Seismic risk analysis for large dams in West Coast basin, southern Ghana

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Abstract Dams are parts of the critical infrastructure of any nation, the failure of which would have a high-risk potential on the people and properties within the dam vicinity. Ghana is one of the most seismically active regions in West Africa and has at least 5 large dams across the region, constructed in strategic locations. The area is characterised by low-to-moderate seismicity, yet historical events suggest that major earthquakes that are potentially damaging have occurred in the study basin. This paper summarises the method used to analyse seismic risk and discusses the seismic hazards of three large dams across the study basin based on the seismicity at the dam sites and their risk due to structural properties and the location of each dam. The peak ground acceleration (PGA) values for the dam sites estimated are within the range of (0.31 g and 0.52 g) for 10,000 years return period. The study shows that one large dam has a high-risk class in the basin. This dam should be inspected and analysed for its seismic safety and people's protection in the downstream paths.

Keywords Seismic risk analysis · Peak ground acceleration · Earthquake · Dam · Ghana

1 Introduction

Dams are critical infrastructure in that they play a significant role in the region's economic, agricultural, and industrial developments. Ghana, located in Western Africa, covers an area of 238,540 km². Of the total area, 4.8% (11,400 km²) can be classified as cultivated land. In general, Ghana can be divided into three basic drainage systems: the Volta River system, the southwestern river basins, and the coastal rivers. Out of the three studied dams, two are located on the River Volta system and globally considered the largest artificial lake by area in the world. The southwestern river system is deemed to be drained about one fifth of the total land area of Ghana. Seismic risk analyses for three large dams in southern Ghana with a wall height of more than 15 m were performed. A simplified procedure based on Bureau (2003) approach assessed the potentially most vulnerable of the three dams. According to the (ICOLD 1989) definition, dams with a wall high of 15 m or more and within 5–15 m of which reservoir capacity exceeding 1 million cubic meters is classified as large dams. The three selected dams (Table 1) are located in the Major basin of the West Coast. The total area covered by the West Coast is 1,436,820 km², extended across 12 countries, from Senegal to the west and Nigeria in the east of West Africa basins. ICOLD (2020) method evaluates the seismic hazard of a dam site and the dam and accessory structure's risk rating separately. However, Bureau (2003) illustrated a procedure that

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Table 1 Properties of dams considered for this study

	Dam	Basin	River	Height (m)	Type ^a	Function ^b	Completed date	Reservoir capacity (million m ³)
^a RF rockfill	Akosombo	W. Coast	Volta	134	RF	E	1965	147,960
^b WS water supply, E energy, I irrigation	Kpong	W. Coast	Volta	20	RF	E+I	1982	200
W. Coast: West Coast	Weija	W. Coast	Densu	17	RF	WS+I	1978	139

combines the two factors to define the dam structures' total seismic risk. The analyses of the total risk for dam structures depend on two factors: (1) the seismic hazard rating at the dam site and (2) the risk rating of the dam and its appurtenant structures.

The seismic hazard for the dam structures at various sites can be based on the peak ground acceleration (PGA). The values of PGAs obtained from the design earthquake produce the seismic loads. Dam type is an important parameter impacting the total risk factor (Bureau and Ballentine 2002; Tosun and Seyrek 2020). Seismic events in Ghana are monitored by the National Digital Seismic Network Observatory (NDSO) established by the government of Ghana. The database consists of natural and artificial seismic activities in 2012 (Ahulu and Danuor 2015). The selected dams located in this study region have moderate seismicity (Fig. 1). No accounts of damage to dams due to seismic activities have been observed within the study area. Ghana earthquakes of 1964 and 1969 were felt near the Akosombo dam and were subjected to induced seismicity (Musson 2014). This paper evaluates the seismic hazard and determines the total seismic risk of these selected dams within the Ghana region and will be used to retrofit and investigate dam structures to avoid structural failure.

2 Seismotectonic model of the dam sites in the basin

Figure 2 shows southern Ghana as part of continental West Africa and the equatorial Atlantic setting of the Gulf of Guinea and transform-fracture system. The first known seismic event in Ghana occurred as far back as 1615, where the fortress of Sao Jorge on the south coast of Ghana, in the present-day Elmina, collapsed (Ambraseys and Adams 1986). Major seismic events have been reported in the southern part of Ghana: In December 1636, M_w 5.7 earthquake

occurred along the north of Axim, where several buildings collapsed. On 10 July 1862, M_w 6.8 earthquake, which is still the most significant event reported in Ghana with an epicentre offshore, affected Accra's capital city. The earthquake of 1939, with an epicentre located about 25 km offshore and a moment magnitude of 6.4, has been the most destructive seismic event ever recorded in Ghana. The mechanism studied of the earthquake of 1939 by Yarwood and Doser (1990) reported that strike-slip fault that occurred parallel to the Ghana coastline might have triggered the earthquake. Two major active faults governed the neotectonics of the West Coast basin in Ghana. They are (1) the Akwapim fault which is the main structural feature in the basin, and (2) the Coastal boundary fault which is a normal fault along the coastal line that strikes approximately north 60°E – 70°E , at about 5 km from the coast.

The Volta passive margin basin in Ghana, Benin, and Burkina Faso formed the Dahomeyide orogen foreland (Affaton et al. 1980). Upper Proterozoic covers Ghana to Late Palaeozoic sediments, which contains Early Proterozoic Birrimian rocks (Fig. 2). Two transform-fracture systems found in the Gulf of Guinea are St. Paul's and Romanche fracture zones and are located close to the coast of Ghana. The seismicity of southern Ghana is associated with the fault systems of the Romanche and St. Paul's fracture zones.

Accra's earthquakes are mainly attributed to the reactivation of faults in the Romanche fracture zone, specifically the Coastal Boundary fault and Akwapim fault (Kutu 2013; Musson 2014; Ahulu et al. 2018). The Coastal Boundary fault became tectonically active in Jurassic times and is still active (Ahulu et al. 2018). The Akwapim fault zone comprises a system of faults trending northeasterly from just west of Accra, along an ancient line of thrust boundaries in the Dahomeyan belt. The presence of neotectonics normal faults along the Akwapim range could mean that the tectonic movement is still active, making faults from SW of the

Fig. 1 Location of dams and seismicity of the study region

Akwapim within the Weija area likely active (Amponsah et al. 2012; Ahulu et al. 2018).

3 Method of analysis

According to the (ICOLD 2010) approach, a dam's total risk is formulated and classified into four (low, moderate, high, and extreme). The hazard class of a dam site based on this method indicates the preliminary seismic evaluation requirements. Based on ICOLD (1989), the seismic risk (also known as "total risk") of dams depends on the structural and

social-economics components. The structural component is based mainly on the capacity of the reservoir and the height of the dam. The social-economics component depends on the evacuation requirements and potential downstream damage.

3.1 Seismic hazard analysis

For the seismic hazard analyses of the dam sites in the basin, all possible seismic sources that can produce significant ground shaking are identified. The study used geological features and seismicity to quantify the seismic activity rate. The historical and instrumental

Fig. 2 Geology and tectonic map of Southern part of Ghana. (Ahulu et al. 2018)

earthquake data were collected from earthquake catalogues (Ambraseys and Adams 1986; Amponsah et al. 2012; Musson 2014; the United States Geological Survey-National Earthquake Information Centre (USGS–NEIC); International Seismological Centre

(ISC)) considering events with moment magnitudes, $M_w \geq 4.0$, recorded within the study area. The compiled catalogues produced events in different magnitude units: local magnitude (M_L), surface magnitude (M_S), body magnitude (m_b), and duration magnitude

(M_d), which were homogenised to the moment magnitude (M_w) using the relationships by Scordilis (2006) and Grünthal et al. (2009) as expressed below:

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

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

$$M_w = 0.85M_L + 0.65 \text{ valid for } 3.0 \leq M_s \leq 6.1, \quad (3)$$

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

A catalogue completeness analysis method by Stepp (1972) determines the completeness of the compiled catalogue with respect to the magnitude and time. The Stepp method depends on the assumption that each magnitude subclass represented as a point process in time and the earthquake occurrence follows a Poisson distribution. The expression of the unbiased mean rate of occurrence of seismic events per unit time interval is given by

$$\bar{\lambda} = \frac{1}{N} \sum_{i=1}^N \lambda_i, \quad (5)$$

$$\sigma_\lambda = \sqrt{\bar{\lambda}/T}, \quad (6)$$

where λ_i is the rate of occurrence of events per unit time interval for each subclass of the event set, N is the number of subclass, σ_λ is the standard deviation, and T is the time interval.

Table 2 shows the completeness analysis at which the catalogue is complete for $M_w \geq 4$ between 1818 and 2018. Thus, all events with magnitude $M_w < 4.0$

Fig. 3 Completeness periods for different magnitude ranges using Stepp method (Stepp 1972)

were excluded from the compiled catalogue, with 35 events left in the working catalogue. The maximum curvature approach by Wiemer and Wyss (2000) determined the catalogue's completeness with respect to time. From Fig. 3 and Fig. 4, the compiled catalogue is complete for $M_w > 4$. The seismic hazard analysis used in the present study is based on the probabilistic framework proposed by Cornell (1968) and subsequently improved by McGuire (1995).

According to ICOLD 2010, the maximum credible earthquake (MCE) is a deterministic event, which is the largest reasonably conceivable earthquake that is possible along a recognised fault or within a geographically defined tectonic framework (Tosun 2020). The MCE is usually defined statistically with a typical return period of 10,000 years. Maximum design earthquake (MDE) is generally characterised by the level of motion equal to what is expected within the dam site from the occurrence of a deterministic evaluation of MCE (Tosun et al. 2007). Weiland (2012) specified that for large dams, the return period for the MDE ground parameters should be taken as 10,000 years based on a probabilistic seismic hazard analysis (PSHA).

The assessment of maximum expected PGA at the dam sites estimated using a probabilistic approach based on the regional-characteristic maximum credible magnitude (M_{max}). For each dam site, M_{max} is determined from earthquakes within a radius of 100 km. It is noted that the value of M_{max} is larger than the commonly used maximum credible

Table 2 Completeness periods for different magnitude classes

Magnitude class (M_w)	Completeness period	Completeness interval (years)
$3.0 \leq M_w < 3.5$	1918–2018	100
$3.5 \leq M_w < 4.0$	1818–2018	200
$4.0 \leq M_w < 4.5$	1818–2018	200
$4.5 \leq M_w < 5.0$	1718–2018	300
$5.0 \leq M_w < 5.5$	1718–2018	300
$5.5 \leq M_w < 6.0$	1615–2018	403
$6.0 \leq M_w \leq 6.8$	1718–2018	300

Fig. 4 Seismic zones and earthquakes in the study region

earthquake for 10,000 years return period (Singh et al. 2011). Due to the unavailability of strong-motion records, the study adopted five different attenuation relationships to calculate the expected peak ground acceleration (PGA) acting on the dam sites. They are Pezeshk et al. (2011), Tavakoli and Pezeshk (2005), Abrahamson et al. (2014), Campbell and Bozorgnia (2014), and Chiou and Youngs (2014). Their equations are shown in the appendix.

There are different approaches available to assess the maximum credible magnitude, $M_{\max}$ (Kijko and Graham 1998; Kijko 2004). However, due to the paucity of recorded data for this study region, $M_{\max}$ was

obtained from the largest observed magnitude M_{obs} in each zone by adding an arbitrary value of 0.5 as expressed by $M_{\max} = M_{\text{obs}} + 0.5$ (Gupta 2002). Thus,

Table 3 Hazard class and rating for the selected dams within the study region

Dam	Maximum PGA	Critical zone	Hazard class	Hazard rating
Akosombo	0.31	C	III	High
Kpong	0.41	B	III	High
Weija	0.52	B	III	High

other researchers have widely used this simple method in regions with limited data (Deif et al. 2011; Poggi et al. 2017; Ahulu et al. 2018). The PGA results are given in Table 3. It should note that each PGA value introduced for a dam site means the average weights of those obtained from five separate attenuation relationships.

According to Mavonga and Durrheim (2009), where information on the location of potential faults that can cause a scenario earthquake is poorly documented, a seismic hazard assessment should be based mainly on the available seismic and geological history of the study area. However, since no available literature correctly identifies this study region slip rates of faulting, fault geometries, and fault segmentation lengths, area source zones (Fig. 4) are used to define the likely seismic source zones. Three seismic zones used to estimate the seismic hazard of the dam sites are based on the geological and seismicity of the study region and in line with the seismic zones adopted by Alulu et al. (2018). Zone A is the offshore zone in the Gulf of Guinea representing the Jurassic era; both zone B (Accra region) and zone C (Ho region) are characteristic of the Neoproterozoic age. Calculated recurrence parameters of b -values and λ for each zone used the maximum-likelihood method implemented in the computer programme ZMAP (Wiemer 2001). It is common to use a unique b -value for all seismic source zones in low-to-moderate seismicity due to limited recorded data (Goitom et al. 2017; Ahulu et al. 2018). As a result, a uniform b -value was calculated and adopted for all the zones (Table 4 and Fig. 5). The a -value calculated is given in Table 4. 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 of an annual number of earthquakes with a magnitude equal to or higher than the minimum magnitude ($M_{\min}$). The seismic hazards were estimated using computer programme R-CRISIS Ver 20.0.0 (Ordaz and Salgado-Gálvez 2018), developed with support from II-UNAM, the Instituto de Ingeniería at UNAM, México. The seismic analysis is carried

Table 4 Recurrent parameters for each zone

Zone	$M_{\min}$	$M_{\max}$	$b \pm \sigma b$	a	λ
A	4.0	7.3	0.69 ± 0.13	4.314	0.045
B	4.0	5.4			0.070
C	4.0	5.5			0.015

Fig. 5 Frequency–magnitude distribution from 1818 to 2018 earthquake catalogue

out on a grid with dimensions $0.5^\circ \times 0.5^\circ$. The results indicate that PGA changes within a wide range based on the seismotectonic setting in the basin.

As a result of seismic hazard analyses performed for the dams within the basin, the maps showing the equivalent PGA were developed by a graphing and data analysis programme, namely, QGIS 3.18, as given in Fig. 6.

The map (Fig. 6) shows that the most critical area in the basin is close to the Akwapim Fault zone in the Accra region of Ghana because the greater acceleration values are seen on this part. In addition, the 1939 Mw 6.4 Accra (Ghana) earthquake was also recorded in the area. The three dams considered are Weija, Kpong, and Akosombo dams. The estimated PGA values range from 0.31 g to 0.52 g for the dams for 10,000 years return period. Figure 7 plots the seismic hazard curves and the 5%-damped elastic spectra for different return periods within the dam sites. The highest hazard is located close to the Weija dam site in the Accra region, where the PGA attains the maximum value of 0.11 g, 0.29 g, and 0.52 g for the return period of 475, 2475, and 10,000 years, respectively. Figure 8 summarises the results from disaggregation for the three dam sites at the return period of 475, 2475, and 10,000 years. From Fig. 8, the contributed hazard is dominated by earthquakes of Magnitude 4.6–5.1 at distances less than 25 km.

3.2 Bureau (2003) method

The approach provides various risk factors and weighting points to approximately assess the total risk

Fig. 6 Seismic hazard map of the study basin as based on maximum design earthquake which represents dam site for 10,000-year return period

factor (TRF) of any dam based on the type of dam, age, size, downstream risk, and vulnerability, which depend on the seismic hazard at the dam site given in Eq. (7). Four risk factors are weighed separately as low, moderate, high, or extreme.

$$\text{TRF} = [(\text{CRF} + \text{HFR} + \text{ARF}) + \text{DHF}] \times \text{PDF}. \quad (7)$$

where CRF is a risk factor of capacity (Table 5), HFR is a risk factor of height (Table 5), ARF is the age-rating factor (Table 6), DHF is the downstream hazard factor, and PDF is the predicted damage factor.

The sum of the first three factors (CRF + HFR + ARF) represented the dam structure influence. The downstream hazard factor (DHF) is based upon the human population and the property's value at risk, as given in Table 7.

DRI is the downstream damage risk index. The downstream damage risk index (DRI) is based on the value of private, commercial, industrial, or government properties in the potential flood path, given in Table 7. The DHF values should preferably be obtained from a combination of a clear dam breach, inundation mapping, and economic studies. When it

Fig. 7 **a** Seismic hazard curves. **b** Uniform hazard spectra for 475-year return period. **c** Uniform hazard spectra for 2475-year return period. **d** Uniform hazard spectra for 10,000-year return period

is not cost effective to determine both ERF and DRI from detailed studies, the DHF can be substituted by the downstream hazard potential rating of NID (National Inventory of Dams), as provided in Table 8. Table 9 shows the numbers of people and values of properties at risk at the three dam sites and is used to obtain the downstream hazard factor.

The predicted damage factor (PDF), the vulnerability rating, is a function of the site-dependent seismic hazard and similar dams' observed performance during earthquakes. The PDF can be defined by the predicted damage index (PDI) and calculated from the dam vulnerability curves provided by Bureau and Ballentine (2002) given in Eq. (8):

$$PDF = 2.5 \times PDI. \quad (8)$$

PDI depends on the dam type and the site seismic hazard and is expressed by the earthquake severity index (ESI). The seismic hazard represents the expected ground motion obtained at the dam site by the scenario earthquake considered, given in Eq. (9).

$$ESI = PGA \times (M_w - 4.5)^3 \quad (9)$$

where PGA is the peak ground acceleration in units of g for each site and M_w is the earthquake moment magnitude. PDI and ESI's relationship for different

Fig. 8 Disaggregation results for dam sites: (a) Akosombo, (b) Kpong, and (c) Weija for different return periods

Table 5 Definition of Dam site risk factor (Bureau 2003)

Risk factor	Contribution to total risk factor (Weighting points)			
	Extreme	High	Moderate	Low
CRF/(acre-feet)	> 50,000 (6)	50,000–1000 (4)	1000–100 (2)	< 100 (0)
HRF/(feet)	> 80 (6)	80–40 (4)	40–20 (2)	< 20 (0)

Table 6 Definition of dam age-rating factors (Bureau 2003)

Risk Factor	< 1900	1900–1925	1925–1950	1950–1975	1975–2000	> 2000
ARF	6	5	4	3	2	1

Table 7 Downstream hazard factors (Bureau, 2003)

Risk factors	Contribution to total risk factor (Weighting points)			
	Extreme	High	Moderate	Low
Evacuation requirements (persons) (ERF)	> 1000(12)	1000–10 (8)	100–1 (4)	None (0)
Downstream damage risk index (DRI)	> High (12)	Moderate (8)	Low (4)	None (0)

dam types obtained from geographical relationships are shown in Fig. 9 and Eq. (10) (Hariri-Ardebili and Nuss 2018).

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

4 Seismic risk analyses and discussions

The seismic risk for dam structures mainly depends on the dam site's seismic hazard rating and the risk rating of the dam structure and its appurtenant structure. Therefore, the Bureau (2003) method, which considers the dam type, age, size, downstream damage potential,

and evacuation requirements, was used to determine the basin's risk analyses. The method recommends four separate risk classes ranging from I (low risk) to IV (extreme risk) as based on the total risk factor (TRF) (Table 10). Following the Bureau's method, all the three dams in the basin are classified in both II and III risk classes, representing moderate- and high-risk rating.

The results of total risk analyses of the dam within the West Coast are summarised in Table 11. The values of the TRF range from 102.7 to 148.4. This indicates that there is no dam having risk classes IV and I in the basin.

Figure 6 shows a map of equivalent PGA values due to seismic hazard analyses performed for the three large dams within the study basin. The PGA values were estimated using a probabilistic approach based on the maximum credible earthquake values for large dams of the return period of 10,000 years.

Table 8 Definition of Downstream hazard factors, based on NID (Bureau 2003)

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

Table 9 Numbers of people and values of properties at risk at various dam sites

Dam	Human population	Values of property	Reference
Akosombo	18,142	3703	Ntiama-Baidu et al. (2017)
Kpong	18,142	3703	Ntiama-Baidu et al. (2017)
Weija	15,892	2670	GSS (2014). Owusu-Ansah et al. (2019)

Fig. 9 Predicted Damage Index (PDI) (Bureau, 2003)

Table 10 Definition of dam risk class (Bureau 2003)

Total risk factor (TRF)	Dam risk class (DRC)
2–25	I (low)
25–125	II (moderate)
125–250	III (high)
> 250	IV (extreme)

The PGA values estimated are based on rock site conditions only. The most critical areas on the map (Fig. 6) are those close to Guinea's Gulf in the Atlantic Ocean.

This study identified one large dam of the basin, which must be reanalysed by selecting appropriate seismic parameters. Rehabilitation design and construction measures, if necessary, may follow in

cases where the dams are found deficient seismically. The dam structures in this study region, e.g. the Weija dam with PGA of 0.52 g, provide water for the Greater Accra regions and affect people and properties located downstream paths when they damage or fail.

The Akosombo dam is the highest structure with 134 m from the riverbed and has the largest storage capacity of $147,960 \times 10^6 \text{ m}^3$ in the study basin. Its construction was started in 1961 and entirely completed in 1965. It was designed to produce electricity with an installed capacity of 1038 MW. Its TRF value is 107.4, and it is identified as risk class II, with a moderate risk rating. The dam is a rockfill embankment dam. This study's seismic hazard analyses will be subjected to a peak ground acceleration of 0.31 g with a maximum credible earthquake of 5.5.

Weija Dam is a zoned earth fill with rock dam, constructed in 1978. The dam length is 375 m, and the crest height is 17.07 m. It is located 18 km west of Accra city on the Densu River. Its primary purpose is to supply water to many parts of the Greater Accra Metropolitan Area. The dam has a reservoir area of 20.5 km^2 , with an average water level of 14.33 m. The design storage capacity of the dam is $113.5 \times 10^6 \text{ m}^3$. The maximum designed water level and storage capacities are 15.25 m and $143.115 \times 10^6 \text{ m}^3$, respectively. The dam identified as a risk class of III with the 2nd highest risk rating of 148.4 within the basin. The seismic hazard analyses performed throughout this study indicate that the Weija dam can be a critical dam within the basins. It will be subjected to a peak ground acceleration of 0.52 g with a maximum credible earthquake of 6.9.

Table 11 The results of potential risk analyses of dams for the selected dams

Dam	Site influence ^a		Structure influence ^b			Downstream influence ^c		TRF ^d	Risk class	Rating
	$M_{\max}^a$	PGA	CRF	HRF	ARF	ERF	DRI			
Akosombo	5.5	0.31	6	6	3	12	12	107.4	II	Moderate
Kpong	5.5	0.41	6	4	2	12	12	102.7	II	High
Weija	6.9	0.52	6	4	2	12	12	148.4	III	High

^a $M_{\max}$ maximum credible earthquake taken at 100 km radius of the dam site, *PGA* Peak ground acceleration in g

^b*CRF* capacity risk factor, *HRF* height risk factor, *ARF* age risk factor

^c*ERF* evacuation requirement factor, *DRI* downstream damage risk factor

^d*TRF* total risk factor

Kpong dam is a rockfill embankment dam on the lower Volta River, located 65 km northeast of Accra. It has a 20-m height from the riverbed and a reservoir capacity of $200 \times 106 \text{ m}^3$. Its construction started in 1977 and was entirely completed in 1982. It was designed to generate 160 MW of electricity and to provide irrigation service to the host environment. Therefore, it will be subjected to a high PGA value (0.41 g) with a maximum credible earthquake of 5.5.

5 Conclusions

For dams with a wall high from 17 to 134 m in the West Coast Basin of Ghana, the seismic hazard and risk rating on three large dams were performed based on the Bureau (2003) methodology. As a result, the following results have been concluded:

- i. The three selected dams have shown moderate- to high-risk classes at the value range (102.7–148.4). The PGA values range from 0.31 g to 0.52 g (high classes). In this study, one destructive earthquake reported within the last 100 years is the 6.4 M_w 1939 Accra (Ghana) earthquake. This earthquake may have influenced the seismic results. Therefore, dam implementation in Ghana by the National Dam Safety Program for dams and their appurtenant structures is encouraged.
- ii. The three dams identified in the study region are old, and their age rise from 38 to 56 years: therefore, these dams should be inspected, analysed seismically, and redesigned if necessary.
- iii. Akosombo dam is identified as a risk class of II with the large reservoir on the main river and still under operation. Prioritise dams with a moderate to high-risk rating that provide electricity for more than one country in the study basin.
- iv. A detailed assessment for the three dams in the future should include stability, reliability, and dynamic analyses to determine the possible dam failures.

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Availability of data and material Data sources for our assessment include that of the International Seismological Centre (ISC). The ISC catalogue, was searched through <http://www.isc.ac.uk/iscbulletin/search/catalogue/>, (last accessed October 2020), and the United States Geological Survey -National Earthquake Information Centre (USGS – NEIC) (<https://earthquake.usgs.gov/earthquakes/search/>) (last accessed October 2020).

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Declarations

Conflict of interest The authors declare that he has no conflict of interest.

Appendix A:

1. Pezeshk et al. (2011):

$$\begin{aligned} \log(\bar{Y}) &= c_1 + c_2 M_w + c_3 M_w^2 + (c_4 + c_5 M_w) \\ &\times \min \{ \log(R), \log(70) \} + (c_6 + c_7 M_w) + (c_6 + c_7 M_w) \\ &\times \max \left[\min \left\{ \log \left(\frac{R}{70} \right), \log(140/70) \right\}, 0 \right] + (c_8 + c_9 M_w) \\ &\times \max \{ \log(R/140), 0 \} + c_{10} R \end{aligned} \quad (\text{A.1})$$

where $(\bar{Y})$ is the median value of PGA or PSA in g, R is the distance computed as

$$R = \sqrt{R_{rup}^2 + c_{11}^2} \quad (\text{A.2})$$

where R_{rup} is the closest distance to fault rupture in km and c_1 to c_{11} are constants as reported by Pezeshk et al. (2011). Note that $\log(140/70)$ is the geometric spreading, $Z(R)$, used for Eastern North America (ENA). The value of 70 is equal to the hybrid empirical method prediction as reported by Pezeshk et al. (2011).

2. Tavakoli and Pezeshk (2005):

$$\ln(Y) = f_1 M_w + f_2 R_{rup} + f_3 (M_w, R_{rup}) \quad (\text{A.2})$$

$$R = \sqrt{R_{rup}^2 + (C_5 \exp[C_6 M_w + C_7 (8.5 - M_w)^{2.5}])^2} \quad (\text{A.4})$$

where Y is the median value of PGA or PSA in (g), M_w is the moment magnitude, R_{rup} is the rupture and define the distance to the fault rupture in (km). f_1 to f_3 are frequencies (Hz), while and c_5 to c_7 are constants as reported by Tvakoli and Pezeshk (2005).

3. Abrahamson et al. (2014)

$$\begin{aligned} \ln Sa(g) = & f_1(M, R_{rup}) + f_{RV} f_7(M) + f_N f_8(M) + f_{AS} f_{11}(CR_{jb}) \\ & + f_5(\widehat{Sa}_{1180} V_{s30}) + f_{HW} f_4(R_{jb}, R_{rup}, R_x, R_{y0}, W, dip, Z_{TOR}, M) + f_6(Z_{TOR}) \\ & + f_{10}(Z_{1.0}, V_{s30}) + Regional + (V_{s30}, R_{rup}) \end{aligned} \quad (\text{A.5})$$

where R_{rup} =rupture distance in (km), f_{RV} =flag for reverse faulting earthquakes, f_N =flag for normal faulting earthquakes, f_{AS} =flag for after-shocks, CR_{jb} =centroid of R_{jb} , $\widehat{Sa}_{1180}$ =median peak spectral acceleration (g) for $V_{s30} = 1.180$ m/s, V_{s30} =Shear-wave velocity over the top 30 m (m/s), f_{HW} =fag for hanging wall sites, R_{jb} =closest horizontal distance to the surface projection of the rupture (km), R_x =horizontal distance from the top edge of the rupture, measured perpendicular to the fault strike (km), R_{y0} =horizontal distance off the end of the rupture measured parallel to strike (km), W =down-dip rupture width (km), Dip =fault dip degrees, Z_{TOR} =depth to top of rupture (km), M =moment magnitude, and $Z_{1.0}$ =depth to $V_s = 1.0$ km/s at the site (m).

4. Campbell and Bozorgnia (2014):

$$\ln(Y) = \begin{cases} f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} + f_{hyp} + f_{dip} + f_{atm}, & \text{otherwise} \\ \ln PGA; & PSA < PGA \text{ and } T < 0.25 \end{cases} \quad (\text{A.6})$$

5. Chiou and Youngs (2014):

$$\begin{aligned} \ln(y_{refij}) = & c_1 + \left\{ c_{1a} + \frac{c_{1a}}{\cosh(2 \cdot \max(M_i - 4.5, 0))} \right\} F_{RVi} + \left\{ c_{1b} + \frac{c_{1d}}{\cosh(2 \cdot \max(M_i - 4.5, 0))} \right\} F_{NMI} \\ & + \left\{ c_7 + \frac{c_{7b}}{\cosh(2 \cdot \max(M_i - 4.5, 0))} \right\} \Delta Z_{TORi} + \left\{ c_{11} + \frac{c_{11b}}{\cosh(2 \cdot \max(M_i - 4.5, 0))} \right\} (\cos \delta_i)^2 + c_2 + (M_i - 6) + \frac{c_2 - c_3}{c_n} \ln(e^{c_n(c_M - M_i)}) \\ & + c_4 \ln(R_{RUPij} + c_5 \cosh(c_6 \cdot \max(M_i - c_{HM}, 0))) + (c_{4a} - c_4) \ln(\sqrt{R_{RUPij}^2 + c_{RB}^2}) \\ & + c_8 \min(\frac{\max(M_i - 40, 0)}{30}, 0) \\ & + \left\{ c_{71} + \frac{c_{72}}{\cosh(\max(M_i - c_{73}, 0))} \right\} R_{RUPij} \min(\frac{\max(M_i - 5.5, 0)}{0.8}) e^{c_{8a}(M_i - c_{8b}) \Delta DPP_{ij}} \\ & + c_9 F_{HWij} \cos \delta_i \left\{ c_{9a} + (1 - c_{9a}) \tanh(\frac{R_{Xij}}{c_{9b}}) \right\} \left\{ 1 - \left(\frac{\sqrt{R_{RUPij}^2 + c_{RB}^2}}{R_{RUPij} + 1} \right) \right\} \end{aligned} \quad (\text{A.7})$$

where M_i = Moment magnitude for earthquake i ; F_{Rvi} = Reverse-faulting flag: 1 for $30^\circ \leq \lambda \leq 150^\circ$ (combined reverse and reverse oblique), 0 otherwise; and λ is the rake angle. F_{Nmi} = normal faulting flag: 1 for $-120^\circ \leq \lambda \leq -60^\circ$ (excludes normal-oblique), 0 otherwise, $\Delta Z_{TORi} = Z_{TOR}$ of centred on the M -dependent average Z_{TOR} (km), δ_i = Fault dip angle, R_{RUPij} = Closest distance to the ruptured plane (km), $\Delta DPP_{ij} = DPP$ centred on the site- and earthquake-specific average DPP , DPP = Direct point param c_{4a} eter for directivity effect. R_{Xij} = Site coordinate measured perpendicular to the fault strike from the fault line, with the down-dip direction being positive (km). c_1 to c_{11} , c_{HM} , c_n , c_M , c_{RB} , $c_{\gamma 1}$, c_{1a} , c_{1b} , c_{7b} , c_{8a} , c_{9a} , c_{9b} , and c_{11b} are constant and are other variations reported by Chiou and Youngs (2014).

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