with spacing each grid 1° x 1° point kept constant at 0,1° by 0,1° and computing return periods of ground motion exceedances to obtaining a very small value of Maximum distance, like 4 to 94 km, to get a report of this probability. We had obtained 0,01520016 km/s^2 and 2,04414004 km/s^2 respectively for an epicentral distance of 4 km and 94 km. The return period of 3028 years (4km) and 27 year (94 km) corresponding at the annual probability exceedance of 0,03% and 3,73% respectively. Accounting for local geologies conditions the average value of PGA in the lake Tanganyika region is less than 1,6 however, this region is mainly dominated by the soft rock/hard rock ratio.

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