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Seismic Hazard Levels in Guinea, West Africa

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ABSTRACT

The occurrence of seismic activities in Guinea is infrequent, although located in a stable continental region. The hazard assessment level in Guinea, West Africa was determined by a probabilistic approach for 10 sites across the region. The calculation was carried out for 10%, 2% and 0.5% probability of exceedance in 50 years using a homogenized 100-year catalogue compiled from different seismic sources; Three prediction relations, developed for Eastern and Central North America for the stable continental region; and the R-CRISIS program. The levels of hazard estimated were high in the Palaeozoic area of Guinea. A uniform b -value of 0.70 ± 0.12 , and individual activity rate (λ) were calculated for the three seismic zones. The maximum PGA values estimated for the study region are 0.08 g, 0.27 g, and 0.57 g for 475, 2475 and 9975 years return periods, respectively. Finding from this study will be useful in planning for the regional infrastructure.

Introduction

The location of the Guinea region far away from any known active plate boundary. The Guinea region is not seismically known and the occurrence of moderate to large earthquakes are infrequent based on available records. The first reported earthquake in Guinea was in 1795, with an estimated surface magnitude of 5.2, which caused considerable damage in the city of Labé¹. The 1818 earthquake with a 5.9 surface magnitude at the epicentre in Futa Djallon massif, northern Guinea. A strong earthquake with considerable damage and a surface magnitude of 4.0 occurred in the Kakulima region but no damage was reported. There was a strong shock in the western part of Guinea, where some local houses along the Konkouré river were destroyed in April 1928 with a surface magnitude of 4.8; renewed shocks followed this in August that caused landslide¹. Since then, some historical earthquakes have also been reported in 1935 and 1939, respectively. Finally, on 22nd December 1983, north-western Guinea experienced a strong earthquake of 6.3 magnitude (M_w). The epicentre of the event located in Gaoual, close to the border of Guinea-Bissau. It resulted in approximately 10 km of surface rupture, which extensively damaged buildings, killing over 300 people and more than 4,000 houses were destroyed^{2,3}. The seismic hazard across the cities of Guinea, West Africa has not been assessed. The seismic source model developed for this study region is separated into three zones, using the available seismicity and local geological

features. The ground motion model is constructed using three different strong-motion attenuation equations. Finally, the hazard estimates for ten cities are computed at 475, 2475, and 9975 years return periods to be the first to be made available in the literature for the Guinea region. As such, they provide valuable data for risk assessment and mitigation, land use management, and planning for present and future infrastructures across the selected cities.

Fig. 1. Geology and tectonic map of Guinea.

Geology of the Guinea

Guinea, West Africa, has a total surface area of 245,000 km². The study region (Fig. 1) is characterised predominantly by Precambrian crystalline and Palaeozoic Rocks, which spread along with the Guinean-Liberian shield. The Fouta Djallon massif made of Silurian shale and Ordovician sandstone has experienced massive arrival in the tertiary of both dolerites and a parent rock gigantic bauxitic with laterite deposits⁴. The northwest of the basin's coastal zone is primarily an unconsolidated-small outcrop of upper cretaceous to Tertiary sedimentary rocks. The Mesozoic contains some Kimberlite dykes and pipes located in the southern area that is diamond-bearing⁵. The Western part of the Africa plate moves at relatively slow rate values within 2.0–15 mm/year⁷. The eastern part is primarily underlain by Archaean and Lower Proterozoic rocks, while upper Proterozoic metasedimentary rocks dominate the north. The coastal plains formed mainly by Quaternary marine

and unconsolidated alluvial sediments. The plain was overlain by older Palaeozoic, with small Tertiary and Upper Cretaceous sedimentary rocks.² explained the faults mechanism that resulted in the 1983 northwest Guinea earthquake recorded in the study. Rocks in Guinea is affected by Rokelide Orogeny like the one in Sierra Leone, characterised by Archean and Pan-African structures⁵.

Compiled Earthquake Catalogue

A carefully compiled list of earthquake catalogues is a critical input in all seismic hazard assessments regardless of the approach adopted. The historical data sources used for this study was compiled¹ and included the first reported event as far back as 1795. The instrumental earthquakes were obtained from international agencies of the USGS online catalogue (<https://earthquake.usgs.gov/earthquakes/search/>), and the International Seismological Centre (ISC) (<http://www.isc.ac.uk/iscbulletin/search/catalogue/>), both were last accessed in December 2020, considering the events with moment magnitudes of $M_w \geq 4.0$, reported in the study region. The catalogue reported different magnitude scales, but the moment magnitude (M_w) scale adopted to unify the compiled catalogue directly represent a reliable scale that describes the size of an event. The study used the relations^{7,8} to convert various magnitudes to M_w using the Eq. (1-3) below,

$$M_w = 0.85M_b + 1.03 \text{ Value for } 3.5 \leq M_b \leq 6.2 \quad (1)$$

$$M_w = 0.67M_s + 2.07 \text{ Value for } 3.0 \leq M_s \leq 6.1 \quad (2)$$

$$M_w = 0.97M_L + 0.58 \text{ Value for } 3.0 \leq M_L \leq 6.0 \quad (3)$$

where M_L = local magnitude (M_L), M_s = surface magnitude, and m_b = body magnitude.

Since different catalogues reported the same events, duplicates were manually removed using the criteria⁹, which include events located within 10 km and recorded within a period of 2 minutes. For duplicate events, the order of priority is as follows: ISC earthquake catalogue followed by the USGS-NEIC earthquake catalogue, and finally¹. The complete catalogue was declustered to remove foreshocks and aftershocks, and seismic swarms, using an algorithm¹⁰, implemented¹¹. The declustered catalogue contained 27 events in the moment magnitude range $4 \leq M_w \leq 6.3$. The spatial and temporal distributions of the declustered catalogue (Fig. 2).

Figure 2. Distribution of declustered catalogue (a) Spatial distribution of earthquake epicentres; (b) temporal distribution of earthquake magnitudes for the period 1918-2018

Seismic hazard analyses

The seismic hazard was performed using a probabilistic framework method^{12,13} to estimate the hazard levels in this study region. The distribution of magnitude-frequency of 27 events in the harmonised catalogue from 1918 to 2018 duration shown in Figure 2. A catalogue completeness analysis method¹⁴ determines the compiled catalogue completeness with regards to the magnitude and time. The Stepp method depends on the assumption

that the magnitude sub-class representing a point process in time and follows a Poisson distribution. The unbiased mean rate of occurrence per unit time interval as shown in the expression,

$$\bar{\lambda} = \frac{1}{N} \sum_{i=1}^N \lambda_i \quad (\text{A4})$$

$$\sigma_{\lambda} = \sqrt{\bar{\lambda}/T} \quad (\text{A5})$$

where λ_i = rate of occurrence of events per unit time interval for each subclass magnitude, N = number of sub-class, σ_{λ} = standard deviation and T = time interval.

Table 1 and Figure 3 show the completeness analysis at which the catalogue is complete for $M_w \geq 4$ between 1918 and 2018. Thus, 27 events having event magnitude $M_w \geq 4.0$ were left on the compiled catalogue. The approach developed¹⁵ determined the completeness of the catalogue with respect to time. From Figure 4, the compiled catalogue is complete for $M_w > 4$.

Table 1. Catalogue completeness for different magnitude sub-classes

Magnitude sub-class	Period of Completeness period	Interval (years)
$3.0 \leq M_w < 3.4$	2018-1918	100
$3.5 \leq M_w \leq 3.9$	2018-1948	70
$4.0 \leq M_w \leq 4.4$	2018-1918	100
$4.5 \leq M_w \leq 4.9$	2018-1918	100
$5.0 \leq M_w \leq 5.9$	2018-1918	100
$6.0 \geq M_w$	2018-1918	100

Since information regarding the local faults for this study region is poorly documented, the determination of seismic hazard was defined on the seismicity and geological setting of the study area. Three seismic zones used to estimate the hazard levels for the ten sites are shown in (Fig. 5). Zone A represents the Palaeozoic craton, while zone B and zone C are characteristic of the Archaean and Lower Proterozoic rocks. Calculated recurrence parameters of b -values and lambda (λ) for each zone expressed exponential using Gutenberg-Richter distribution¹⁶,

$$\text{Log}_{10}(N) = a - bM \quad (\text{A6})$$

where N = number of events with magnitudes equal to, or greater than, M , a -value = activity rate which defines Gutenberg-Richter relation intercept at M equal zero.

The b -value indicates the relative number of large and small earthquakes and representing slope of the Gutenberg-Richter relation, $\lambda = b \ln(10)$.

Figure 3. Catalogue completeness periods

It is common to use a unique b -value for source zones in low-to-moderate seismicity due to limited recorded data^{17,18}. As a result, a uniform b -value was calculated and adopted for all the zones (Table 2) and Figure 4. The a -value calculated is provided in Table 2. The λ -parameter is known to vary significantly from the different zones within a given area. It was estimated differently for each zone by taking the average number of earthquakes for magnitude equal to or higher than the minimum magnitude ($M_{\min}$). The maximum-likelihood method¹¹ on a computer programme ZMAP estimated the recurrence parameters. The seismic hazard levels were estimated using a PSHA software, R-CRISIS Ver 20.0.0¹⁹. The seismic analysis is carried out on a grid with dimensions $0.5^\circ \times 0.5^\circ$.

Fig. 4. Frequency-Magnitude Distribution from 1818-2018 earthquake catalogue.

Table 2. Recurrent parameters for each zone

Zone	$M_{\min}$	$M_{\max}$	$b \pm \sigma b$	a	λ
A	4.0	6.8	0.70 ± 0.12	4.215	0.18
B	4.0	4.8			0.05
C	4.0	5.2			0.04

Many methods are available to assess the maximum credible magnitude, $M_{\max}$ ^{20,21}. Due to the lack of recorded data for this study region, the $M_{\max}$ was obtained from the largest observed magnitude M_{obs} in each zone by adding an arbitrary value of 0.5 as expressed by $M_{\max} = M_{\text{obs}} + 0.5$ ²¹. The catalogue spanning over 100 years, was complete for $4.0 \geq$. The maximum observed magnitude (M_{obs}) could be underestimated. However, other researchers have widely used this simple method in regions with limited data^{18,23,24}. The accuracy of the focal depths is generally poor in this study region owing to the limited available information. However, based on the seismic sources available for this study, the earthquake foci are within 0 to 15 km. Consequently, the hazard analyses were carried using the same value of 10 km for all zones. The ground-motion prediction equations (GMPEs) are essential in the definition of the ground motion model. Although regional attenuation relationships calibrated from local seismic data are preferred, these were not available for the study region owing to limited data, and in three zones, lack of recorded strong-ground motions. Consequently, three Ground motion prediction equations (GMPEs)²⁵⁻²⁷ developed on Eastern North America that is frequently used for a stable continental

region where the study region is applicable estimated the likely ground motion in this study. Three GMPEs were used for the hazard calculation by assigning the same weight for each of them, thereby representing confidence levels in the model.

Fig. 5. Seismic source zones for the study region

Seismic hazard calculations

The seismic hazard calculations^{12,13} in this study region were performed using the R-CRISIS software A probabilistic seismic hazard analyses software developed with support from II-UNAM, the Instituto de Ingeniería at UNAM, México¹⁹. The software is available for free on the R-CRCIS website upon request and was used extensively in the assessment. The analysis is carried out on 0.5-degree grids under the following conditions:

- Calculations were made for 0.5%, 2%, and 10% probability of exceedance in 50 years, corresponding to return 475, 2475 and 9975 years return periods, respectively.
- Minimum magnitude of $M_{\min} = 4.0$ was adopted, considered to cause engineering damage.

- Calculations were carried out to produce PGA in terms of hazard maps, hazard curve and seismic hazard curves

In Guinea West Africa, where information on faults is not available, the input parameter such as M_{max} values was assessed and considered in the hazard calculations. M_{max} was assessed by adding an arbitrary value of 0.5²².

6. Hazard results and Discussion

Figure 6 shows the hazard maps in terms of mean PGA for 475, 2475, and 9975 years return periods. The results show highest levels of seismic estimated are observed in zone A where the PGA are 0.08g, 0.27 g and 0.56 g at 475, 2475, and 9975 years return periods, respectively, for the city of Labé and Gaoual. Figure 7 plots the seismic hazard curves for ten selected cities within the Guinea region (PGA values listed in Table 3). For 475 years return period (Fig. 6a) corresponding to 10% probability of exceedance in 50 years, hazard levels close to 1.0 g are observed in 5 cities (Gaoual, Labé, Kindia, Kamar, and Manéah). A band of lower hazard levels of 0.02 g extends toward the east and northeast of the Archaean-lower Proterozoic area (zone B and C). The cities of Siguiri, Kankan, Nzérékoré and Kissidougou fall within this band. These four cities share a border with neighbouring countries (Sierra Leone, Liberia, and the Ivory Coast). At 2475 and 9975 years return periods, the hazard levels increasing, but the trend remains the same. Figure 7a shows the seismic hazard curve in terms of Peak spectral acceleration for the ten sites. The gap in (Fig. 7a) confirms the cities with higher levels of seismic hazards. Figure 7(b-d) show resulting spectral acceleration (SA) curves against periods for the ten selected sites at 475, 2475, and 9975 years return periods. The hazard levels of all the sites increase with higher return periods. Taken Labé as an example, the second-largest city in Guinea after the capital Conakry in terms of economic advantage, the spectral acceleration (SA) at 0.1 s, is 0.15 g, 0.42 and 0.84 g at 475, 2500 and 9975 years return periods, respectively.

Table 3. Peak ground acceleration (PGA) likely to be exceeded with probability of 10%, 2% and 0.5% corresponding to 475-year, 2475-year and 9975-year return periods, respectively for the selected sites within Guinea.

City	Latitude	Longitude	Probabilistic		
			PGA (g)		
			475 Years	2475 Years	9975 Years
Conakry	9.509	-13.712	0.054	0.190	0.441
Kankan	10.383	-9.300	0.023	0.074	0.174
Siguiri	11.416	-9.166	0.022	0.066	0.151
Nzérékoré	7.750	-8.816	0.019	0.077	0.196
Labé	11.316	-12.283	0.080	0.270	0.560
Kindia	10.049	-12.854	0.080	0.268	0.555
Manéah	9.7333	-13.416	0.078	0.263	0.552
Gauoal	11.750	-13.200	0.080	0.270	0.560
Kamsar	10.650	-14.616	0.072	0.244	0.518
Kissidougou	9.1833	-10.100	0.022	0.077	0.192

Figure 6. Seismic hazard maps at (a) 475-year (b) 2475-year (c) 9975-year, return periods.

Figure 7. (a) Seismic hazard curves for 10 major cities in Guinea. Seismic hazard curves 10 for selected cities within Guinea at (b) 475-year (c) 2475-years (d) 9975-year, return periods.

Conclusion

A PSHA of Guinea, West Africa, was performed based on a catalogue duration of 1918-2018 years, estimated to be complete for magnitude $M_w > 4$ from three catalogues of Ambraseys and Adams, ISC and USGS. The analysis is subject to a potential source of uncertainty.

The maximum credible magnitude ($M_{\max}$) determined based on the large observed earthquake magnitude in the region may be underestimated. No strong ground motion was available in this study region. Therefore, the attenuation relations adopted are based on numerical simulations. The compiled catalogue covered 100 years duration with few earthquakes and was used to estimate recurrence parameters which may introduce error in the analysis. Three Seismic source zones are proposed based on geology and seismicity due to lack of information on local faults. The study produces hazard maps for ten sites using a probabilistic approach. The results show that at 475, 2475 and 9975 years return periods, there are significant seismic hazards within the Conakry and five other cities close to the Gulf of Guinea –despite low to moderate levels of seismicity reported in the region. From this study, six out of ten cities selected (Gaoual, Labé, Kindia, Kamar, Manéah and Conakry) fall within the high hazard levels for the new seismic hazard maps. The hazard levels estimated are critical since the ten cities now seeing sizeable infrastructure development. Therefore, the seismic risk associated with an increase in population and the expansion of the regional infrastructure can be significant. Thus, to protect the local population and to sustain the region's economic development, it is critical to mitigating against such risks, which, from the engineering design view, can be achieved by designing and building new infrastructure using the seismic hazard maps proposed in this study.

Data availability

The dataset generated during and/or analysed during the current study are available from the corresponding author upon request.

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Conflict of interests

The author declares no competing interests.