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
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 trigged 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 $60^\circ$E–70$^\circ$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

### Table 1 Properties of dams considered for this study

| Dam      | Basin   | River | Height (m) | Type | Function | Completed date | Reservoir capacity (million m$^3$) |
|----------|---------|-------|------------|------|----------|----------------|----------------------------------|
| Akosombo | W. Coast| Volta | 134        | RF   | E        | 1965           | 147,960                          |
| Kpong    | W. Coast| Volta | 20         | RF   | E + I    | 1982           | 200                              |
| Weija    | W. Coast| Densu | 17         | RF   | WS + I   | 1978           | 139                              |
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
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:

\[ M_w = 0.85m_b + 1.03 \text{ valid for } 3.5 \leq m_b \leq 6.2, \]  
\[ M_w = 0.67M_s + 2.07 \text{ valid for } 3.0 \leq M_s \leq 6.1, \]  
\[ M_w = 0.85M_L + 0.65 \text{ valid for } 3.0 \leq M_s \leq 6.1, \]  
\[ M_w = 1.47M_d - 1.49. \]

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

\[ \bar{\lambda} = \frac{1}{N} \sum_{i=1}^{N} \lambda_i, \]  
\[ \sigma_{\lambda} = \sqrt{\frac{\lambda}{T}}, \]

where \( \lambda_i \) is the rate of occurrence of events per unit time interval for each subclass of the event set, \( N \) is the number of subclass, \( \sigma_{\lambda} \) 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 \( M_w < 4.0 \) 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

| 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                           |
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, $M_{\text{max}}$ (Kijko and Graham 1998; Kijko 2004). However, due to the paucity of recorded data for this study region, $M_{\text{max}}$ was obtained from the largest observed magnitude $M_{\text{obs}}$ in each zone by adding an arbitrary value of 0.5 as expressed by $M_{\text{max}}=M_{\text{obs}}+0.5$ (Gupta 2002). Thus,

| 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          |

Fig. 4 Seismic zones and earthquakes in the study region
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 lambda ($\lambda$) 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 $\lambda$-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 ($M_{\text{min}}$). 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 out on a grid with dimensions $0.5^0 \times 0.5^0$. 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 $M_w$ 6.4 Accra (Ghana) earthquake was also recorded in the area. The three dams considered are Weija, Kpong, and Akosombo. 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.

### Table 4 Recurrent parameters for each zone

| Zone | $M_{\text{min}}$ | $M_{\text{max}}$ | $b \pm \sigma_b$ | $a$ | $\lambda$ |
|------|------------------|------------------|------------------|-----|----------|
| A    | 4.0              | 7.3              | $0.69 \pm 0.13$  | 4.314 | 0.045    |
| B    | 4.0              | 5.4              | $0.070$          |      |          |
| C    | 4.0              | 5.5              | 0.015            |      |          |

3.2 Bureau (2003) method

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

\[
TRF = [(CRF + HFR + ARF) + DHF] \times PDF. 
\]  

(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
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):

$$PDF = 2.5 \times PDI.$$  \hspace{1cm} (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).

$$ESI = PGA \times (M_w - 4.5)^3.$$  \hspace{1cm} (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)  |
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 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) |
|--------------|-----------------------------------------------------|
| 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) |

### 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               | Ntiamoa-Baidu et al. (2017)             |
| Kpong   | 18,142          | 3703               | Ntiamoa-Baidu et al. (2017)             |
| Weija  | 15,892          | 2670               | GSS (2014). Owusu-Ansah et al. (2019)   |
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 $147,960 \times 10^6$ 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 $113.5 \times 10^6$ m$^3$. The maximum designed water level and storage capacities are 15.25 m and $143.115 \times 10^6$ 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.

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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 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 |
|-------|---------------------|--------------------------|---------------------------|---------|------------|--------|
|       | $M_{\text{max}}$ $^a$ | PGA                      | CRF HRF ARF               | ERF DRI |            |        |
| Akosombo | 5.5                 | 0.31                     | 6 6 3                     | 12 12   | 107.4      | II     |
| Kpong  | 5.5                 | 0.41                     | 6 4 2                     | 12 12   | 102.7      | II     |
| Weija  | 6.9                 | 0.52                     | 6 4 2                     | 12 12   | 148.4      | III    |

$^a$ $M_{\text{max}}$ 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 × 10^6 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 Mw 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):

$$\log (\bar{Y}) = c_1 + c_2 M_w + c_3 M_w^2 + (c_4 + c_5 M_w) \times \min \{\log (R), \log (70)\} + (c_6 + c_7 M_w) \times \max \{\min \{\log (R/70), \log (140/70)\}, 0\} + (c_8 + c_9 M_w) \times \max \{\log (R/140), 0\} + c_{10} R$$

where $\bar{Y}$ is the median value of PGA or PSA in g, $R$ is the distance computed as
\[ R = \sqrt{R_{rup}^2 + c_{11}^2} \]  
(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):

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

\[
R = \sqrt{R_{rup}^2 + (C_2 \exp(C_6 M_w + C_7 (8.5 - M_w)^{2.3}))^2} \quad (A.4)
\]

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 Tavakoli and Pezeshk (2005).

3. Abrahamson et al. (2014)

\[
\ln(Y_{rup}) = c_1 + \left\{ c_{1a} + \frac{c_{1b}}{\cosh(2 \max(M_w - 4.5, 0))} \right\} F_{RV} + \left\{ c_{1b} + \frac{c_{1f}}{\cosh(2 \max(M_w - 4.5, 0))} \right\} F_{NMj}
+ \left\{ c_7 + \frac{c_{11}}{\cosh(2 \max(M_w - 4.5, 0))} \right\} \Delta Z_{TORi} + \left\{ c_1 + \frac{c_{11}}{\cosh(2 \max(M_w - 4.5, 0))} \right\} (\cos \delta_i)^2 + c_2 + (M_i - 6) + \frac{c_2 - c_1}{c_8} \ln \left( e^\theta (c_8^2 - M_i) \right) + c_4 \min\left( \frac{\max(M_i - 40.0, 0)}{30}, 0 \right) + c_5 F_{RIP0j} \frac{\max(M_w - 5.5, 0)}{0.8} e^{c_9 \theta - c_{10} \theta_{hyp}} j + c_4 F_{常委会} \cos \left( c_{1a} + (1 - c_{1a}) \tan \theta \right) \frac{R_{RX}}{c_{10}} \left\{ 1 - \frac{\sqrt{R_{RIP0j}^2 + c_{2b}^2}}{R_{RIP0j} + 1} \right\} \quad (A.7)
\]

\[
\ln(\text{PGA}) = f_1 (M, R_{rup}) + f_2 (M, R_{rup}) + f_3 (M, R_{rup}) + f_4 f_5 (CR_{ja}) + f_6 \left( \widehat{SA}_{1180} V_{sa} \right) + f_7 \left( \widehat{SA}_{1180} V_{sa} \right) + f_8 \left( \text{Regional} + (V_{sa}, R_{rup}) \right) \quad (A.5)
\]

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 aftershocks, \( CR_{ja} \) = centroid of \( R_{ja} \), \( \widehat{SA}_{1180} \) = median peak spectral acceleration (g) for \( V_{sa} = 1.180 \) m/s, \( V_{sa} \) = Shear-wave velocity over the top 30 m (m/s), \( f_{HW} \) = flag for hanging wall sites, \( R_{ja} \) = closest horizontal distance to the surface projection of the rupture (km), \( R_i \) = horizontal distance from the top edge of the rupture, measured perpendicular to the fault strike (km), \( R_{jo} \) = 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):

\[ \ln(Y) = \begin{cases} f_{\text{PGA}} + f_{\text{SN}} + f_{\text{AS}} + f_{\text{SN}} + f_{\text{AS}} + f_{\text{SN}} + f_{\text{AS}}, & \text{otherwise} \\ \ln(\text{PGA}) = \text{PGA} < 0.25 \end{cases} \quad (A.6) \]

5. Chiou and Youngs (2014):
where $M_i =$ Moment magnitude for earthquake $i$; $F_{RVi} =$ Reverse-faulting flag: 1 for $30° \leq \lambda \leq 150°$ (combined reverse and reverse oblique), 0 otherwise; and $\lambda$ is the rake angle. $F_{NMi} =$ normal faulting flag: 1 for $-120° \leq \lambda \leq -60°$ (excludes normal-oblique), 0 otherwise. $\Delta Z_{TORi} = Z_{TORi}$ of centred on the $M$-dependent average $Z_{TOR}$ (km), $\delta_i =$ 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 $c_{40}$ et 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 $c_{11}$, $c_{HM}$, $c_{M}$, $c_{RB}$, $c_{g1}$, $c_{1av}$, $c_{1b}$, $c_{7a}$, $c_{9a}$, $c_{9b}$, and $c_{11b}$ are constant and are other variations reported by Chiou and Youngs (2014).

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**References**

Abrahamson NA, Silva WJ, Kamai R (2014) Summary of the ASK14 ground motion relation for active crustal regions. Earthq Spectra 30(3):1025–1055. https://doi.org/10.1193/070913EQS198M

Affaton P, Sougy J, Trompette R (1980) The tectono-stratigraphic relationships between the upper Precambrian and lower Paleozoic Volta Basin and the pan-african Dahomeyide orogenic belt (West Africa). Am J Sci 280(3):224–248. https://doi.org/10.2475/ajs.280.3.224

Ahulu ST, Danuor ST, Asiedu DK (2018) Probabilistic seismic hazard assessment of southern part of Ghana. J Seismol 22:539–557. https://doi.org/10.1007/s10950-017-9721-x

Ahulu S, Danuor SK (2015) Ghana’s experience in the establishment of a national digital seismic network observatory. J Seismollog 19(3):667–683. https://doi.org/10.1007/s10950-015-9846-z

Ambraseys NN, Adams RD (1986) Seismicity of West Africa. Ann Geophys 4(B6):679–702

Amponsah P, Leydecker G, Muff R (2012) Earthquake catalogue of Ghana for the time period 1615–2003 with special reference to the tectono-structural evolution of southeast Ghana. J Afr Earth Sci 75:1–13. https://doi.org/10.1016/j.jafrearsci.2012.07.002

Bureau GJ (2003) Dams and appurtenant facilities in earthquake engineering handbook. Edited by Chenh WF, Scawthorn C, CRS Press, Bora Raton, pp 26.1–26.47

Bureau GJ, Ballentine GD (2002) A comprehensive seismic vulnerability and loss assessment of the State of South Carolina using HAZUS. Part VI. Dam inventory and vulnerability assessment methodology. 7th National Conference on Earthquake Engineering, July 21–25, Boston, Earthquake Engineering Research Institute, Oakland, CA

Campbell KW, Bozorgnia Y (2014) NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% Damped Linear Acceleration Response Spectra. Earthq Spectra 30(3):1087–1114. https://doi.org/10.1109/062913EQS175M

Chiou BSJ, Youngs RR (2014) Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. Earthq Spectra 30(3):1117–1153. https://doi.org/10.1193/072813EQS219M

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 58(5):1583–1606

Dagne Y, Sandler LH (2020) “We’re Leaving Everything Behind” The Impact of Guinea’s Souapiti Dam on Displaced Communities

Deif A, Hamed H, Ibrahim HA, Elenean KA, El-Amin E (2011) Seismic hazard assessment in Aswan, Egypt. J Geophys Engi 8(4):531–548. https://doi.org/10.1088/1742-7188/8/4/006

Ghana Statistical Service (2014) 2010 Population and housing census district analytical report; Ga South Municipality. Accra: http://www.statsghana.gov.und the Weija Dam near Accra, Ghana. www.statsghana.gov.gh. Accessed 26 Feb 2021

Grünthal G, Wahlström R, Stromeyer D (2009) The unified catalogue of earthquakes in central, northern, and northwestern Europe (CENEC)—updated and expanded to the last millennium. J Seismol 13(4):517–541. https://doi.org/10.1007/s10950-008-9144-9

Gupta ID (2002) The state of the art in seismic hazard analysis. ISET J Earthq Technol 39(4):311–346

Hariri-Ardebili MA, Nuss NK (2018) Seismic risk prioritisation of a large portfolio of dams: revisited. Adv Mech Eng 10(9):1–20. https://doi.org/10.1177/1687814018802531

Goitom B, Werner MJ, Goda K, Kendall JM, Hammond JOS, Oguzbaghi G, Oppenheimer C et al (2017) Probabilistic seismic-hazard assessment for Eritrea. Bull Seismol Soc Am 107(3):1478–1494. https://doi.org/10.1785/0120160210

ICOLD (1989) Selecting parameters for large dams—guidelines and recommendations: ICOLD Committee on Seismic Aspects of Large Dams, Bulletin, vol 72, p 36

ICOLD (2010) Selecting seismic parameters for large dams. Committee on Seismic Aspects of Dam Design, International Commission on Large Dams, Paris

Kijko A (2004) Estimation of the maximum earthquake magnitude, mmax. Pure Appl Geophys 161(8):1655–1681. https://doi.org/10.1007/s00024-004-2531-4
Kijko A, Graham G (1998) Parametric-historic procedure for probabilistic seismic hazard analysis. Part I: estimation of maximum regional magnitude \( m_{\text{max}} \). Pure Appl Geophys 152:413–442. https://doi.org/10.1007/s000240050161

Kutu JM (2013) Seismic and tectonic correspondence of major earthquake regions in Southern Ghana with mid-atlantic transform-fracture zones. Int J Geosci 4:1326–1332. https://doi.org/10.4236/ijg.2013.410128

Mavonga T, Durrheim RJ (2009) Probabilistic seismic hazard assessment for the Democratic Republic of Congo and surrounding areas. S Afr J Geol 112(3–4):329–342. https://doi.org/10.2113/gssajg.112.3-4.329

McGuire RK (1995) Probabilistic seismic hazard analysis and design earthquakes: closing the loop. Bull Seismol Soc Am 85(5):1275–1284. https://doi.org/10.1016/0148-9062(95)83355-9

Musson RMW (2014) The seismicity of Ghana. Bull Earthq Eng 12(1):157–169. https://doi.org/10.1007/s10518-013-9555-z

Ntiamoa-Baidu Y, Ampomah BY, Ofosu EA (eds) (2017) Dams, development and downstream communities: implications for re-optimising the operations of the Akosombo and Kpong Dams in Ghana. Digibooks Gh. Ltd., Tema

Ordaz MM, Sagado-Gálvez A (2018) R-CRISIS Validation and Verification Document. ERN Technical Report. Mexico City, Mexico

Owusu-Ansah JK, Dery JM, Amoako K (2019) Flood vulnerability and coping mechanisms around the Weija Dam near Accra, Ghana. Geojournal 84(6):1597–1615. https://doi.org/10.1007/s10708-018-9939-3

Pezeshk S, Zandieh A, Tavakoli B (2011) Hybrid empirical ground-motion prediction equations for Eastern North America using NGA models and updated seismological parameters. Bull Seismol Soc Am 101(4):1859–1870. https://doi.org/10.1785/0120100144

Poggi V, Durrheim R, Tuluka GM, Weatherill G, Gee R, Pagani M, Nyblade et al. (2017) Assessing seismic hazard of the East African Rift: a pilot study from GEM and AfricaArray. Bull Earthq Eng 15: 4499–4529. https://doi.org/10.1007/s10518-017-1052-4

Scordilis EM (2006) Empirical global relations converting \( M_s \) and \( m_b \) to moment magnitude. J Seismol 10:225–236. https://doi.org/10.1007/s10950-006-9012-4

Singh M, Kijko A, van den Berg L (2011) Seismic risk ranking for large dams in South Africa. Acta Geophys 59(1):72–90. https://doi.org/10.2478/s11600-010-0044-3

Stepp JC (1972) Analysis of Completeness of the Earthquake Sample in the Puget Sound Area and its effect on statistical estimates of earthquake hazard. In: Proceedings of the International Conference on Microzonation, Seattle, USA (2), pp 897–910

Tavakoli B, Pezeshk S (2005) Empirical-stochastic ground-motion prediction for Eastern North America. Bull Seismol Soc Am 95(6):2283–2296. https://doi.org/10.1785/0120050030

Tosun H, Seyrek E (2010) Total risk analyses for large dams in Kızılirmak basin. Turkey Nat Hazards Earth Syst Sci 10(5):979–987. https://doi.org/10.5194/nhess-10-979-2010

Tosun H, Zorluer I, Orhan A, Seyrek E, Savaş H, Türköz M (2007) Seismic hazard and total risk analyses for large dams in Euphrates basin. Turkey Eng Geol 89(1–2):155–170. https://doi.org/10.1016/j.englgeo.2006.10.003

Wieland M (2012) Seismic design and performance criteria for large storage dams. In: 1999 15th World Conference on Earthquake Engineering, Lisbon Portugal

Wiemer S (2001) A software package to analyse seismicity: ZMAP. Seismol Res Lett 72(2):373–382. https://doi.org/10.1785/0120050030

Yarwood DR, Doser DI (1990) Deflection of oceanic transform motion at a continental margin as deduced from waveform inversion of the 1939 Accra. Ghana Earthquake Tectonophys 172(3–4):341–349

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