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PROBABILISTIC SEISMIC HAZARD ANALYSIS OF SOUTH-WESTERN NIGERIA

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ABSTRACT: For about ten decades, the seismic record of Nigeria has shown the occurrence of several magnitudes of earthquakes. This is contrary to the belief of some people in time past that Nigeria is aseismic. In number and in size, most of the witnessed earthquakes in Nigeria are found to occur in her South-Western region. Researchers have also begun to warn recently that some regions of Nigeria should prepare for devastating earthquakes in years to come. Hence this paper aimed at the probabilistic seismic hazard analysis of the South-Western region of Nigeria using the available historical and instrumentally recorded data. The Gutenberg-Richter (G-R) recurrence law was used to assess the seismicity parameters and to generate a model for calculating the mean annual rate of exceedance and to forecast probable future earthquake occurrence in the South-West. The findings of this assessment established that the South-West region of Nigeria is likely to experience earthquake magnitude as high as 7.2 in the year 2028 with a probability of 36.79%. Hence, this work enlightens on the extent of probable future earthquake magnitude in South-Western Nigeria and it is recommended that the government of Nigeria and inclined agencies begin to look into earthquake in this region.

Keywords: Earthquakes, Magnitudes, Recurrence Interval, Assessment, Intensity

1. INTRODUCTION

Most people see earthquakes as acts that emanate from the sovereign God rather as events that warrant a proper investigation. Earthquake is a global phenomenon experienced especially in high seismic regions of the earth. According to [1], its occurrence generates both vertical and horizontal ground motions which can also result in the vibration of constructed structures [2]. Major disasters such as an earthquake can also cause a devastating effect on the economy of nations leaving such nation to go through many years of recovery [3]. Among the nations of the earth that experience earthquake, Nigeria has not been left out. [4] pointed out that the developments in the history of geology in Nigeria raise a question on her seismic safety as against the belief which had been for long that Nigeria is aseismic. Nevertheless, this belief still reigned until recent tremors in Nigeria and especially her South-West region. Since a major earthquake can possibly occur due to build up from several tremors, it should not be overlooked. The National Space Research and Development Agency (NARSDA) researchers recently reaffirmed that Nigeria is not immune to earthquake occurrence after critically looking into a recent tremor that occurred on the 11th of September 2009 at about 03:10:30 am in Abeokuta, South West region of Nigeria. The event was reported to have a magnitude of 4.8 and intensity of 7 [5]. To be more elaborate on this same event, [6] went further to say that the three seismographic stations namely Centre for Geodesy and Geodynamics (CGG) and Toro had the event captured since the available stations began operation a year before the event took place. The effect of this event was felt as vibrations in some towns in the South-Western part of Nigeria.

Many other tremors and earthquakes have been witnessed in Nigeria with Ibadan being the first city to witness earthquake in 1949 and Warri being the first city to witness tremor in 1923. This paper is aimed at assessing probable future earthquake occurrence in the South-Western part of Nigeria using probabilistic seismic hazard analysis approach.

1.1 Earthquake Forecasting

There is a clear difference between forecasting and the prediction of an earthquake. [7] stated earthquake prediction to be a clear declaration of one or more future earthquakes occurrence with a certain magnitude and time interval while forecasting is a statement of probability that specific one or more earthquakes of clear magnitude will occur in a specific time and a specific region. Conflicting opinions due to lack of common ground have been major a characteristic of earthquake assessment through history [8]. Despite this, several models have been and are being developed to assess future earthquakes [9]. Some of the widely used models given by [10] are the string block Burridge-Knopov model and Gutenberg-

Richter relationship. These models make it possible and realizable to know aforetime the probabilities of occurrence of a future earthquake in a particular region [11].

1.2 Gutenberg-Richter Recurrence Law

The occurrence of an earthquake in any region of the world follows the Gutenberg-Richter (G-R) recurrence law developed by [12] . According to [13], Earthquake of great depths also follows the G-R recurrence law. The G-R relationship is represented by the Eq. (1).

$$\log_{10} N = a - bM \qquad (1)$$

The N in the Eq. (1) is the cumulative number of earthquakes occurring in the considered region, "a" and "b" are the seismicity parameters and "b" is usually referred to as b-value and is derived from the slope of the generated G-R plot while "a" is the intercept of the G-R plot. The M in the Eq. (10) is the magnitude of the earthquake. For more than fifty years now, the linearity of the G-R law remains established [14].

1.3 Earthquake Recurrence Interval

Recurrence interval is referred to as the duration of time between consecutive events, that is, the time with which an event is likely to occur again [15]. Rare events such as the occurrence of earthquakes in geophysics, droughts, and floods in hydrology and hurricane in climate, have become a topic of interest for more than one discipline. The practicality of application and scientific findings have taken the study of these rare events to be a matter of importance. These studies have shown that rare events that rarely occur and are extremely high or low have the potential of generating large effects [16]. One of the key parameters needed for the assessment of seismic hazards is the recurrence interval of large earthquakes which relates to the seismogenic fault's dynamic process. In a recurrence cycle, small earthquakes can also be background earthquakes [17]. Paleoseismic studies have shown that quasiperiodic is the nature of large earthquakes, that is, its unpredictability nature and does not give itself to precise measurement. Earthquakes that are small have high regularity. The average recurrence interval for a series of earthquakes is the ratio of average earthquake slip to the loading rate [18].

2. MATERIAL AND METHODS

The data used for this assessment is instrumental and historical data of Nigeria seismology of about 10 decades which have been explored and published by few researchers among whom is [19]. Conversions were carried out from intensity scale to local magnitude for some of the events reported with the intensity scale using the expression [20] related as presented in Eq. (2).

$$M_L = 1 + 0.667 I_o \qquad (2)$$

The M_L and I_o in equation 2 represent earthquake local magnitude and earthquake intensity respectively.

Excel Sheet was employed to plot the Fig. 1 while Matlab was instrumental in generating all other plots presented in the work.

2.1 Regionalization of Nigeria Seismicity

The regionalization of the Nigeria seismicity was achieved by distributing all the seismic events that ever occurred in Nigeria into their respective region so as to assess the percentage of the earthquake that ever occurred in each region and to know the region with the most seismic events. The Eq. (3) was employed to this effect.

$$\text{Percentage Earthquake Occurrence}(\%) = \frac{\text{Total Number of Earthquake in a Region}}{\text{Total Number of Earthquake in Nigeria}} \times 100\% \qquad (3)$$

2.2 The Gutenberg-Richter Relationship Plot for South-Western Nigeria

The major approach employed for this probability seismic hazard analysis is the Gutenberg-Richter recurrence law. The Cumulative number of earthquake events was plotted against the earthquake magnitudes to obtain the Gutenberg-Richter plot of Fig. 2 and this relates to the expression in Eq. (1). The plot gave the seismicity parameters a and b-value for the south-west region and it also gave the maximum size of earthquake that can be expected in the region based on the employed data.

The Poisson probability model in the Eq. (4) was used to establish the probability of occurrence of an earthquake in its recurrence year.

$$P[N = n] = \frac{(\lambda t)^n e^{-\lambda t}}{n!} \qquad (4)$$

n in the equation represents the number of events, λ represents the annual mean rate of exceedance and t is a number of years.

2.3 Yearly Earthquake Occurrence and Earthquake Recurrence Interval for South-Western Nigeria

The logarithmic value of the y-axis of the

G-R plot in the Fig. 2 gave the number of earthquake yearly occurrence while the recurrence interval of the earthquake of different magnitude was found using the Eq. (5).

$$\textbf{Recurrence Interval} = \frac{1}{\textbf{Number of earthquake occurrence per year}} \quad (5)$$

2.4 Annual Probability of Occurrence Using Bounded G-R Law

The Probability distribution function (PDF) and the Cumulative distribution function (CDF) from the bounded Gutenberg-Richter recurrence law were further used to find the probability of yearly earthquake occurrence of magnitudes of interest. [21] presented the expressions in the Eq. (6-9) for the probability density function and the cumulative density function of bounded G-R law.

$$\ln(m) = v_0 e^{-\beta m} \quad (6)$$

Where $v_0 = 2.303a$ and $\beta = 2.303b$ with a and b being seismicity parameters while the activity rate that corresponds to m_{min} is given by the following expression:

$$\propto = v_0 e^{-\beta m_{min}} \quad (7)$$

$\propto_i$ is derived from α and the expression that relates the distribution $f_i(m)$ to β, m_{min} and m_{max} is stated as follows:

$$PDF = f_i(m) = P[M = m] = \frac{\beta e^{[-\beta(m - m_{min})]}}{[1 - e[-\beta(m_{max,i} - m_{min})]} \quad (8)$$

$$CDF = f_i(m) = P[M < m] = \frac{1 - e^{[-\beta(m - m_{min})]}}{[1 - e[-\beta(m_{max,i} - m_{min})]} \quad (9)$$

m_{min} and $m_{max,i}$ related in equation 7, 8 and 9 represent the minimum earthquake magnitude and the maximum earthquake magnitude respectively.

The PDF in Eq. (8) measures the probability that earthquake of a certain magnitude will occur yearly and the CDF in Eq. (9) measures the probability that earthquake will be less than a magnitude of interest.

The minimum earthquake magnitude was set at 3.0 due to the limited available data and the maximum earthquake magnitude was set at 7.2 from the result of the G-R plot.

2.5 Probability Distributions for Earthquakes in South-Western Nigeria

Several probability distribution models such as Burr model, Rayleigh model, Weibull model and Exponential model were employed to test for the distribution of earthquakes in the South-West and comparison established between the PDF and the CDF of these models and that of the bounded GR recurrence law.

3. RESULTS AND DISCUSSIONS

3.1 Regionalization of Nigeria Seismicity

The seismicity of Nigeria was regionalized using the Nigeria seismic data that is available from 1939 to 2016. [19] explored and published the used data. The Plot presented in the Fig. 1 from the regionalization of the seismic events shows that 12.50%, 21.88%, 3.13%, 50%, 9.38% and 3.13% of the seismic events ever witnessed in Nigeria occurred in the North-West, North-East, North-Central, South-West, South-South and the South East respectively between the year 1933 and the year 2016.

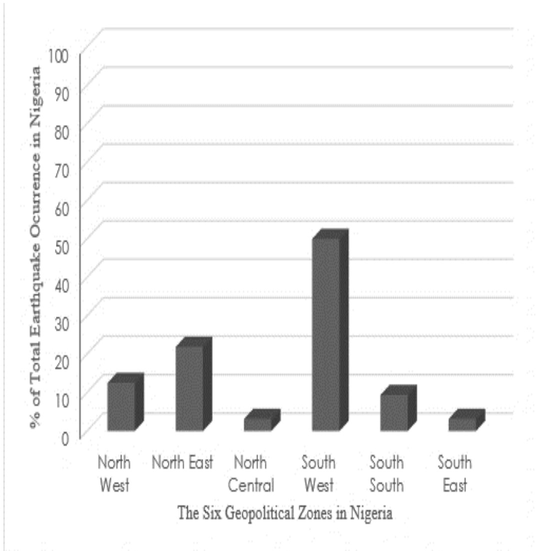

Fig.1 Regionalization of Nigeria Seismicity

Hence seismic event in Nigeria has been predominantly in the region of her south-west and more seismic events are likely to occur in this same zone. The South-West has not only experienced seismic events in number only; high magnitudes such as 5.0 and 6.5 occurred in the South-West years ago. Thus, the South West region was chosen for this Probabilistic seismic hazard analysis assessment.

3.2 The Gutenberg-Richter Relationship Plot for South-Western Nigeria

The Gutenberg-Richter plot generated for the South-West region of Nigeria based on her seismic data is shown in the Fig. 2. Earthquake magnitude as high as 6.0 to 7.2 has the chances of occurring in the South-West in the future as revealed by the line of best fit of the G-R plot in the Fig. 2. In line with this result, [22] forecast findings also show that the earthquake of magnitudes greater than 5.0 is likely to occur in the South-West between the year 2008 and the year 2038. The forecast of [22] left expected magnitude to be open-ended but the magnitude of 7.2 is the limit of the possible earthquake magnitude to be expected in the south-west having worked with the available data. The seismicity parameter b-value which is also the slope of the G-R plot equals 0.905.

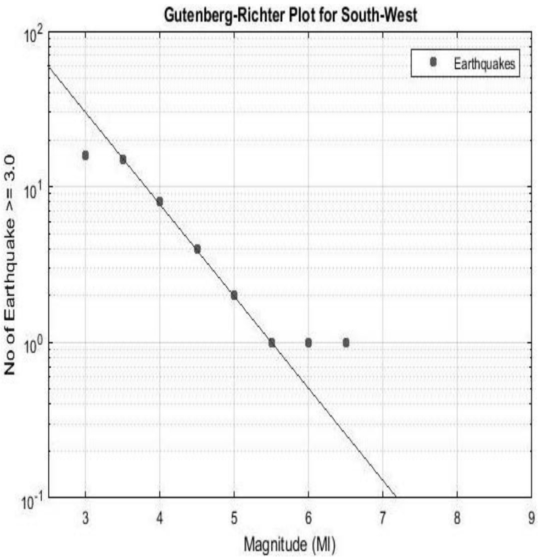

Fig.2 Gutenberg-Richter relationship Plot

When b-value ranges between 0.72 ± 0.07 to 1.20 ± 0.015 according to [23], the seismotectonic setting of such region is that of an intraplate. Hence, the seismotectonic setting of the South-West region of Nigeria in response to seismic events is that of an intraplate. This means that the seismic events lie outside the region of the margin plate. The resulting value of "a" is 14.8 and this is high. The value of "a" tends to the high side when the number of events under consideration is few and such is the case of the South West region in Nigeria.

$$\mathbf{\log_{10} \lambda m = 14.8 - 0.905M} \qquad (\mathbf{10})$$

The Eq. (10) is therefore proposed for the South-West region of Nigeria based on the value of "a" and b-value and it is only valid for the expression in Eq. (11) for the determination of the mean annual rate of exceedance.

$$\mathbf{0 \leq M \leq 7.2} \qquad (\mathbf{11})$$

$\boldsymbol{\lambda m}$ in equation 10 is the annual mean rate of exceedance and $\mathbf{M}$ is the magnitude of earthquake.

The a and b-value are dependent on the number of events under consideration. These parameters are therefore subject to change with more future seismic events.

3.3 Yearly Earthquake Occurrence and Earthquake Recurrence Interval for South-Western Nigeria

The number of earthquake occurrence to be expected in the South-West per year is on the high side for very small seismic magnitudes just as it is generally around the globe. Small magnitude earthquakes have more occurrences than large magnitude that comes once in years. The Fig. 3 and the Fig. 4 present plots for the yearly occurrence and the recurrence interval of earthquake respectively for the South-West.

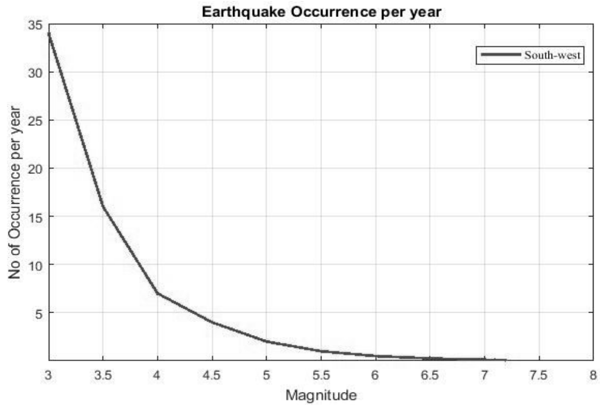

Fig. 3 Earthquake Yearly Occurrence

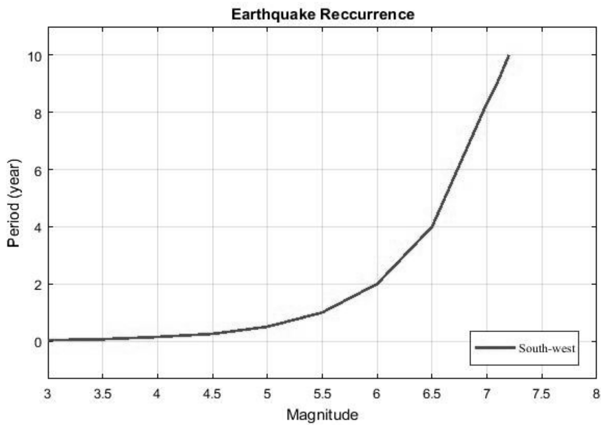

Fig. 4 Earthquake Recurrence interval

From the plot in the Fig. 3, earthquake magnitudes of 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, 7.1 and 7.2 are likely to occur 34 times, 16 times, 7 times, 4 times, 2 times, 1 time, 0.5 times, 0.25 times, 0.12 times, 0.11 times and 0.1 times respectively per year.

Earthquake magnitudes of 6.0, 6.5, 7.0, 7.1

and 7.2 have the recurrence intervals of 2 years, 4 years, 8.4 years, 9.09 years and 10 years respectively for the south-west zone. Taking the count from the time this assessment was carried out, the South-West is likely to experience earthquake magnitudes as high as 6.0 in the year 2020; 6.5 in the year 2022; 7.0 between the year 2026 and 2027; 7.1 between the year 2027 and 2028 and 7.2 in the year 2028. The probability that these earthquakes will occur in the recurrence year is 36.79%. [22] also stated 6.0% to 91.1% probability for earthquake greater 5.0 magnitude to occur between the year 2017 and 2028.

3.4 Annual Probability of Occurrence Using Bounded G-R Law

The probability distribution function and the cumulative distribution function using the bounded G-R recurrence law is shown for the discrete earthquake events in Table 1 and Table 2 respectively. The Probability that earthquake of a certain magnitude will occur annually is quite high for Events with small magnitudes and quite low for events with high magnitudes.

Table 1 Probability Distribution Function of Earthquake in South Western region

Earthquake Magnitude	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.2
PDF= X=x	0.7400	0.2500	0.0910	0.0320	0.0114	0.0040	0.0014	0.0005	0.0003
CDF= X<x	0.6474	0.8757	0.9563	0.9847	0.9947	0.9982	0.9995	0.9999	1.0000

Magnitude 3.5 being the least considered magnitude in Table 2 has an annual 74% probability of occurrence while magnitude 7.2 has an annual 0.03% probability of occurrence. Thus, the chances that an earthquake of magnitude 7.2 will occur yearly is low.

The cumulative distribution function on the other hand in the Table 1 appears to have high probabilities for values below magnitudes of interest. This is because the probability is open to a range of several events below the certain magnitude of interest. Hence, CDF for bounded range as presented in Table 2 is further generated.

Table 2 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< 7.0
CDF	0.0806	0.0284	0.0100	0.0035	0.0013	0.0004

The CDF for magnitude 4.0 < M < 4.5 is 8.06% annually and CDF for 6.5< M< 7.0 is as low as 0.04% annually.

3.5 Probability Distributions for Earthquakes in South-Western Nigeria

The Fig. 5 and the Fig. 6 show the PDF and CDF plots using the Burr distribution model, Weibull distribution model, Rayleigh distribution model and the Exponential distribution model. The models were used to ascertain the distribution of earthquake in the South-West.

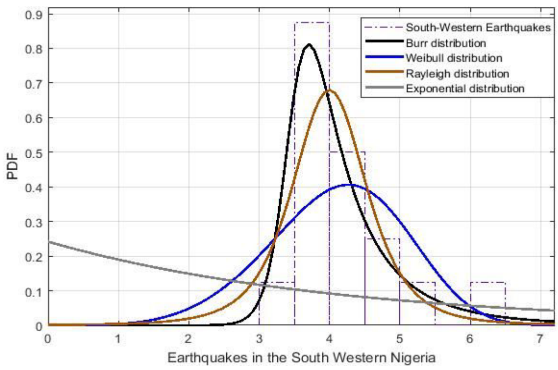

Fig.5 Probability Distribution Models for Earthquake

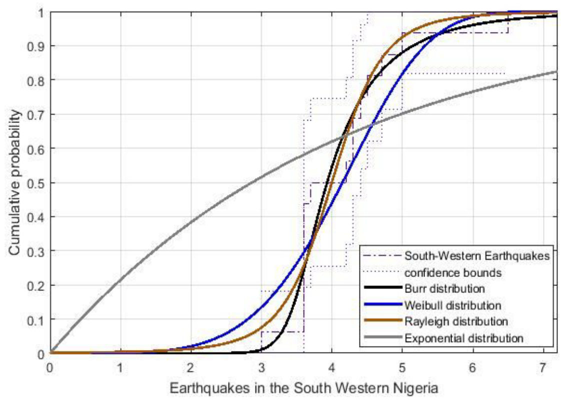

Fig.6 Cumulative Distribution Models for Earthquake

By observation, the Burr distribution model and the Rayleigh distribution model seem to fit the earthquake data more compared to the other two distribution models. Hence the corresponding PDF and CDF for the Burr and Rayleigh distribution models are presented in Table 3 and Table 4 respectively.

Table 3 PDF for Burr & Rayleigh Distribution model for earthquakes in the South-Western Nigeria

Earthquake Magnitude	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Burr	0.63932	0.302562	0.14486	0.073962	0.040013	0.022737	0.013472
Rayleigh	0.679582	0.419576	0.150028	0.050936	0.019333	0.008339	0.004017

Table 4 CDF for Burr & Rayleigh Distribution model for earthquakes in the South-Western 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	0.226877	0.10651	0.052462	0.027509	0.015225	0.008823
Rayleigh	0.29015	0.133642	0.045595	0.016137	0.006472	0.002934

The results of the PDF and the CDF using Burr and Rayleigh distribution model are relatedly close and slightly higher to the PDF and CDF given by the bounded GR recurrence law. Nevertheless, the fitness of Burr and Rayleigh models in this forecast is in response to how well the data follow the trend of the models.

4. CONCLUSION

The findings of this assessment established that the South-Western region of Nigeria having experienced an earthquake of magnitude 6.5 in past is at the risk of experiencing future devastating earthquakes. Probable earthquake magnitudes as high as 6.0 in the year 2020; 6.5 in the year 2022; 7.0 between the year 2026 and 2027; 7.1 between the year 2027 and 2028 and 7.2 in the year 2028 have a likelihood of occurrence with a 36.79% probability. The b-value for South-Western Nigeria is 0.905 and this suggests that the seismotectonic setting of the South-West is that of an Intraplate. Therefore, the Eq. (10) and the Eq. (11) is proposed for the assessment of the annual mean rate of exceedance of earthquake in South-Western Nigeria. Rather than considering Nigeria as aseismic, it fits better to categorize Nigeria as a low seismic region.

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