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Probabilistic Seismic Hazard Analysis of Nigeria: The Extent of Future Devastating Earthquake.

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Abstract. The several past seismic occurrences in Nigeria has recently led to warnings from research agencies and the forecast of large earthquake from researchers in Nigeria. Nevertheless, the major forecast from researchers has appeared to be open ended. To this end, this paper aimed at the probabilistic seismic hazard analysis of Nigeria and the limit to probable future earthquake magnitudes in Nigeria. The Gutenberg-Richter recurrence law was majorly employed for the purpose of this research. The Findings of this research established that Nigeria is at the risk of experiencing earthquake magnitudes as high 6.0 in the year 2020; 6.5 between the year 2021 and 2022; 7.0 between the year 2025 and 2026 and 7.1 in the year 2028 with a 36.79% probability. The probability that an earthquake of magnitude 7.1 will be experienced from 2019 to 2028 also ranges from 9% to 36.79%. The findings of this work inform on the sizes of probable future earthquake magnitude and it is recommended that the government of Nigeria pays rapt attention to earthquakes in Nigeria.
Keywords: earthquakes; magnitudes; recurrence interval; probability; intensity

1. Introduction

Earthquake is a global phenomenon experienced in most regions of the world. It is classified as one of the most devastating natural disasters that pose threat and has the capability to impact negatively on both human lives and the built environment. While other natural disasters such as drought, flood, famine, hurricane, tsunami and more can be devastating at the occurrence, an earthquake can cause much more damage in a swipe, depending on its magnitude. Hence, the continuous occurrence of earthquake events across the globe has continued to be a concern to humanity and some researchers have self-tasked themselves to work tirelessly to device means to mitigate the aftermaths of earthquake occurrence in the nations of the earth [1].

When an earthquake occurs, the trail of the adverse resulting impacts is not limited to the moment of its occurrence. The impact of an earthquake occurred in a nation can lead to a major setback in her development and her economic status and this can even linger for years after the event had occurred based on the magnitude of the earthquake [2] [3]. According to [4], Earthquakes occur due to the sudden release of built-up energy within the rocks. Other activities carried out on land surface can also stimulate earthquake. Some of these activities include drilling of boreholes and erection of heavy buildings.

Earthquake is experienced by most nations of the earth depending on their level of seismicity, while some nations are known for high seismicity, some are known for none and some are known for low seismicity. Nigeria among other nations of the earth has reflected dispersed seismic events within the period of 1933 to recent times. Many of the events that occurred in time past were not captured due to non-availability of seismic recording instruments.

Nigeria in the past was believed to be certified free from earthquake hazards but the instrumental and historical records of Nigeria as presented in Table 1 has shown contrary to this belief. While the past earthquakes are believed to have occurred along the faults in Nigeria, future earthquake occurrences in Nigeria are also expected to occur along the seismic faults.

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Table 1: Historical/Instrumental Earthquakes in Nigeria (Source: [5])

S/N	Year-Month-Day	Origin Time	Felt Areas	Intensity/Magnitude	Probable Epicenter	Coordinates	
1	1933	-	Warri	-	-	05º 45^{1} 23^{11}E	05º 31^{1} 42^{11}N
2	1939-06-22	19:19:26	Lagos, Ibadan, Ile-Ife	6.5 (Ml)	Akwapin fault in Ghana	03º 23^{1} 00^{11}E	06º 30^{1} 11^{11}N
3	1948-07-28	-	Ibadan	-	Close to Ibadan	-	-
4	1961-07-02	15:42	Ohafia	-	Close to ijebu-Ode	-	-
5	1963-12-21	18:30	Ijebu-Ode	V	Close to Ijebu-Ode	-	-
6	1981-04-23	12:00	Kundunu	III	At Kundunu Village	-	-
7	1982-10-16	-	Jalingo, Gembu	III	Close to Cameroun Volcanic Line	-	-
8	1984-07-28	12:10	Ijebu-Ode, Ibadan, Shagamu, Abeokuta	VI	Close to Ijebu Ode	-	-
9	1984-07-12		Ijebu Remo	IV	Close to Ijebu Ode	03º 23^{1} 00^{11}E	07º 11^{1} 45^{11}N
10	1984-08-02	10:20	Ijebu-Ode, Ibadan, Shagamu, Abeokuta	V	Close to Ijebu Ode	-	-
11	1984-12-08	-	Yola	III	Close to Cameroun Volcanic Line	-	-
12	1985-06-18	21:00	Kombani Yaya	IV	Kombani Yaya	-	-
13	1986-07-15	10:45	Obi	III	Close to Obi town	08º 46^{1}E	08º 22^{1}N
14	1987-01-27	-	Gembu	V	Close to Cameroun Volcanic Line	11º 15^{1}E	06º 42^{1}N
15	1987-03-19	-	Akko	IV	Close to Akko	10º 57^{1}E	10º 17^{1}N
16	1987-05-24	-	Kurba	III	Close to Kurba village	10º 12^{1}E	11º 29^{1}N
17	1988-05-14	12:17	Lagos	V	Close to Lagos	-	-
18	1990-06-27	-	Ibadan	3.7(ML)	Close to Ijebu-Ode	03º 58^{1}E	17º 22^{1}N
19	1990-04-05	-	Jerre	V	Close to Jerre Village	-	-
20	1994-11-07	05:07:51	Ojebu-Ode	4.2(ML)	Dan Gulbi	-	-

21	1997	-	Okitipupa	IV	Close to Okitipupa Ridge	-	-
22	2000-08-15	-	Jushi-Kwari	III	Close to JushiKwari village	07º 42¹E	14º 03¹N
23	2000-03-13	-	Benin	IV	Benin City (55km from Benin)	-	-
24	2000-03-07	15:53:54	Ibadan, Akure, Abeokuta, Ijebu-Ode, Oyo	4.7 (ML)	Close to Okitipupa	-	-
25	2000-05-07	11:00	Akure	IV	Close to Okitipupa Ridge	-	-
26	2001-05-19	-	Lagos	IV	Close to Lagos city	-	-
27	2002-08-08	-	Lagos	IV	Lagos city	-	-
28	2005-03	-	Yola	III	Close to Cameroun Volcanic Line	-	-
29	2006-03-25	11:20	Lupma	III	Close to Ifewara	-	-
30	2009-09-11	-	Abomey-Calavi	II	Close to Benin	-	-
31	2011-11-05	-	Abeokuta	4.4	Close to Abeokuta	-	-
32	2016-07-10	-	Saki	IV	Oyo State	-	-
33	2016-08-10	-	Igbogene	III	Bayelsa	-	-
34	2016-09-11	-	Kwoi	III	Kaduna State	-	-
35	2016-09-12	-	SambangDagi	III	Kaduna	-	-

There are also indications from the development of recent times that devastating earthquakes are likely to occur in Nigeria and in West Africa in the nearest future and it is, therefore, important that these indications be taken into cognizance [6][7]. [8] explained that the reason why Nigeria hardly experiences earthquake hazard like other high earthquake-prone nations is likely to be as a result of the location of her geological framework which is believed to be situated in her continent's mobile belt between the Congo and West Africa Craton where notable damage was reported to have occurred in the past leading to bit of impact on the adjacent craton.

The prevention of earthquake occurrence in any country is impossible, different approaches that help to assess their likelihood of occurrence go a long way in helping authorities to make decisions and to implement certain rules that will help minimize or mitigate the aftermath of the hazards [9]. Despite the fact that researchers have warned that Nigeria is at the risk of experiencing devastating earthquakes in the nearest future, there is still no knowledge of the extent of the probable future earthquake magnitude. Hence, probabilistic seismic hazard analysis has been carried out for Nigeria in this research with the employment of the Gutenberg-Richter recurrence law.

1.1 Earthquake Forecast

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In the study of earthquakes, it is possible to pinpoint locations where future earthquakes have the likelihood of occurrence by examining tectonic plates' movement in a location. Nevertheless, this approach can still turn out to be inaccurate. Hence, scientists are yet to successfully discover an approach to predict future earthquakes, considering time and location with accuracy and precision [10]. According [11], Earthquake forecast is a statement of probability that an earthquake of a particular magnitude will occur at a particular time and at a particular location. Earthquake forecast is distinctively different from earthquake prediction as many confuse the two to be the same. Unlike in forecasting, prediction comes as a statement of certainty.

Several researchers have related different approaches to assess future earthquakes in times past. As follow, some of these approaches include the study of radon gas emission, seismic waves study, and future earthquake assessment using animal unusual behavior prior to major earthquake event:

i. [12] pointed out that radon emission as earthquake precursor is a good facilitator of knowledge towards earthquake prediction. Studies have shown that there is always very high radon concentration at the site of earthquake occurrence. Hence, its concentration level in groundwater and soil is a good indicator.

ii. The earliest unusual behavior of the animal in response to earthquake occurrence was that of 373BC in Greece in which animals migrated from their different homes to safe locations few days to a major earthquake [13]. [14] described the responses of animals to the earthquake as an inbuilt escape instinct or survivor instinct due to the ability of the animals to sense seismic signals.

iii. Seismic waves carry earthquake energy which can be analyzed for some seismic parameters that will make earthquake assessment feasible. The seismogram is used for capturing these waves and the output is presented as seismograph which is analyzed for the extraction of necessary parameters such as earthquake magnitude, frequency and wavelength [12].

1.2 Gutenberg-Richter Recurrence Law

The Gutenberg-Richter recurrence law was first proposed by [15]. This relationship relates the cumulative number of the earthquake to the magnitude of the earthquake in a region. The Gutenberg-Richter recurrence law is presented in the equation 1.

$$\log_{10} \mathrm{N} = \mathrm{a} - \mathrm{bM} \tag{1}$$

According to [16], global earthquake occurrences including the ones with great depth follow the trend of the G-R recurrence law. The "N" in the equation 1 represents the total number of earthquakes, a and b are referred to as seismicity parameters while "M" is the magnitude of earthquakes. The establishment of the G-R recurrence law's linearity has remained unchanged for more than fifty years [17].

2. Material and Methods

The data used for the purpose of this assessment was the instrumental and the historical data presented in Table 1. The equation 2 as related by [18] was employed for the conversion of every event reported using intensity scale to the Richter magnitude scale.

$$\mathrm{M_L} = 1 + 0.667\mathrm{I_o} \tag{2}$$

.

The Gutenberg-Richter recurrence law presented in the equation 1 was used to generate the Gutenberg-Richter plot of Fig. 1 for Nigeria by plotting the cumulative number of earthquakes in Nigeria against the corresponding magnitudes. The seismicity parameter "a" was derived from the intercept of the plot in Fig. 1 and the b-value was derived by finding the gradient of the plot.

The logarithmic values of the vertical axis of the G-R plot gave the yearly occurrence for each earthquake magnitude while the recurrence interval for each magnitude was obtained by using the equation 3.

$$\text{Recurrence Interval} = \frac{1}{\text{Number of earthquake occurrence per year}} \quad (3)$$

The equation 4-5 related by [19] for the bounded Gutenberg-Richter relationship was used to establish the probability distribution function and the cumulative distribution function for the yearly occurrence of earthquake magnitudes of interest.

$$\beta = 2.303b \quad (4)$$

$$\text{PDF} = f_i(m) = P[M = m] = \frac{\beta e^{[-\beta(m - m_{min})]}}{[1 - e[-\beta(m_{max,i} - m_{min})]} \quad (5)$$

$$\text{CDF} = f_i(m) = P[M < m] = \frac{1 - e^{[-\beta(m - m_{min})]}}{[1 - e[-\beta(m_{max,i} - m_{min})]} \quad (6)$$

The M_{max} was set as 7.1 as obtained from the G-R plot of the Fig. 1 while the M_{min} was set at the magnitude of 3.0. Other distribution models such as Burr, t Location-Scale, Rayleigh, and Gamma distribution models were used to test for the distribution of earthquake events in Nigeria and the PDF and CDF for the best fitting distribution models was compared to that of the bounded Gutenberg-Richter distribution model.

The poison probability distribution model of equation 7 was employed to establish the probability that certain selected earthquake magnitude will occur in the recurrence year and also that earthquake magnitude of 7.1 will occur in Nigeria from 2019-2028.

$$P[N = n] = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \quad (7)$$

This was done for each consecutive year starting from the time this research was carried out to the recurrence interval year for an earthquake of magnitude 7.1.Matlab 2017a version software was very instrumental in generating all the plots presented in the paper.

3. Results and Discussion

The results obtained from this assessment is well outlined out as follows:

3.1 The Gutenberg-Richter Relationship Plot for Nigeria

The Gutenberg-Richter plot generated for Nigeria using her instrumental and historical data is presented in the Figure 1. From the critical analyses of the G-R plot, it shows that earthquake magnitude that is as high 7.1 is likely going to be experienced in Nigeria in the future. The G-R approach also gave 7.1 magnitudes as the limit to the possible earthquake magnitude in Nigeria. As a basis for comparison, [20] forecasted that earthquake magnitude greater than 5.0 will be experienced in the nearest future. While the findings of [20] is open-ended, the results of this research gave a guide to the extent of earthquake magnitude to be expected in Nigeria. The b-value for Nigeria from the plot is 0.99.

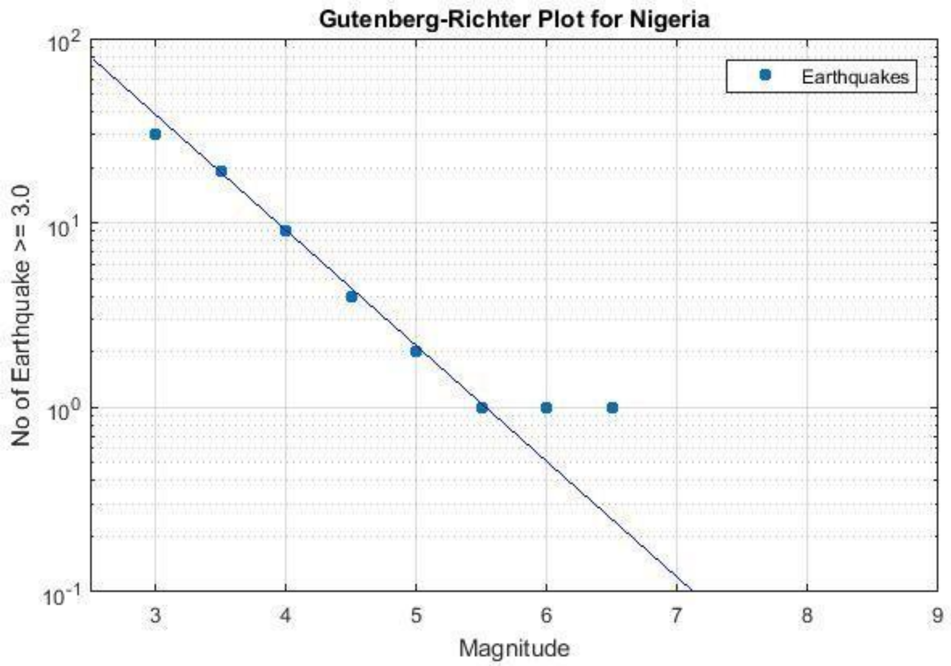

Fig. 1 Gutenberg-Richter relationship Plot

According to [21], when the b-value ranges between 0.72 ± 0.07 to 1.20 ± 0.015, the seismotectonic setting of such region is that of an intraplate. Hence, Nigeria's seismotectonic setting is of intraplate. This suggests that the seismic events that ever occurred in Nigeria lie without the margin plate's region. The value of "a" is found to be 16.8. The value of "a" is high and due to infrequent earthquake occurrences in Nigeria.

$$\log_{10} \lambda m = 16.8 - 0.99M \quad (8)$$

The equation 8 is therefore proposed for the determination of the mean annual rate of exceedance for earthquake magnitude of interest. The equation 8 is only valid for Nigeria provided that it obeys equation 9.

$$0 \leq M \leq 7.1 \quad (9)$$

The "a" and b-value solely depends on the number of events being considered. Therefore, these values are subject to slight changes if more seismic events are considered in the future.

3.2 Yearly Earthquake Occurrence and Earthquake Recurrence Interval for Nigeria

The yearly occurrence of earthquake magnitude and the recurrence intervals for earthquake magnitudes are shown in the Figure 2 and the Figure 3 respectively. Earthquakes with smaller magnitudes have a higher number of occurrences yearly than earthquakes with high magnitudes. This is similar to nature of earthquakes globally. From Figure 2, earthquake magnitudes of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, and 7.1 are likely to occur 38 times, 19 times, 9 times, 4.2 times, 2.3 times, 1 time, 0.5 times, 0.27 times, 0.13 times, and 0.1 times respectively in a year.

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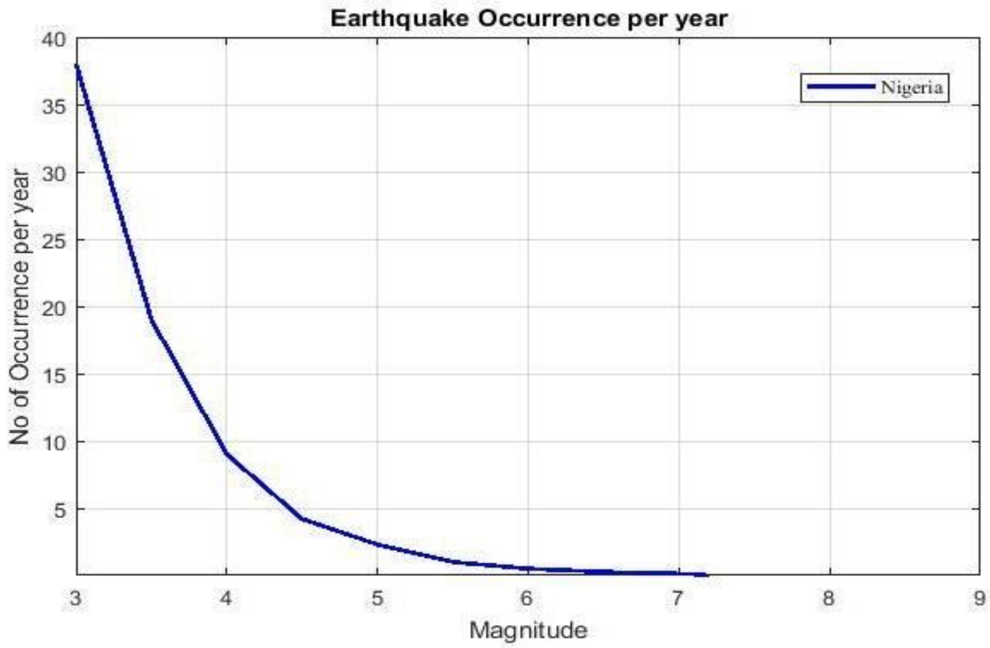

Fig. 2 Earthquake Yearly Occurrence

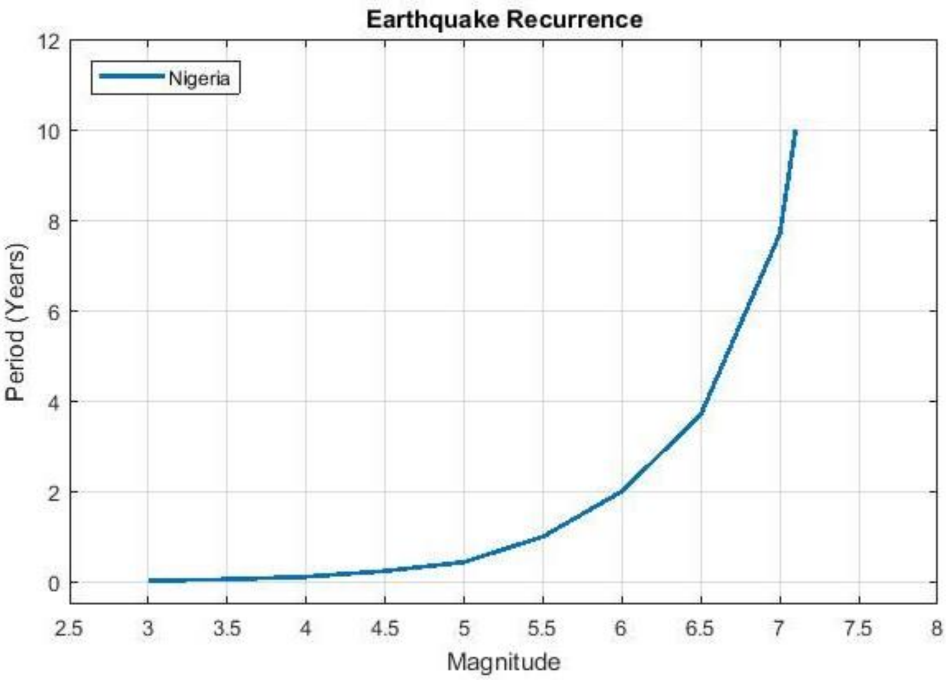

Fig. 3 Earthquake Recurrence interval

Likely also, the recurrence interval of earthquakes as shown in the Figure 3 reveals that earthquake magnitudes of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0 and 7.1 have the recurrence intervals of 0.026 year, 0.053 year, 0.111 year, 0.2938 year, 0.435 year, 1 year, 2 years, 3.704 years, 7.692 years and 10 years respectively in Nigeria. Therefore, assessing the results from the year 2018 shows that there is the likelihood of occurrence for earthquake magnitudes as high as 6.0 in the year 2020; 6.5 between the year 2021 and 2022; 7.0 between the year 2025 and 2026 and 7.1 in the year 2028. The probability that these earthquakes will occur in the recurrence year is 36.79%. [20] also stated 6.0% to 91.1% probability for earthquake greater 5.0 magnitude to occur between the year 2017 and 2028.

3.3 Annual Probability of Occurrence Using Bounded G-R Law

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The probability distribution function and the cumulative distribution function using the engagement of the bounded G-R recurrence law is shown for the discontinuous earthquake events in Table 2 and Table 3 respectively. Earthquake magnitudes with small values exhibited a higher probability of occurrence and vice versa.

Table 2 Probability Distribution Function of Earthquake in Nigeria

Earthquake Magnitude	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.1
PDF=X=x	0.7293	0.2332	0.0746	0.0239	0.0076	0.00244	0.0008	0.0003	0.0002
CDF= X<x	0.6802	0.8978	0.9674	0.9896	0.9967	0.9990	0.9997	0.9999	1.0000

The least earthquake magnitude under consideration being 3.5 in Table 2 has an annual 72.94% probability of occurrence while magnitude 7.1 has an annual 0.02% probability of occurrence. Thus, the chances of yearly occurrence for an earthquake of magnitude 7.1 is low.

The cumulative distribution function on the other hand in Table 2 appears to have high probabilities for values below magnitudes of interest. This is because the probability is open to arrange of several events below the certain magnitude of interest. Hence, CDF for bounded range as presented in Table 3 is further generated.

Table 3 Cumulative Distribution function of earthquake within bounded range

Earthquake Magnitude	4.0<M<4.5	4.5<M<5.0	5.0<M<5.5	5.5<M<6.0	6.0<M<6.5	6.5<M<7.1
CDF	0.0696	0.0222	0.0071	0.0023	0.0007	0.0003

The CDF for magnitude 4.0 < M < 4.5 is 6.96% annually and CDF for 6.5< M< 7.1 is as low as 0.03% annually.

3.4 Probability Distributions for Earthquakes in Nigeria

The Plots for the PDF and CDF using the Burr, t Location-Scale, Rayleigh, and Gamma distribution models are presented in the Figure 4 and Figure 5. While Rayleigh distribution appears to have no correlation with the seismic data in Nigeria, the Burr and t Location distributions tend to fit better by observation. This is the same both for the PDF and the CDF.

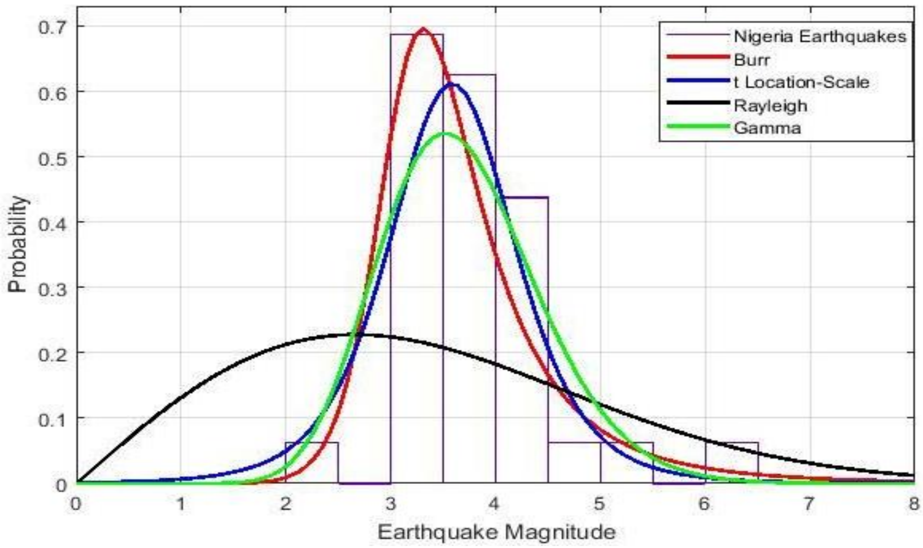

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Fig. 4 Probability Distribution Models for Earthquake

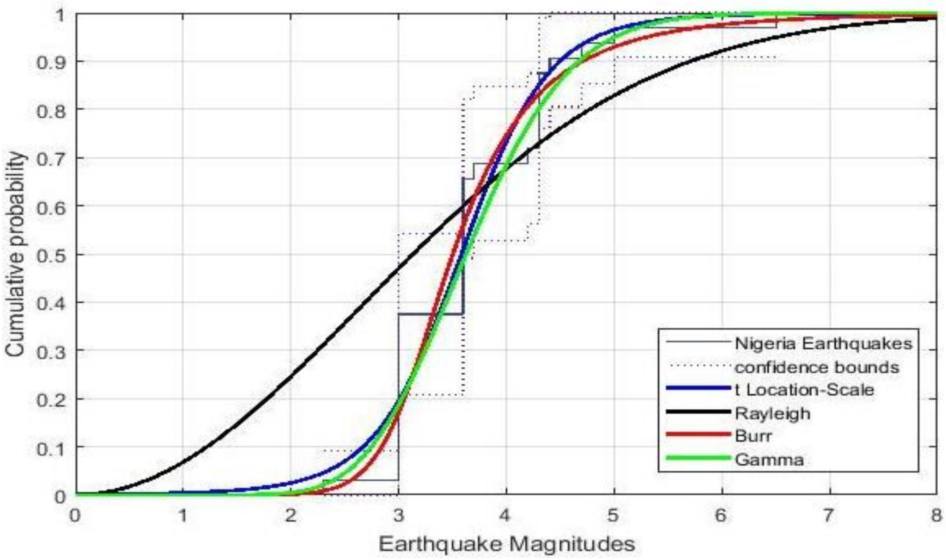

Fig. 5 Cumulative Distribution Models for Earthquake

Hence the corresponding PDF and CDF for the Burr and t Location-Scale distribution models are presented in Table 4 and Table 5 respectively.

Table 4 PDF for Burr &t Location Distribution model for earthquakes in Nigeria

Earthquake Magnitude	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Burr	0.349938	0.166391	0.082108	0.042954	0.023723	0.013731	0.008275
t Location-Scale	0.472999	0.207019	0.071628	0.024539	0.00907	0.003686	0.00164

Table 5 CDF for Burr &t Location Distribution model for earthquakes in Nigeria

Earthquake Magnitude	4.0<M<4.5	4.5<M<5.0	5.0<M<5.5	5.5<M<6.0	6.0<M<6.5	6.5<M<7.0
Burr	0.123435	0.059386	0.030072	0.016129	0.009104	0.00537
t Location-scale	0.16647	0.064278	0.021889	0.007713	0.002967	0.001254

The results of the PDF and the CDF using Burr and t Location-scale distribution model are relatedly close and slightly higher to the PDF and CDF given by the bounded GR recurrence law.

3.5 Probability of 7.1 Magnitude from 2019 to 2028 in Nigeria

The Figure 7 presents the plot showing the probability that earthquake magnitude of 7.1 will occur in Nigeria from 2019 to 2028.

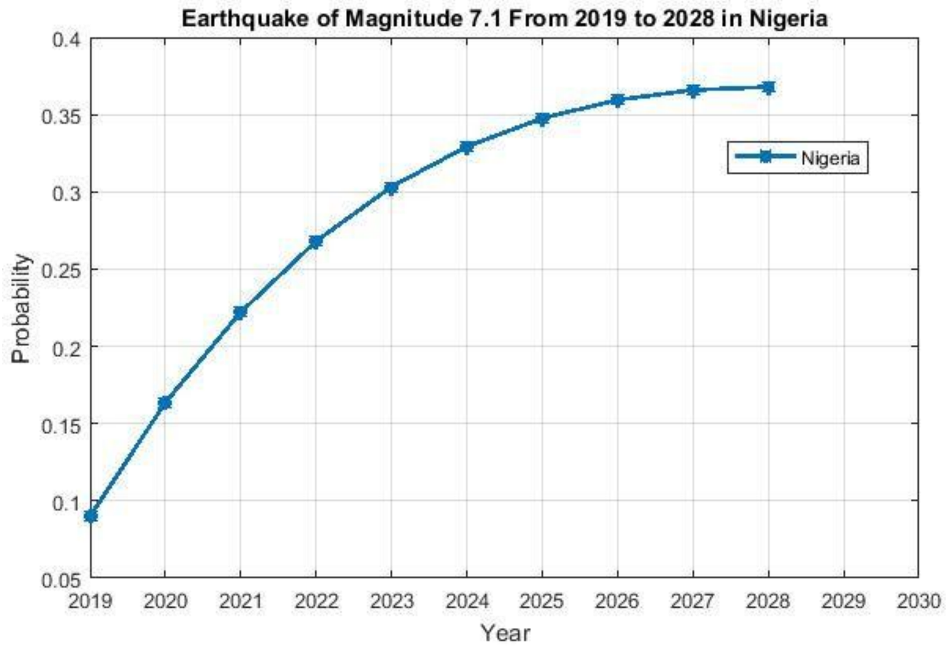

Fig. 7 The probability of 7.1 earthquake magnitude occurrence from 2019 to 2028

The Plot of Fig. 7 shows a yearly and gradual leap in the probability of magnitude 7.1 from 9% in 2019 to 36.79% in 2028.

4. Conclusion

The findings of this assessment established that Nigeria is at the risk of experiencing devastating earthquakes in the future. These Probable earthquake magnitudes are as high as 6.0 in the year 2020; 6.5 between the year 2021 and 2022; 7.0 between the year 2025 and 2026 and 7.1 in the year 2028. The probability that these events will take place in the forecasted year is 36.79%. The probability that an earthquake of magnitude 7.1 will also occur from 2019 to 2028 is between 9% and 36.79%. The b-value for Nigeria is 0.99 and this suggests that the seismotectonic setting of Nigeria is that of an Intraplate. The equation 8-9 is also proposed for the assessment of the annual mean rate of exceedance for earthquakes in Nigeria. It is therefore recommended that the Nigerian authority begins to enforce the law as regards earthquake considerations in structural designs in places such as the South-West region that has displayed most seismic events in times past. It is also recommended that activities such as heavy rock blasting should be relocated to non-residential places to reduce earthquake stimulations in residential areas.

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