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Seismic Risk Analysis for Large Dams in West Africa Region

Stephen Ayanfe Irinyemi, Domenico Lombardi, Syed Mohammed Ahmad

Department Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK

Email address:
stephen.irinyemi@postgrad.manchester.ac.uk (S. A. Irinyemi)

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Abstract: Dams are critical infrastructures, the failure of which would cause a catastrophic effect on a regional scale. West Africa has more than 150 large dams across the region, constructed in strategic locations which pose a potential risk for people and properties at the downstream paths. A method of seismic risk analysis for large dams within the West Africa region is discussed to evaluate the seismic hazard rating at the dam sites and the risk rating of its appurtenant structures. Although the study region is considered as a stable continental, two major earthquakes with casualty figures have been reported in Ghana and Guinea areas of the study basins in 1939 and 1983, respectively. This paper summarizes the procedures for analyses seismic risk and explain the seismic hazards of seventeen large dams selected within the study basins based mostly on the significance of each dam and location of earthquakes in and around the dam sites. The results show the values of peak ground acceleration (PGA) at dam sites ranges from 0.02 g to 0.45 g. A hazard map of PGA indicating preliminary analysis of dam structures was developed for the study basins. Based on the results of this analyses, 59% of the analysed dams identified as high-risk dams while the rest dams fall within the moderate-risk class. These dams require further analyses for their safety to protect the populace and the built environments along the downstream paths.

Keywords: Dam, Seismic Risk, Peak Ground Acceleration, West Africa Basins

1. Introduction

The seismic risk for large embankment dams of 15 m high or more from the foundation, and within 5 to 15 m whose reservoir capacity is more than 3 million cubic meters, were performed based on the data of ICOLD [1]. It assesses the seismic hazard at the dam site and the risk rating of dam and appurtenant structure differently. The method [2] estimates the total seismic rating by combining the two factors The analyses of the total risk for an existing and proposed dam structures depends on two factors: (1) the seismic hazard rating at the dam site (2) the risk rating of the dam and its accessory structures. The peak ground acceleration (PGA) estimated within the dam site represents seismic hazard for the dam structures. This study proposed a seismic zone map that estimates the seismic hazard within the dam sites. According to ICOLD [1], the risk rating associated with a dam structure generally depends on the capacity of reservoir, evacuation requirements, dam height, and downstream damage factors. A method [2] considered all the four listed factors to define the total seismic risk. The failure or loss of strength for embankment dams may be due to liquefaction or the dam itself. Method [1] explains safety about embankment dams due to earthquakes that involve loss of strength, instability of the dam, foundation materials or due to excessive deformations. Dam regulating bodies should ensure the safety of dam during seismic events and present minimum risk to people and properties within the dam vicinity.

Seismic activity in the study region has been at a relatively low level based on available recorded history. The first reported earthquake in Ghana was the 1615 with an estimated surface magnitude of 5.7 which caused damage along the coast and inland area [3]. On 22nd December 1983, the north-western Guinea experienced a damaging earthquake of 6.3 magnitude (M_w). The epicentre of earthquake was located in Gaoual, near the border with Guinea-Bissau. It resulted in approximately 10 km of surface rupture, which extensively damaged buildings, killing around 300 people and more 5,000 houses were destroyed [4, 5]. Evidence of dam damage by an earthquake has not been reported in the region. The 17 selected dams located in this study basins have shown moderate seismicity (Figure 1).

Seventen selected dams located in the Major basins of the West Coast and Niger River are studied. These dams have been designed to perform hydroelectric power generation and water supply, energy, irrigation, flood control and navigation and entirely constructed and fully operated (Table 1). The total area cover by the West Coast is 958,150 km^2, extended across 12 countries, from Senegal to the west and Nigeria in the east of this study basins. The Niger River has a drainage basin of 2,117,000 km^2. The source is taken from the forested mountainous plateau in central Guinea. It runs in a crescent through the border between Mali and Benin, discharging its source to the Gulf of Guinea in the Atlantic Ocean through Niger Delta in Nigeria. Seismic activities in Ghana part of the study region are being monitored by the National Digital Seismic Network Observatory (NDSO) beginning from 2012, established by the government of Ghana [6]. Nigeria established seismographic stations known as the Centre for Geodesy and Geodynamics (CGG), Toro, and became functional in 2008 to record events [7].

This study evaluates the seismic hazard and determines the total seismic risk of these seventeen selected dams within the West Africa region (Figure 1) and will be used to set dam safety priority and maintain the dam structures to avoid seismic failure.

Table 1. *Properties of selected dams.*

Dam name	Country	Basin	River	Height (m)	Type[a]	Function[b]	Completed date	Reser. Capacity (× 1000 m^3)
Akosombo	Ghana	WT. Coast	Volta	134	RCF	EN	1965	147,960,000
Asejire	Nigeria	WT. Coast	Osun	26	ERF	WS	1969	32,913
Banieya	Guinea	WT. Coast	Samou	30	ERF	EN	1969	223,000
Bakolori	Nigeria	N. River	Sokoto	48	ERF	IR	1978	450,000
Dadin Kowa	Nigeria	N. River	Kano	42	RCF	IR+WS+EN	1988	2,855,000
Garafiri	Guinea	WT. Coast	Konkouré	80	ERF	EN	1999	1,600,000
Goronyo	Nigeria	N. River	Rima	21	ERF	IR	1984	976,000
Ilauko	Benin	WT. Coast	Ilauko	22	GRV	WS	1979	23,500
Jibiya	Nigeria	N. River	Katsina	22	ERF	IR+WS	1990	142,000
Kale	Guinea	WT. Coast	Samou	20	GRV	EN	1963	14,000
Kiri	Nigeria	N. River	Gongola	20	ERF	IR	1982	615,000
Kpong	Ghana	WT. Coast	Volta	20	RCF	EN+IR	1982	200,000
Mt. Coffee	Liberia	WT. Coast	St. Paul	19	RCF	EN	1966	238,600
Nangbeto	Togo	WT. Coast	Mono	52	ERF	IR+EN	1987	1,710,000
Oyan	Nigeria	WT. Coast	Oyan	30	GRV	IR+WS+EN	1983	270,000
Souapiti	Guinea	WT. Coast	Konkouré	117	GRV	EN	2019	6,300,000
Weija	Ghana	WT. Coast	Densu	17	RCF	WS+IR	1978	139,000

[a]GRV: gravity, ERF: earthfill, RCF: rockfill. [b]WS: water supply, EN: energy, IR: irrigation WT. Coast: West Coast; N. River: Niger River.

2. Seismo-Tectonic Setting in the Study Basins

The neotectonics of West Coast and Niger River Basins of the study region show five main structural elements (Figure 2): (1) Akwapim Fault Zone (AFZ), which is considered as the main seismotectonics in Ghana within the West Coast basin trends through northeastwards direction from the West of Accra and subjected to different faulting systems. Report shown that faults occurred through the ancient line of thrust in the boundary of Ghana and Togo [8]. (2) The Coastal Boundary Fault (CBF) represents the northern boundary of basins during upper Jurassic era to recent age [8]. CBF strikes approximately north of 60^0-70^0 in the east from 3 to 5 km in the direction of the Coast, where several kilometres block down throws to the south [8]. (3) Romanche Fracture Zone (RFZ), which represents fault system that occurred offshore, is related to the opening of the Atlantic Ocean [9]. RFZ is about 6-11 km wide parallel to the Coast [9]. It is noted that the separation of Oceanic crust from the continental at the mid-Atlantic Ridge is represented by zone of inactive transform fault known as RFZ. (4) Saint Paul's Fracture Zone (StPFZ). The feature of StPFZ has been linked to the escarpment of the Liberia marginal plateau and the deep structural trend that merge the continental slope in the Côte d'Ivoire at the Western part of the Abidjan together with its alignment [10]. The microearthquakes reported in Ghana are attributed to the reactivation of faults along the RFZ along the intersection of CBF and AFZ [11]. (5) Ifewara-Zungeru fault trends north-northeast to the south-southwest directions from the southwestern part of Nigeria [12]. Ifewara zone forms major part of the Schist belts within the Southwestern. The Nigeria Basement Complex which is found in Nigeria is part of African Crystalline structure [13].

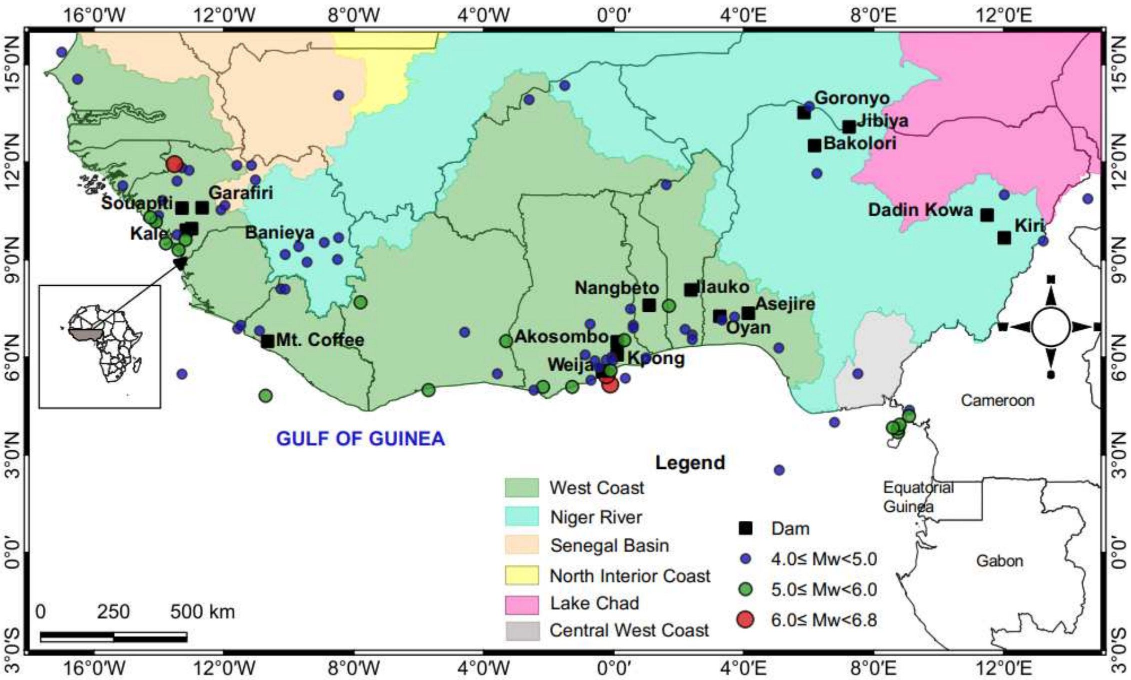

Figure 1. Location of dams and seismicity in the study basins.

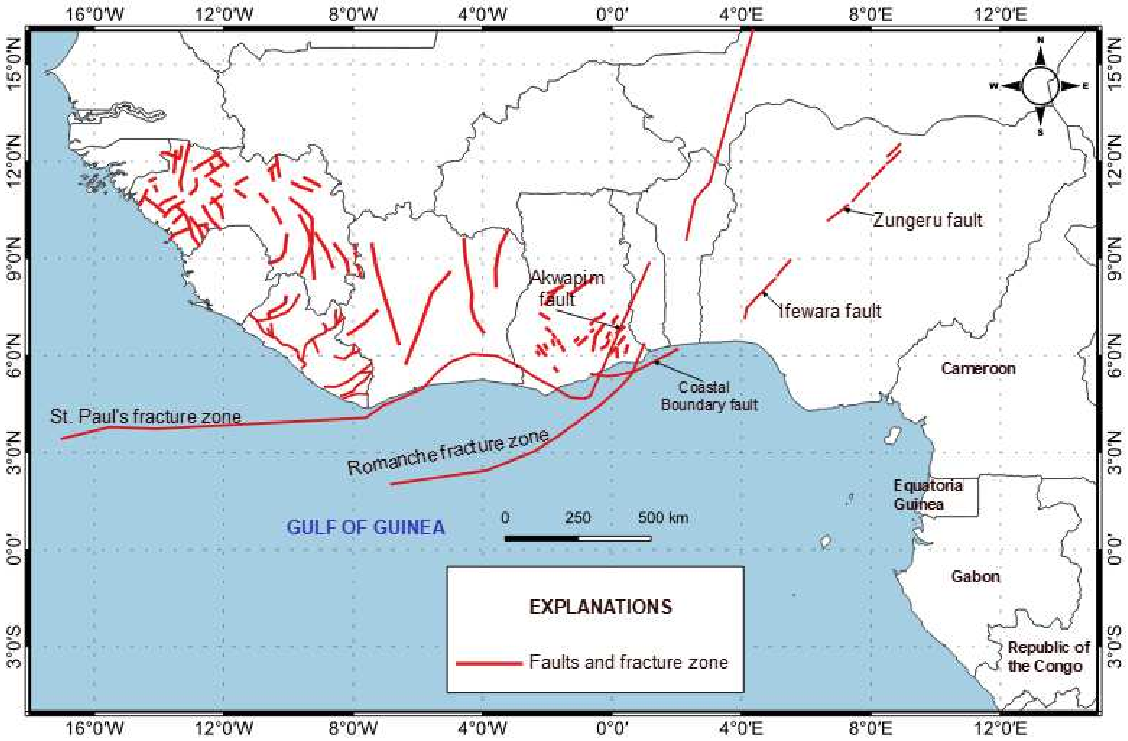

Figure 2. Main structural features for the study region.

3. Method of Analysis

A recommendation by [1] provides the simplified method to estimate the total risk factor associated with a specific dam. The method usually considers the calculation of both seismic hazard within the dam site and the risk rating of the dam structures separately. The method recommends four groups (low, moderate, high, and extreme) regardless of the type of dam into four to seismically assess the hazard at the dam site.

3.1. Seismic Hazards Analysis

Determination of seismic hazard involves identify all possible seismic sources likely to cause ground shaking within a particular dam site. Extensive studies about the dam sites used the geological features and seismicity to quantify the seismic activity rate in the basins. Fourteen seismic zones separated the total area covering the basins. The seismic source zones defined for the hazard assessment are shown in Figure 3. Available Earthquake data were sourced from earthquake catalogues [3, 9, 14], The United States Geological Survey (USGS) and International Seismological Centre (ISC).

The compiled catalogues reported events in different magnitude units: local-magnitude (M_L), surface-magnitude (M_S), body-magnitude (m_b) and duration-magnitude (M_d), which were unified into moment-magnitude (M_w) using the expression of Scordilis and Grünthal et al. [15, 16] in equations (1-4).

$$M_w = 0.85 m_b + 1.03, \text{ valid when } m_b = (3.5\text{- } 6.2) \quad (1)$$

$$M_w = 0.67 M_s + 2.07, \text{ valid when } M_s = (3.0\text{- } 6.1) \quad (2)$$

$$M_w = 0.85 M_L + 0.65, \text{ valid when } M_L = (3.0\text{- } 6.1) \quad (3)$$

$$M_w = 1.47 M_d - 1.49 \quad (4)$$

Throughout this study, considerations are given to seismic source zones and earthquakes reported within a radius of 300 km around the identified dam sites. The hazard analysis for this present study is based on the probabilistic framework [17, 18].

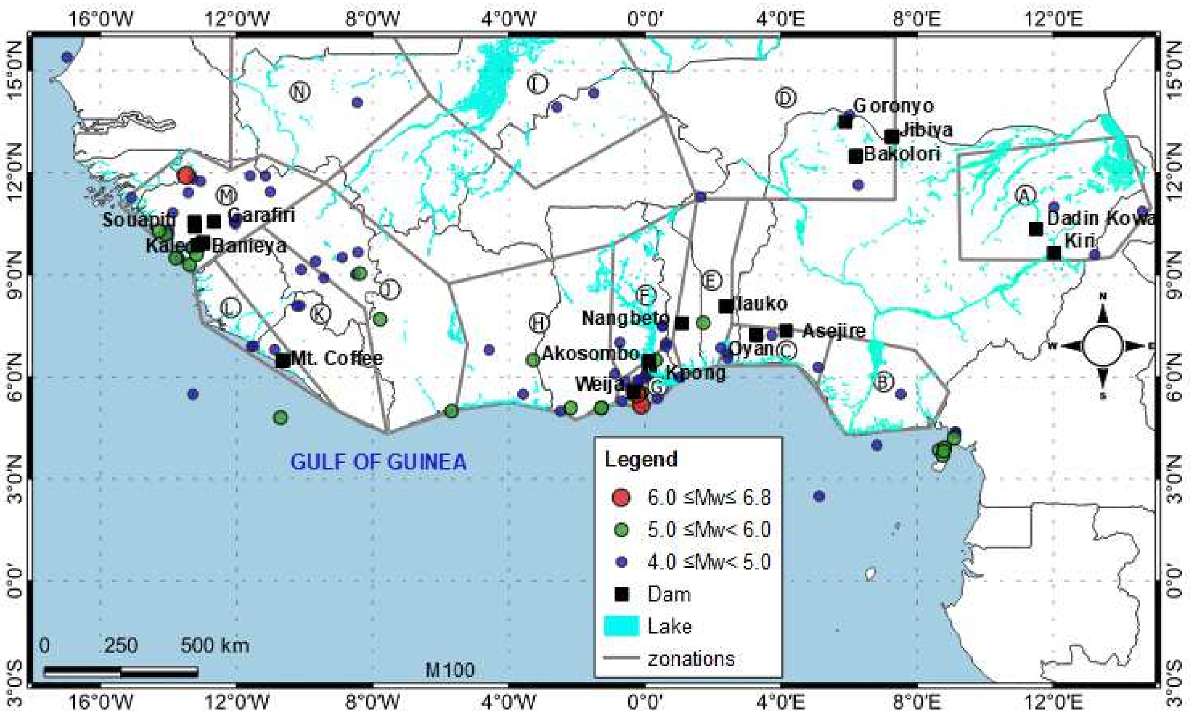

Figure 3. *Seismic source zones and earthquake within the basins from 1615 to 2018 years.*

Due to the lack of strong-motion records, various attenuation relationships were employed to estimate the maximum expected value of peak ground acceleration (PGA) acting at the identified dam sites. The determination of PGA values acting at the dam sites, considered five suitable Ground-motion prediction equations (GMPEs) [19-23].

Maximum credible magnitude (MCE) represents the deterministic event as the largest earthquake of event that occurred along an identified fault or defined from a tectonic framework [24] and was calculated based on the method of Gupta [24] due to limited seismic data, as given in Equation 5. The value of each PGA estimated for the identified dam sites (Table 3) represent the mean PGA values determined from five GMPEs. The recurrence parameters b-values and λ were calculated using the method of Wiemer and Wyss [25] implemented in a research tool known as ZMAP [26]. In the area with low-to-moderate seismicity activities, the same b-value can be estimated for all seismic source zones due to limited recorded data.

Table 2. *Seismicity parameters used in the study model.*

Zone		M_{min}	M_{max}	$b \pm \sigma b$	*a*	λ
Group -01	G	4.0	7.3	0.63± 0.13	3.916	0.156
Group -02	M	4.0	6.8	0.60± 0.11	3.370	0.165
	A	4.0	5.3			0.015
	B	4.0	5.3			0.010
	C	4.0	5.3			0.030
	D	4.0	4.7			0.015
	E	4.0	6.1			0.004
Group -03	F	4.0	4.8	1.12± 0.29	6.584	0.015
	H	4.0	6.2			0.020
	I	4.0	4.8			0.010
	N	4.0	4.8			0.010
	J	4.0	6.4			0.035
	K	4.0	5.3			0.020
	L	4.0	5.2			0.015

Table 3. *Calculated hazard class and rating of identified dams in the study region.*

Dam name	PGA[x]	Zone location	Hazard classification	Hazard rating
Akosombo	0.39	F	III	High
Asejire	0.12	C	II	Moderate
Banieya	0.24	M	II	Moderate
Bakolori	0.03	D	I	Low
Dadin Kowa	0.04	A	III	Low
Garafiri	0.24	M	II	Moderate
Goronyo	0.03	D	I	Low
Ilauko	0.06	E	I	Low
Jibiya	0.02	D	I	Low
Kale	0.24	M	II	Moderate
Kpong	0.44	G	III	High
Kiri	0.04	A	I	Low
Mt. Coffee	0.13	L	II	Moderate
Nangbeto	0.10	E	II	Moderate
Oyan	0.17	C	II	Moderate
Souapiti	0.24	M	II	Moderate
Weija	0.45	G	III	High

[x]PGA: Peak ground acceleration in g.

$$M_{max} = M_{obs}+0.5 \quad (5)$$

As a result, a unique b-value was obtained and classified into three groups and the a-value calculated are given Table 2. The λ-parameter varies from the different zones within a given area. It was estimated separately for each zone as the average of an annual number of magnitude events which are equal to or higher than the threshold magnitude ($M_{\min}$).

A PSHA program known as R-CRISIS [27] determined the seismic hazards. The seismic analysis conducted on 0.5^0 x 0.5^0 grids. The PGA results calculated in the study region varies based on the geological setting in the basins.

A graphing and data analysis program, namely QGIS 3.14, as given in Figure 4 generated the seismic hazard in this study basins. The map showing the equivalent PGA were developed by the probabilistic seismic hazard analyses for seventeen identified dams within the basins. PGA values (Table 3) were estimated using a probabilistic approach based on regional-characteristic maximum credible magnitude ($M_{\max}$) values for large dams of 10,000 years return period [28].

The most critical zone estimated based on this study is close to the Akwapim Fault zone in the Accra region of Ghana, where the maximum PGA values are evaluated. The 1939 M_w 6.4 Accra (Ghana) earthquake was also recorded in the area. This zone is significant for the three selected dams considered in Ghana part of this study. The dams are Akosombo, Kpong and Weija dams. The values of PGA obtained are within 0.39 g to 0.45 g for the dams. PGA values were estimated based on rock site conditions only. The most critical areas on the map (Figure 4) are those close to Guinea's Gulf in the Atlantic Ocean.

3.2. Seismic Risk Analysis

The approach used [2] recommendation, which provides different factors and various weighting points to classify seismic risk for a particular dam on account of the age of dam, type of dam, reservoir capacity, downstream risk potential, and vulnerability of the dam coupled with the seismic hazard at the dam site as expressed in Equation 6 [2, 29]. The Total risk factors (T_oRF) are classified as Extreme, high, moderate, or low.

$$T_oRF = [(C_aRF + H_iFR + A_gRF) + D_oHF] \text{ x } P_oDF \quad (6)$$

where C_aRF represent the capacity of risk factor (Table 4), H_iFR is the risk factor for the dam height (Table 4) with the effect of causing significant flooding due to high and large reservoir storage. A_gRF is the age of dam risk factor indicating that the older the dams, the more vulnerable the dams due to deterioration effect, inadequate maintenance, outdated construction method or reservoir siltation (Table 5). Finally, D_oHF means the downstream hazard factor, while P_oDF indicates the predicted damage factor [2]. Dam structure influence is represented by the addition of three factors (C_aRF + H_iFR + A_gRF). The downstream hazard factor (D_oHF):

$$D_oHF = E_vRF + D_oRI \quad (7)$$

E_vRF is the Evacuation requirements factor that mostly depends on the number of people at downstream path and is defined in Equation 7, as provided in Table 6. The downstream damage risk index (D_oRI) which usually depend on government, industrial, commercial, or private properties located in the downstream paths are listed in Table 6. The values of D_oHF are determined from a combined factor taken from detailed dam breaches, economic studies and or preferably inundation mapping [2]. The values of DHF requires timely checking whenever latest information becomes available or when the dam is modified, raised, or repaired [2]. The D_oHF can be replaced by the downstream hazard potential rating of N_aID (National Inventory Dams) when it is difficult to determine both E_vRF and D_oRI from detailed studies, as shown in Table 7.

Table 4. *Dam site risk factor [2].*

Risk -Factor	Weighting points assigned to the Total Risk Factor in parentheses			
	Extreme	High	Moderate	Low
C_aRF / (acre-feet)	Above 50,000 (6)	50,000-1000 (4)	1,000-100 (2)	Below 100 (0)
H_iFR / (feet)	Above 80 (6)	80-40 (4)	40-20 (2)	Below 20 (0)

Table 5. *Dam age rating factors [2].*

Risk Factor	<1900	1900-1925	1925-1950	1950-1975	1975-2000	>2000
A_gRF	6	5	4	3	2	1

Table 6. *Downstream hazard factors [2].*

Risk Factors	Weighting points assigned to the Total Risk Factor in parentheses			
	Extreme	**High**	**Moderate**	**Low**
E_vRF	Above 1000 (12)	1000-10 (8)	100-1 (4)	None (0)
D_oRI	Above High (12)	Moderate (8)	Low (4)	None (0)

Table 7. *Downstream hazard factors, According to N_aID [2].*

Downstream hazard potential rating (N_aID)	Loss of human lives	Economic, environmental, or lifeline losses	D_oHF
Low	When none expected	Low, limited to owner's property	2
Significant	When none expected	Yes	12
High	Likely, one or more expected	Yes, or probable but not strictly required	24

The vulnerability rating is a function of site-specific seismic assessment which is represented by the dam predicted damage factor (P_rDF) [30]. Each dam can be calculated using Equation 8. P_oDI in the Equation 8 is the predicted damage index (P_rDI) and obtained through dam vulnerability curves [30, 31].

$$P_rDF = 2.5 \times P_oDI \tag{8}$$

P_oDI, the potential damage index is primarily determined according to the type of dam and the seismic hazard at the dam site as expressed in terms of Earthquake Severity Index (ESI) [2]. The ESI is obtained from the scenario earthquake that produced the expected ground motion, as shown in Equation 9.

$$ESI = PGA \times (M_w - 4.5)^3 \tag{9}$$

where (PGA) is the peak ground acceleration (g) for each specific site, M_w is the earthquake moment magnitude. Both Figure 5 and Equation 10 show the relationship between P_oDI and ESI [32].

$$PDI = \begin{cases} 1.08\, exp\,(0.297\, log\,(ESI))\text{ Arch} \\ 1.28\, exp\,(0.296\, log\,(ESI))\text{ Rockfill} \\ 1.69\, exp\,(0.139\, log\,(ESI))\text{ Gravity} \\ 1.96\, exp\,(0.185\, log\,(ESI))\text{ Earthfill} \\ 2.77\, exp\,(0.356\, log\,(ESI))\text{ HF−tailings} \end{cases} \tag{10}$$

4. Seismic Risk Results and Discussions

The evaluation for the total risk factors for dam structures is done based on the seismic hazard rating at the dam site and the seismic risk rating of the dam structure. The [1] approach, which considers the dam structure component, downstream hazard factors and evacuation requirements estimated the risk analyses of selected dams within the basins. The approach provided four individual classes of risks to assess the Total Risk Factor (TRF), as demonstrated in Table 8. Following the Bureau's method, all the seventeen selected dams in the basins are analysed as both moderate and high-risk classes.

The dam's total risk estimated across the West Coast and Niger River are shown in Table 9. and Figure 6. The TRF values obtained are within 68 to 166. The result means no dam is classified as IV and I within the basins.

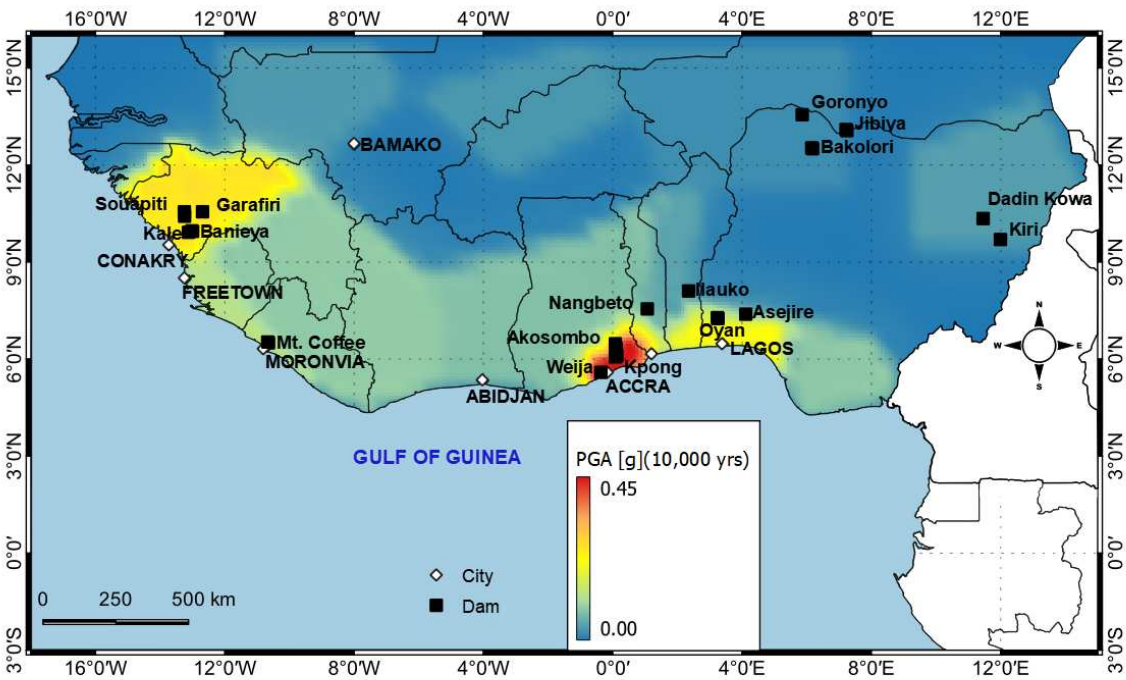

Figure 4. *Seismic hazard map using MCE at the dam site for 10,000-return period.*

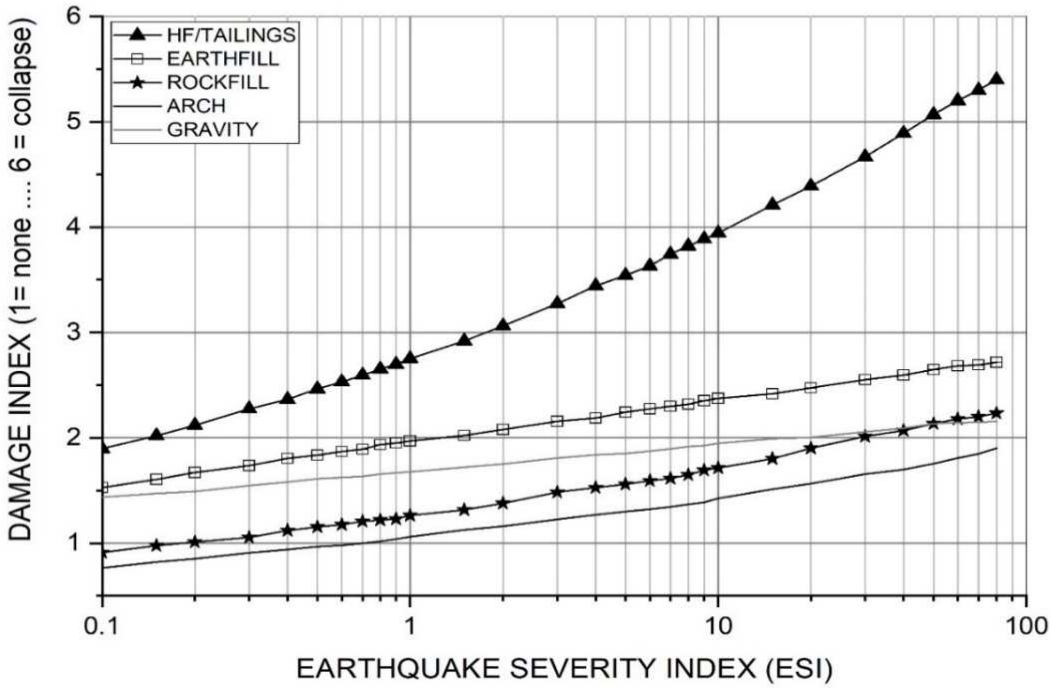

Figure 5. *Predicted Damage Index (P_rDI) [2].*

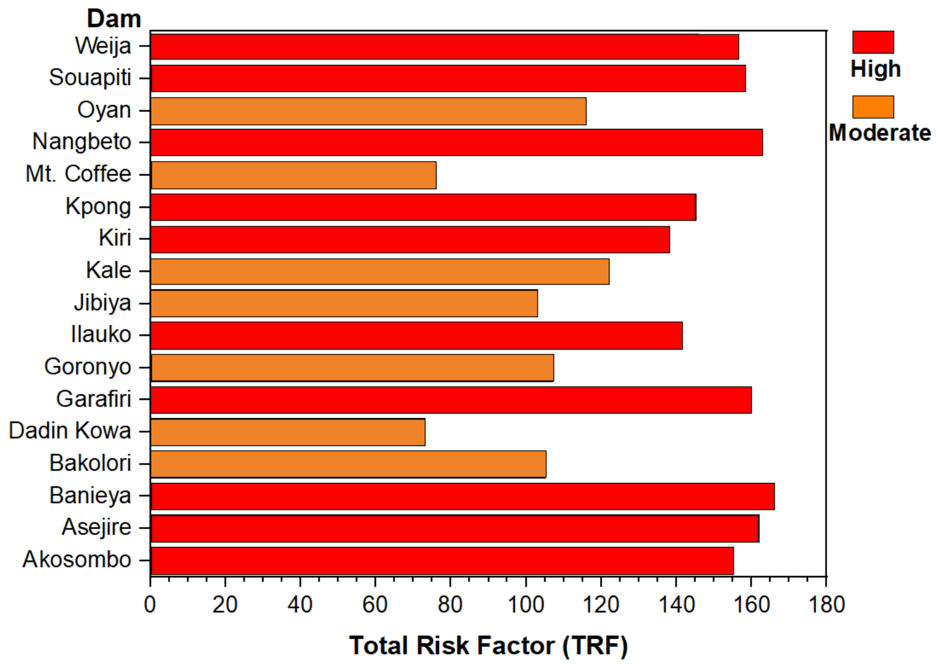

Figure 6. *Total Risk Factor for the selected dams.*

Table 8. *Dam risk class [2].*

Total Risk Factor (T_oRF)	Dam Risk Class (D_aRC)
From 2 to 25	I = low
From 25 to 125	II = moderate
From 125 to 250	III = high
Above 250	IV = extreme

Out of seventeen dams identified, seven are analysed as risk-class of II, and the rest ten dams fell into risk-class of III (Figure 6). This means 41% of selected dams shown risk-class of II, while others identified as risk-class of III (Table 9).

The results indicated that dams with the high-risk rating are seen on the West Coast Basin close to the Gulf of Guinea. Out of the seven dams with moderate-risk rating, one is located on the south-eastern, and three on northern parts of Niger River basin. They have completely located on the secondary branches of Niger river.

Table 9. *The estimated potential risk analyses for the selected dams.*

Dam name	Site component		Structure component			Downstream component		T_oRF	Risk class	Rating
	M_{max}	PGA	C_aRF	H_iRF	A_gRF	E_vRF	D_oRI			
Akosombo	6.9	0.39	6	6	3	12	12	155	III	High
Asejire	6.1	0.12	6	6	3	12	8	162	III	High
Banieya	6.8	0.24	6	6	3	8	8	166	III	High
Bakolori	4.7	0.04	6	6	2	12	12	98	II	Moderate
Dadin Kowa	5.2	0.03	6	6	2	12	12	68	II	Moderate
Garafiri	6.8	0.24	6	6	2	8	8	160	III	High
Goronyo	4.8	0.03	6	4	2	12	12	100	II	Moderate
Ilauko	6.1	0.06	4	4	2	12	12	132	III	High
Jibiya	4.8	0.02	6	4	2	12	12	96	II	Moderate
Kale	6.8	0.24	4	4	3	8	8	122	II	Moderate
Kiri	5.3	0.04	6	4	2	12	12	129	III	High
Kpong	6.9	0.44	6	4	2	12	12	145	III	High
Mt. Coffee	5.2	0.13	6	4	3	12	8	71	II	Moderate
Nangbeto	6.1	0.10	6	6	2	12	12	152	III	High
Oyan	4.8	0.17	6	6	2	12	8	108	II	Moderate
Souapiti	6.8	0.24	4	6	1	12	12	158	III	High
Weija	6.9	0.45	6	4	2	12	12	146	III	High

This study identified some large important dams in the basins that can be reanalysed using appropriate seismic parameters. Three dam structures in this study region with PGA values, e.g., Akosombo (0.39g), Nangbeto (0.10g) and Souapiti (0.24) dams provide electricity for more than one country and may affect people and properties located in the downstream paths when they damage or fail.

The Akosombo dam is a 134-m rock-fill dam that has a storage capacity of 147,960,000 × 1000 m^3. It is located in Akosombo town in south-eastern Ghana and about 75 km southeast of Accra on the Volta River. The construction started in 1961 and was completed in four years in 1965. The dam was designed for maximum water level of 84.73 m, and a minimum water level of 73.15 m. It generates energy for industry usage with an upgraded capacity of 1,020 megawatts in 2006 (https://en.wikipedia.org/wiki/Akosombo_Dam). The seismic hazard estimated for the Akosombo dam shows that the dam can be critical in the basins. The seismic hazard analysis produced a PGA value of 0.39 g with a maximum credible magnitude of 6.9 with a high-risk rating. Numerical analysis should be performed for the Akosombo dam to determine the dam stability.

Dadin Kowa and Asejire dams are located in Nigeria. The dams were estimated as hazard classes of II and III at PGA values of 0.03 g and 0.12 g, respectively (Table 3), and both dams having the same function in their locations as given in Table 1.

Weija Dam is a zoned earth-fill dam along Densu river in West Coast basin, located 18 km west from the state capital, Accra in Ghana. It has a 17 m from the riverbed. The reservoir capacity is 139,000 × 1000 m^3. The construction was completed in 1978. Its reservoir supplies large volume of water and provide irrigation services to Accra city and its environs. The dam is 43 years old but obviously cannot meet the latest seismic design standard. Thus, its seismic upgrade is needed since the estimated seismic risk is 146 and classified as a high-risk dam.

Banieya Dam is an earth-fill embankment dam on the Samou river, located 78 km north-east of Guinea capital, Conakry. The dam is 30 m high from riverbed and a storage capacity of 223,000 × 1000 m^3. Opening 51 years ago. It produces energy and supply water to the Kindia region in Guinea with 5.2 MW capacity. 0.24 g PGA value was estimated based on the seismic hazard analysis and an MCE of 6.8. The dam is a high-risk rating with the highest value of 166 within the basins. Stability analysis can be performed for Banieya dam, which is about 226 km from the epicentre of the 1983 M_w of 6.3 Guinea earthquake.

Nangbeto Dam is an earth- fill embankment dam on the Mono River located in Togo, about 148 km in the northeast of Lomé, Capital of Togo. The dam is 52 m high, and the construction was completed in 1987 with a reservoir capacity of 1,710,000 × 1000 m^3. It was designed to provides hydroelectric power (65.5 MW) to both Togo and Benin as well as creating fisheries and supplying water for the purpose of irrigation. Based on the seismic hazard estimated for this study, the dam PGA and MCE are 0.10 g and 6.1, respectively. It is classified as a high-risk rating of 152. This dam should be assessed and analysed seismically to avoid future failure.

5. Conclusions

For this study, seventeen selected dams located in the West Coast and Niger River Basins of West Africa were analysed to obtain their total seismic rating following the simplified method proposed by Bureau [2].

i. The ten selected dams have identified as high-risk class at the value range (129-166.0). The PGA values obtained vary within 0.04-0.45 g (low to high-risk classes). Two destructive earthquakes documented within the study basins are the 6.4 Mw 1939 Accra (Ghana) earthquake and the 6.3 Mw 1983 Guinea earthquake. These earthquakes may have influenced the seismic results.
ii. Proper criteria should be selected to determine seismic analysis parameters due to the study basins. According to the results obtained, seven dams are estimated as high-risk

class. Thus, these dams should be re-visited for inspection, analysis seismically and redesigned if necessary.

iii. Implementation of dams in West Africa under the program known as National Dam Safety Program for dams and their accessory structures should be encouraged. The result of seismic risk analyses shows that Akosombo dam is classified as a moderate-risk class and the dam was designed to produce electricity for Ghana and the neighboring countries. The dam is identified as the dam with the largest reservoir capacity in West Africa region. This dam should be prioritised since the risk rating is moderate which could be critical to the dam.

iv. Further dam site assessments should include seismotectonic regime, surface rupture identification, local site effects, and reliability analysis.

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