Bulletin of Earthquake Engineering
https://doi.org/10.1007/s10518-025-02103-2

ORIGINAL ARTICLE

Stochastic event-based probabilistic earthquake risk assessment framework for Uganda: towards informing the National Policy for Disaster preparedness and management

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Received: 25 July 2024 / Accepted: 11 January 2025

Abstract

Catastrophic earthquakes in Uganda have the potential for detrimental consequences on the socio-economic welfare and resilience of communities. Despite considerable efforts in predicting earthquake risk across Africa, a national comprehensive seismic risk study for Uganda does not exist. With increasing population, urbanisation and rapid construction, seismic risk is escalating fast and is compounded by the high vulnerability of buildings and scanty disaster prevention and mitigation strategies. This study uses the probabilistic event-based risk calculator of the *OpenQuake*-engine to assess potential risks resulting from future earthquakes. Although the building exposure model is largely inferred and projected from the national population and housing census of 2014, total replacement costs are obtained by performing series of interviews with local engineering practitioners. Analytical vulnerability curves are selected from Global Earthquake Model (GEM) database. Seismic hazard studies confirm that western Uganda is exposed to the highest level of seismicity where peak ground accelerations on rock ground can reach up to 0.27 g over a 475-year return period. Relative to Uganda's gross domestic product, the associated seismic risk estimates indicate mean economic loss ratios of 0.36%, 2.72% and 4.94% over 10, 50 and 100-year return periods respectively; with mean annual economic loss of US$ 74.7 million (0.34% relative to the total replacement value) and annual deaths averaging 71 persons across the whole country. It is envisaged that the findings will inform strategic land use planning patterns, earthquake insurance pricing and foster the continuous improvement of Uganda's National Policy for Disaster Preparedness and Management.

Keywords Uganda, stochastic event-based modelling · Probabilistic seismic hazard analysis · Structural vulnerability · Building exposure · Probabilistic seismic risk assessment · Sub-Saharan Africa

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Published online: 03 February 2025

1 Introduction

Earthquakes can potentially cause widespread and devastating damage to the built and natural environment, eventually affecting their communities (Baker et al. 2021; Daniell et al. 2011). Uganda is located between the two seismically active branches of the East African Rift System (EARS), a tectonic environment that exposes the country to earthquakes with moment magnitude (M_w) between 6.0 and 7.2. Moreover, many seismic events with M_w < 6.0 have been recorded across the country (Midzi et al. 1999; Twesigomwe 1997). Following the major earthquakes across Uganda, for instance the 1929 Masaka (6.3M_w), 1966 Toro (6.7M_w), 1994 Kisomoro (6.3M_w) and 2016 Bukoba (5.9M_w), several structures were damaged in addition to the numerous deaths and injuries (Balikuddembe and Sinclair 2018; Maasha 1975; Midzi and Manzunzu 2014). Economic losses worth US$ 60 million were incurred when the 1994 Kisomoro earthquake of 6.3 M_w struck Kabarole, Bundibugyo and Kasese districts in western Uganda. Furthermore, 8 people were killed and several injuries registered (Kahuma et al. 2006; NEDC 1994). Moreover, economic losses were exacerbated by co-seismic landslides around the epicentral region (Oleng et al. 2023, 2024a). The recent 2016 Bukoba earthquake of 5.9 M_w generated an estimated economic loss of US$ 458 million, with 11 deaths and over 440 injuries in the Kagera region of the Uganda-Tanzania border (Balikuddembe and Sinclair 2018; Oleng et al. 2024b).

Damage to buildings, injuries and fatalities in future events are likely to escalate due to Uganda's rapidly increasing population and urbanisation. Besides, the largest fraction of buildings in Uganda is mainly substandard and more than half of the housing stock comprises unreinforced masonry buildings which are more vulnerable to earthquakes, especially when seismic design principles are ignored (Brzev et al. 2013; Silva et al. 2015; Vicente et al. 2011). In this regard, seismic risk in Uganda ought to be comprehensively evaluated in order to develop reliable national risk mitigation strategies such as reinstating and enforcing standards and regulations towards design and construction of seismic-resistant structures, strengthening/retrofitting existing buildings located in earthquake prone areas, adequate emergency response planning at urban and district scale, and transferring financial costs of reconstruction and/or repair through creation of insurance and reinsurance schemes (Baker et al. 2021; Gkimprixis et al. 2021; Salgado-Gálvez et al. 2017).

Seismic risk assessment essentially requires hazard estimates which are then combined with the exposure and vulnerability models in order to predict possible consequences such as fatalities and infrastructure damages resulting from future earthquakes (Baker et al. 2021). Whereas deterministic seismic hazard analysis (DSHA) utilizes discrete models to obtain scenario earthquakes responsible for the worst-case ground motion (Reiter 1991), conventional probabilistic seismic hazard analysis (PSHA) initially proposed by Cornell (1968) accounts for all earthquake magnitudes, distances and number of logarithmic standard deviations. Moreover, the epistemic and aleatory uncertainties associated with the earthquake model can be rationally incorporated to give more realistic hazard predictions (Crowley 2005; Reiter 1991). Recent studies (e.g.Johnson et al. 2023; Oleng et al. 2024b; Sianko et al. 2020) used stochastic event-based modelling approaches, described in literature (e.g., Baker et al. 2021 and Musson 1999), to generate synthetic earthquake catalogues by randomising key hazard parameters required for a PSHA.

Understanding the presence of exposed assets, especially the distribution of human population, buildings and other infrastructure such as roads and bridges, is an important aspect towards accurate seismic risk estimates (Baker et al. 2021; Sianko et al. 2023). The exposure model typically provides details on the number and geographical location, taxonomy, value, floor areas, and night/transit/daytime occupancy, vulnerability characteristics, average built-up area and replacement cost of assets. However, many African countries suffer from substantial lack of data required for a comprehensive seismic risk analysis. Except for Malawi that has a national exposure model (Kloukinas et al. 2020; Ngoma et al. 2019), many countries within Sub-Saharan Africa rely on national population and housing census data from local and global databases (e.g., De Bono and Chatenoux 2015; Gamba et al. 2012; Jaiswal et al. 2010 and Jaiswal and Wald 2008) to perform seismic risk analyses. For Uganda, projections based on the 2014 national housing and population census (UBoS 2016) can be used to estimate the exposure model. Thereafter, several building classification systems like PAGER-STR (Jaiswal and Wald 2008), ISK-UE project (Mouroux and Le Brun 2006), European Macroseismic Scale (Grünthal 1998), HAZUS (FEMA 2003), and World Housing Encyclopedia (EERI 2000) can be used to classify buildings into different taxonomies which are organised as a series of expandable tables with information pertaining to their various attributes (Brzev et al. 2013).

However, there are notable data insufficiencies in the 2014 Uganda national housing and population census (UBoS 2016) and as such, it is challenging to develop detailed exposure models from these statistics alone. In such incidences, high resolution satellite imagery and gridded maps showing building patterns can be complementarily used (Dooley et al. 2020; Sirko et al. 2021). In addition to satellite imagery maps and other global datasets, national statistics can be spatially disaggregated to more realistically reflect the distribution of assets. For instance, Paul et al. (2022) developed a novel uniform exposure model for the African continent, from which it is indicated that the concentration of buildings in the urban centres of East Africa could nearly triple over the next decades. Recently, the Global Earthquake Model (GEM) Foundation based on national statistics, socio-economic data and local data largely provided by the corresponding national institutions/agencies to comprehensively develop a worldwide database of residential, commercial and industrial buildings (Yepes-Estrada et al. 2023). Following the hazard and exposure models, the susceptibility of exposed assets to damage from earthquakes is then evaluated using fragility/vulnerability models (Baker et al. 2021; Sianko et al. 2023).

Considering damage states such as slight, moderate, extensive and complete (Hazus-MH 2003) and for a certain level of ground motion, the probability of exceedance (POE) can be predicted using fragility curves explicitly derived for particular building types. On the other hand, vulnerability curves can be derived by converting a set of fragility curves consequence models (e.g., Coburn and Spence 2002; Erdik 2017; Kohrangi et al. 2021 and So and Spence 2013). Fragility/vulnerability models can be empirically calibrated through direct field observation of post-earthquake damages (Calvi et al. 2006; Crowley and Pinho 2011; Rossetto and Ioannou 2018). Although empirical approaches require fewer modelling assumptions, a careful survey of both undamaged and damaged buildings is required for robust and unbiased predictions; yet the already cumbersome field surveys pose huge challenges in obtaining key parameters of interest (Baker et al. 2021). Alternatively, conceptually straightforward analytical methods can offer more flexibility especially if asset-specific features are broadly incorporated into the predictions (Jayaram et al. 2012). Analytical fragility and vulnerability models are developed using nonlinear time history analysis (e.g., D'ayala et al. 2014; Ellingwood and Kinali 2009 and Singhal and Kiremidjian 1996) and other simplified methods such as pushover analysis (e.g., Crowley et al. 2004; Kircher et al. 1997 and Silva et al. 2014). In the absence of both numerical models and empirical observations, consequence functions can be developed based on expert opinion (Jaiswal et al. 2012).

In view of the fact that the efficacy of Uganda's seismic risk reduction and management strategies is undermined by the absence of a comprehensive national seismic risk framework, this study presents the first stochastic probabilistic earthquake risk assessment framework for Uganda; by combining the existing exposure and earthquake hazard models with the seismic vulnerability of the building inventory using the event-based calculator of *OpenQuake* engine *(*Pagani et al. 2014). Despite the lack of sufficient information regarding Uganda's building stock, the exposure model is projected from the 2014 population and housing census (UBoS 2016). To estimate the Uganda exposure model in a more representative manner, subsequent adjustments are made on the additional information obtained from the GEM Foundation and the uniform exposure model of for Africa (Paul et al. 2022; Yepes-Estrada et al. 2023). Although fragility and vulnerability curves specifically developed for Uganda are non-existent, the country's building taxonomies are mapped with analytical vulnerability curves selected from the global vulnerability model database of the GEM Foundation (Martins and Silva 2023).

This paper begins with a sequential description of the location and demography of the study area which is preceded by the underlying methodology adopted prior to explaining the fault-oriented spatially smoothed seismicity technique (e.g., Williams et al. 2023) adopted to develop a stochastic event-based PSHA for Uganda. The subsequent sections present the exposure and vulnerability models used to describe the probability distribution of losses for a combination of intensity measure types and levels. The remaining parts of the paper present and discuss the results including earthquake ruptures, seismic hazard outputs, loss exceedance curves, mean annual losses and aggregated asset loss statistics which are then compared with previous regional and global predictions. The framework proposed in this work not only aims to provide practitioners, policymakers, insurance companies and government stakeholders with practical earthquake risk appraisal techniques, but also make informative contributions towards improving the National Policy for Disaster Preparedness and Management (NPDPM 2010).

2 Location and population distribution of Uganda

Figure 1 shows the location of the study area on the African continent and the estimated population density map of Uganda (number of people per 100-metre grid cell, at a resolution of 3 arc seconds), together with the epicentral location of major earthquakes that occurred in and around Uganda between 1900 and 2022. The fault system shown in Fig. 1 is obtained from the global homogenised database of Styron and Pagani (2020); and it indicates that Uganda lies between the Albertine (western) and Gregory (eastern) arms of the EARS from which the majority of earthquakes are instigated. The population density of Uganda, obtained from the 2014 national census and geoportal of climate prediction and applications centre (ICPAC 2024; UBoS 2016), is projected for 2024 using the cohort-component method for projecting population (CCMPP) described by the department of economic and social affairs (population division) at the United Nations. In its application to the coun-

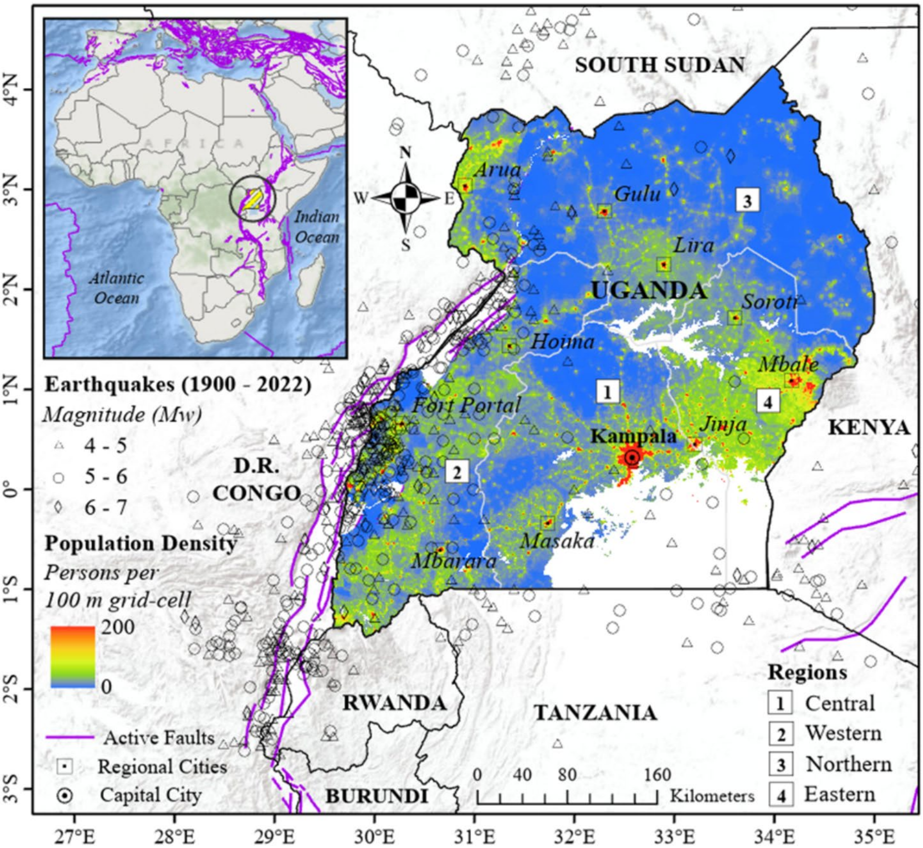

Fig. 1 Location of Uganda on the African continent; and its 2024 population density estimated per 100-metre grid (3 arc seconds resolution), position of the East African Rift System (EARS) relative to major cities, and major earthquake ($M_w \geq 4$) epicentres that occurred between 1900 and 2022

try-level population in question, the CCMPP accounts for three demographic components within the projection interval: fertility, mortality and net international migration (United Nations 2024).

While population projections are typically associated with greater uncertainty, actual population estimates from preliminary results of the National Population and Housing Census (UBoS 2024) were used for validation. The most densely populated urban areas consist of approximately 200 persons per 100-metre cell grid. In addition to the north-eastern territory, which is largely semi-arid, the least populated areas are mostly occupied by game parks and forests. Although most regions around past earthquake epicentres in western Uganda are relatively less populated compared with the central and eastern parts of the country, the growing economic activity and rapid urbanization which has led to the creation of major regional cities (e.g., Fort Portal, Hoima and Mbarara) are likely to increase the human and housing population in these areas, thereby posing increasing seismic risks.

To better represent the human exposure to earthquake risk across Uganda, the population distribution of the country is aggregated for the major administrative units (district/

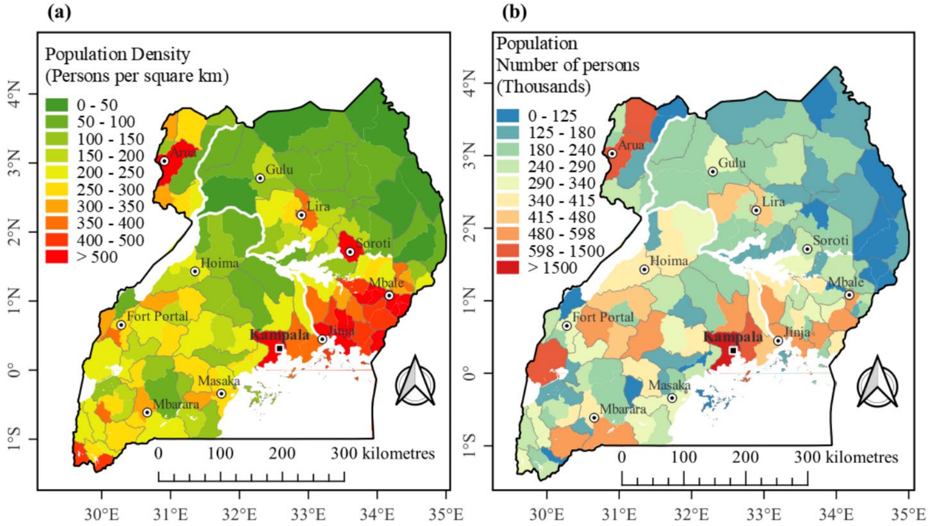

Fig. 2 Population projections for the baseline year 2024, aggregated for major administrative units and presented for: **a** district population per square km, and **b** total number of persons per district

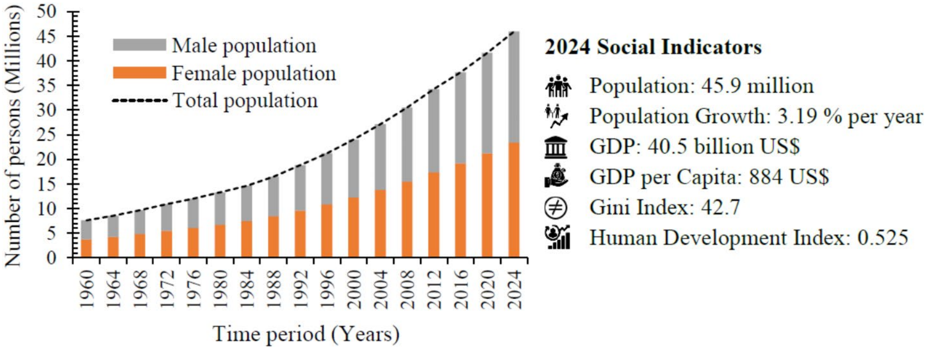

Fig. 3 Temporal population distribution of Uganda between 1960 and 2024 (UBoS 2024); and the social indicators for the country towards earthquake risk assessment

municipality/county) as shown in Fig. 2a-b. It can be seen that Kampala capital city and its immediate environs comprise the most highly populated areas, followed by the border trade districts and regional cities. The social indicators and the temporal distribution of Uganda's population over the past few decades are shown in Fig. 3. Uganda's population has grown at an average annual rate of 3.19%; and as at June 2024, the population of the country was estimated at over 45.9 million (UBoS 2024).

3 Methodology: event-based probabilistic seismic risk analysis

Many earthquake risk assessment studies performed at various regional and national levels have been executed using platforms like *Hazus-MH* (FEMA 2003), *CRISIS* (Ordaz and Salgado-Gálvez 2017) and *Seisan* (Havskov and Ottemöller 2003). In the present study, the first national earthquake risk assessment framework for Uganda is proposed using a stochastic event-based modelling approach in *OpenQuake* engine (Pagani et al. 2014). The calculation workflow, illustrated in Fig. 4, computes the probability of losses and loss statistics for a collection of exposed assets, based on the probabilistic seismic hazard (Silva et al. 2012). Within this methodological procedure, stochastic event sets representing regional seismicity over a given investigation time are generated using MC simulations (e.g., Musson 1999 and Sianko et al. 2020). The number of event occurrences is then simulated by sampling the corresponding probability distribution for each rupture created by seismic sources. Whilst considering inter-event variability of ground motions and intra-event residuals, spatially correlated ground motion realisations are generated for each stochastic event rupture. Epistemic uncertainties associated with the seismic source and ground motion models are included through a logic tree approach. Whereas the POE for different loss levels over a given time period is described by loss exceedance curves, the loss maps show the loss values that have a specified POE within the particular investigation time. Despite the computational cost and complexity of MC simulations, the approach is adopted with the view of allowing model flexibility. Moreover, reliable predictions of the total loss value at higher return periods is determined when the spatial variability of intra-event residuals is incorporated within the MC simulations (Baker et al. 2021; Jayaram and Baker 2009).

4 Probabilistic seismic hazard model for Uganda

To quantify the seismic hazard across Uganda, earthquake catalogues are compiled from numerous sources (e.g., Albini et al. 2013; Ambraseys and Adams 1991; DGSM 2022; Giacomo et al. 2018; ISC 2022; Maasha 1975; Storchak et al. 2013; Storchak et al. 2015 and USGS 2022), merged and refined using the GEM catalogue toolkit (Weatherill 2014) and the ZMAP (2022) algorithm of Wiemer (2001). Based on the geology and seismo-tectonic setting of the region, a fault-oriented spatially distributed seismicity approach (Vilanova et al. 2014) is used to delineate seismic source zones as shown in Fig. 5. Calibrated seismicity parameters (a- and b-values), defined in the Gutenberg and Richter (1944) law and their associated standard deviations are estimated using the Weichert (1980) maximum likelihood method. More detailed information relating to frequency-magnitude-distributions (Gutenberg-Richter recurrence parameters shown in Fig. 5) adopted herein can be found in the study by Oleng et al. (2024b). Whilst the Kijko (2004) estimators are suitable for determining maximum magnitudes (M_{max}), the lack of source-scaling relationships for Uganda was problematic (Oleng et al. 2024b). Accordingly, M_{max} values are arbitrarily estimated by adding a conservative increment of 0.5 magnitude units to the observed maximum earthquake size in each source zone (Poggi et al. 2017).

In PSHA, suitable ground-motion models (GMMs) are required to predict the site responses arising from possible ruptures. Except the semi-theoretically calibrated GMM derived by Twesigomwe (1997), there are no GMMs explicitly developed based on strong

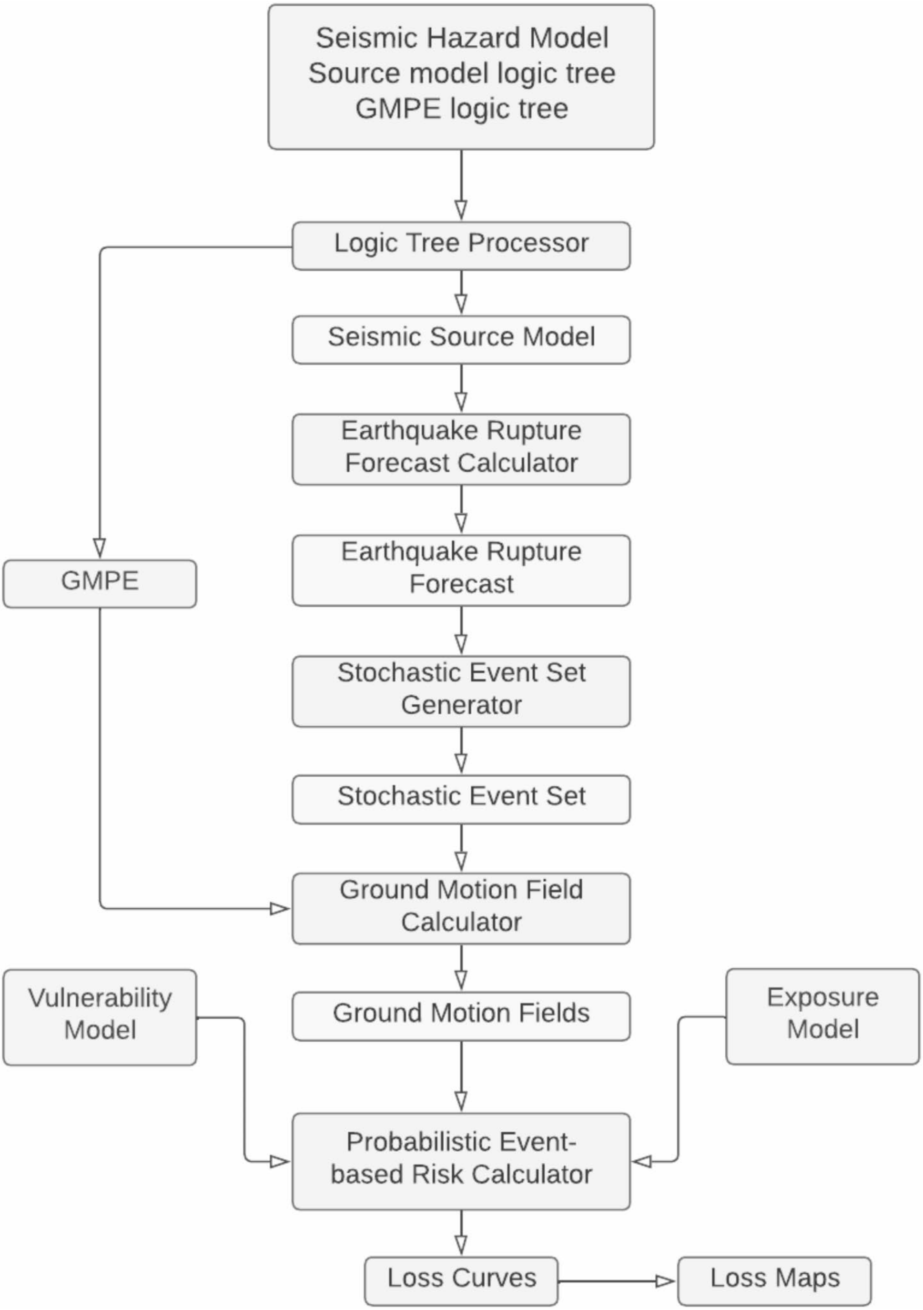

Fig. 4 Schematic diagram showing the chronological workflow of the probabilistic event-based risk and loss calculator embedded in the *OpenQuake*-engine

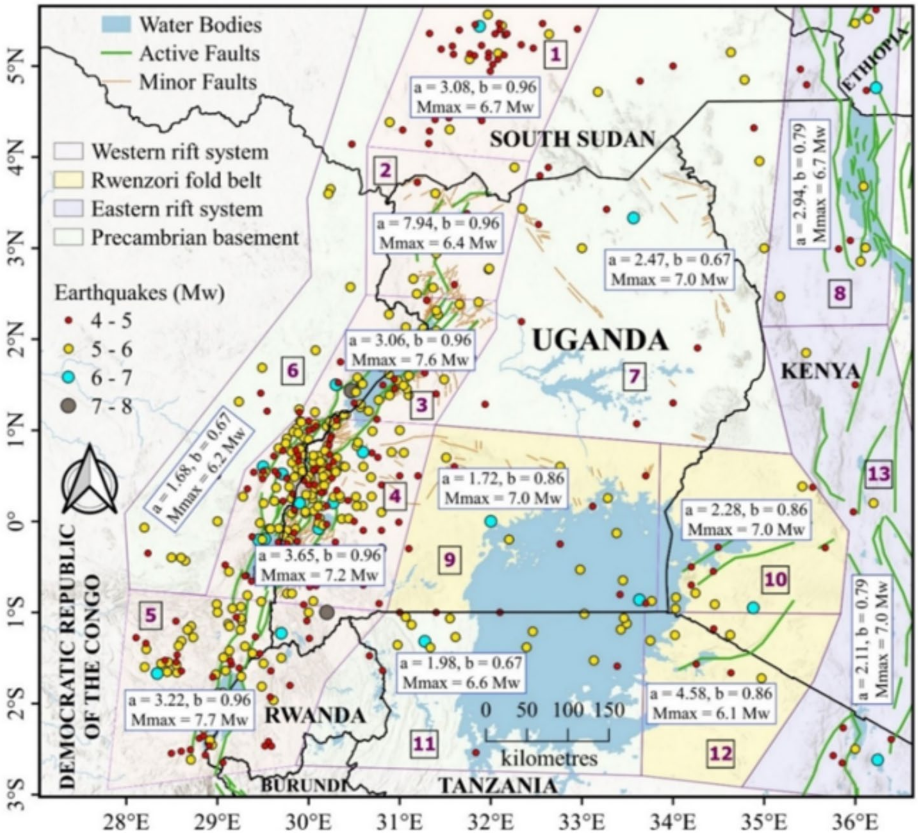

Fig. 5 Epicentres of $M_w \geq 4.0$ earthquakes which hit Uganda and its neighbouring countries between 1900 and 2022, major and minor active fault systems, area source zonation model and the calibrated seismicity parameters used to perform the stochastic event-based PSHA for Uganda

ground motion records for Uganda (Bwambale et al. 2015; Poggi et al. 2017; Oleng et al. 2024b); and as such, no published quantitative study that compares ground-motion observations from past larger magnitude events in the country exists. Due to severe lack of data availability from seismic networks across Uganda, as no ground-motion response records from large magnitude events are available, a selection criterion which relies on direct assessment and comparison of GMM features (Cotton et al. 2006) is adopted herein. Subsequently, suitable GMMs for each tectonic regime are selected using functionalities of the GEM ground motion toolkit (Weatherill et al. 2014). Whereas the GMMs of Akkar et al. (2014) and Chiou and Youngs (2014) are used to model ground motion in active shallow crust, seismic response in stable continental tectonic regime is predicted using the GMMs of Atkinson and Boore (2006) and Pezeshk et al. (2011). The associated epistemic uncertainties are captured by implementing a logic tree with weights assigned (summarised in Table 1) according to the likelihood of each clustered tectonic types. Whilst epistemic uncertainties related to the existing level of knowledge and/or adopted simplifications and initial assumptions are quantified using a logic-tree implementation strategy, aleatory (or

Table 1 Weighting scheme for the GMM logic tree implementation in PSHA calculation

Source Group	Area Zone	Active Shallow Crust		Stable Continental Crust	
		AA	CY	PA	AB
Western Rift System	1, 2, 3, 4, 5	0.250	0.250	0.250	0.250
Rwenzori Fold Belt	9, 10, 12	0.375	0.375	0.125	0.125
Eastern Rift System	8, 13	0.000	0.000	0.500	0.500
Congo-Uganda-Tanzania craton	6, 7, 11	0.500	0.500	0.000	0.000

random) component of the seismic model uncertainty is generally captured through the hazard integral.

Zones sharing similar weights are grouped into four categories and four GMMs are applied (*AA* Akkar et al. 2014; *CY* Chiou and Youngs 2014; *PA* Pezeshk et al. 2011; and *AB* Atkinson and Boore 2006).

Whilst the Uganda seismic code of practice for structural designs (US319:2003) (UNBS 2003) defines seismic source/site conditions using the standard penetration test, many modern seismic design codes (e.g., BSSC 2004 and CEN 2004) characterise local site conditions using the average velocity of seismic shear waves in the upper 30 m layer of soil ($V_{s,30}$) value (Silva et al. 2015). Moreover, numerous GMMs summarised by Douglas (2021) are calibrated against the $V_{s,30}$ values (Bommer 2022). In this work, site conditions are first modelled using the slope-based $V_{s,30}$ reference values ranging between 180 and 900 m/s (Allen and Wald 2007). Although site-dependent hazard maps may be useful, possible discrepancies between the resolutions of site condition maps and hazard computation grids might pose a problem. Since the slope-based site classification map derived by Allen and Wald (2007) comes from very crude estimations, its use in a PSHA can lower the accuracy of the proposed hazard maps. Moreover, there are no published quantitative studies that compare the $V_{s,30}$ estimates with observed values across the country. More representative hazard estimates are derived for free rock conditions, with a fixed $V_{s,30}$ reference value of 760 m/s assumed for each site (Oleng et al. 2024b).

5 Exposure model

5.1 Composition of the building stock in Uganda

The building stock in Uganda comprises traditional timber, daub and wattle, adobe blocks with mud mortar, fired clay bricks with cement mortar; all roofed with either grass-thatched, galvanised iron-sheet or burnt clay tiles (Hashemi 2017; Twesigomwe 1997). The wattle and daub buildings (e.g., Fig. 6a) are especially spread in the rural countryside and villages. Most of the adobe with mud mortar constructions are found in old government buildings such as the former Jinja prison administrative unit shown in Fig. 6b. On the other hand, buildings consisting of fired clay brick walls which are held together with cement mortar (e.g., schools, hospitals and shops shown in Fig. 6c) typically consist of two gable walls or poorly supported parapets with little resistance to horizontal forces. Modern-style category constructions (e.g., depicted in Fig. 6d) include multi-storey and bungalows that comprise load bearing fired clay brick or concrete block walls with strip foundations and/or framed column-beam layouts resting on pad foundation footings.

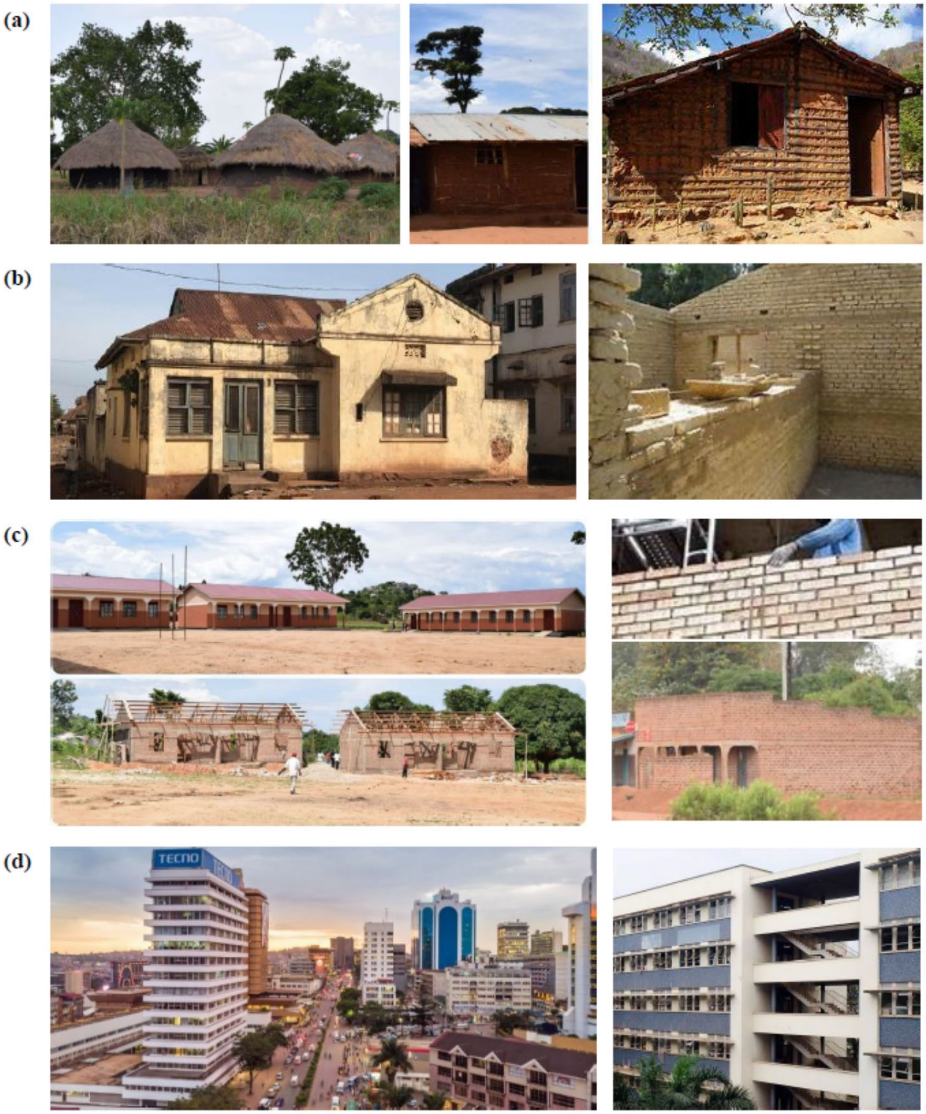

Fig. 6 Common building types constituting Uganda's building stock: **a** wattle-and-daub, **b** adobe with mud mortar, **c** fired bricks with cement mortar, and **d** modern-style buildings

5.2 Building typologies

The attributes adopted in this work use the building typology nomenclature defined in the GEM building taxonomy (Brzev et al. 2013; Silva et al. 2022). Attributes encoded in the condensed strings generally include primary construction material, type of vertical and lateral load-bearing system, number of storeys, and ductility class. In this study, information regarding Uganda's building stock is extracted from the GEM Foundation (Yepes-Estrada et al. 2023) and the uniform exposure model for Africa (Paul et al. 2022). The data herein is

Table 2 Distribution of estimated building stock across the four regions of Uganda

Building category	Number of buildings ('000) located in each region*				Total ('000)
	Central	Eastern	Northern	Western	
Residential	2,675	2,514	1,982	2,450	9,621
Commercial	55	52	41	50	198
Industrial	24	22	18	22	86
Total ('000)	2,754	2,588	2,041	2,522	9,905

*The regional boundaries of Uganda are indicated in Figs. 1 and 18

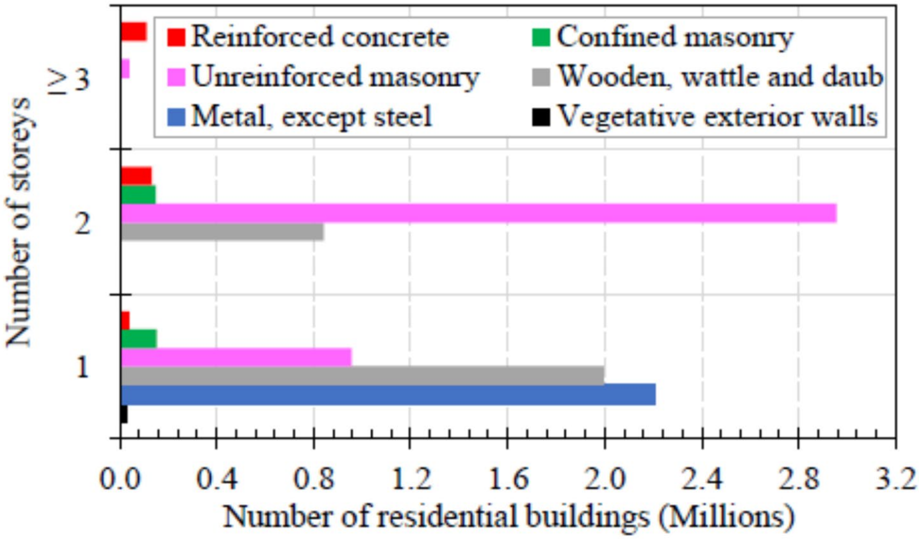

Fig. 7 Distribution of the residential buildings according to their number of storeys

largely inferred from the 2014 national population and housing census (UBoS 2016) where buildings in each region are projected for a baseline year of 2024 and categorised according to their occupancy categories of residential, commercial, and industrial buildings as shown in Table 2. Whilst the majority of national population and housing census such as UBoS (2016) largely provide information in terms of dwellings instead of building counts, numerous previous studies (e.g., Crowley et al. 2020; Dolce et al. 2021 and Yepes-Estrada et al. 2023) have estimated the number of buildings for each typology as follows:

$$N_B = \frac{N_D}{N_J \times N_K} \tag{1}$$

where N_B is the number of buildings for each typology, N_D is the number of dwellings, N_J is the number of units per storey, and N_K is the number of storeys per building class. In this work, N_D, N_J, and N_K are obtained from within the 2014 national population and housing census of the country (UBoS 2016). The number of residential buildings according to the number of storeys for each building typology is depicted in Fig. 7. Metal, wooden wattle and daub, and unreinforced masonry constitute the bulk of bungalows. Most buildings exceeding three storeys are reinforced concrete, whilst the highest number of two-storey buildings are unreinforced masonry. The spatial distribution for each building typology is mapped out in Fig. 8a-f.

To appropriately characterise vulnerability of buildings to ground shaking, the benchmark seismic design regulations and code level are required to investigate the construction age (built year) of buildings in the exposure model. Unfortunately, provisions in the Uganda seismic code of practice for structural designs (US 319:2003) published by UNBS (2003) are less rigorous compared with those of modern design codes such as Eurocode 8−1 (CEN 2004); and as such, this study does not deem the construction age of buildings to be consequential in the assessment of seismic risk presented herein. However, future studies will rely on wall material categories from available census data (e.g., UBoS 2024) to estimate the building proportions in each construction age (Paul et al. 2022; Pesaresi et al. 2015). The ductility levels considered across Uganda's building stock are categorised as non-ductile, low ductility or moderate ductility. In this study, all unreinforced masonry, wooden, wattle and daub, metal (except steel) and exterior vegetative wall buildings are non-ductile; with at least 80% of all the other typologies including reinforced concrete, confined masonry and steel buildings exhibiting a low ductility threshold. Overall, the exposure model used in this work considers 92.6% of all building typologies within the country's building stock as non-ductile. Whereas Uganda has an insignificant number of high ductility structures, 5.9% and 1.5% respectively represent the proportion of buildings with low and moderate ductility levels.

5.3 Estimation of building economic value

In seismic risk analysis, replacement costs of a building account for: (1) structural components like foundations, columns, walls, slabs and staircases; (2) non-structural components including partition walls, facades, finishes, mechanical and electrical services, and ceiling works; and (3) building contents for instance office equipment and machinery. Considering that the main construction material and occupancy class typically dictate the replacement cost of each component, Yepes-Estrada et al. (2023) assumed "*build back better*" concept (e.g., Der Sarkissian et al. 2023; Dube 2020 and Mannakkara et al. 2014) whilst relying on cost handbooks and expert opinion to estimate the total replacement cost of buildings as follows:

$$TRC = C_A \times A_D \times N_D \tag{2}$$

where *TRC* is the total replacement cost of the building, C_A is the cost per area, A_D is the area of dwelling or establishment, and N_D is the number of dwellings or establishments. Similarly, Paul et al. (2022) based on national building cost statistics and a literature review of independent international cost books to estimate the replacement costs of buildings in Africa.

Although the economic value of buildings in the uniform exposure model for Africa is estimated by Paul et al. (2022), this study further adjusts the total replacement costs of buildings following surveys conducted for various building taxonomies in the country. Engineering practitioners are interviewed, and consideration given to local market rates for materials, equipment and labour using single rate approximate estimating approach. In this method, total replacement costs are determined as the product of cost per square metre

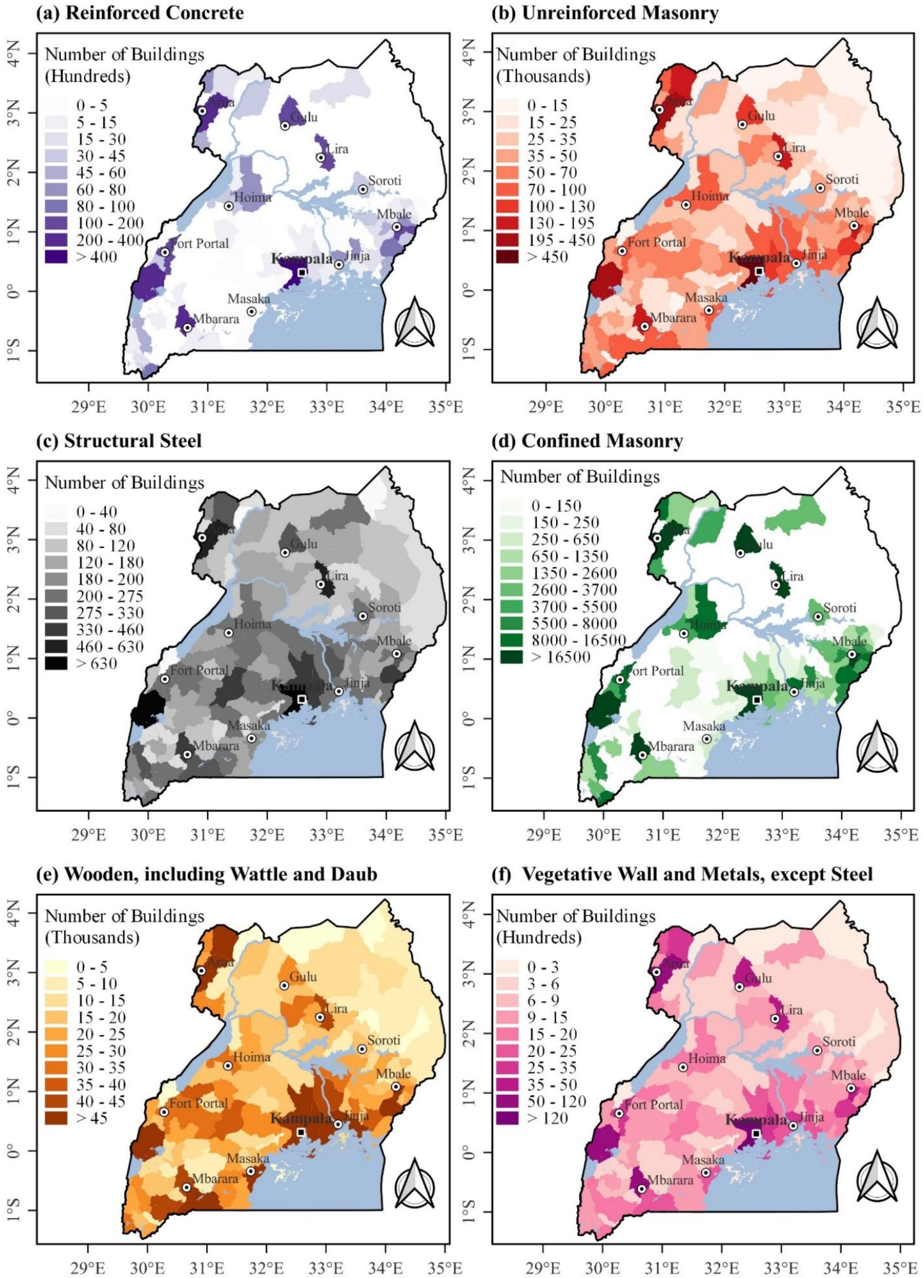

Fig. 8 Spatial distribution of the building exposure aggregated at district level and presented for: **a** reinforced concrete, **b** unreinforced masonry, **(c)** structural steel, **d** confined masonry, **e** wooden, including wattle and daub, and **f** exterior vegetative wall and all other metals except steel

of a given building and its total floor area. Within this floor area method, different types of slabs and their corresponding costs per square meter are taken into consideration. Even though no substantive deductions are made for internal partition walls, ducts, lifts and/or stairs, the costs of past similar buildings are used to establish a sound and realistic costs per square meter. The fluctuation in costs of building materials, labour rates and price variations regarding equipment hire are considered in addition to the experiences and subjective judgements of engineering practitioners. For each building typology, the cost per square metre is standardised for the 2024 baseline year and local currency values converted to US$.

A summary of the total replacement costs for each settlement type is presented in Fig. 9. Replacing RC and MCF buildings costs about US$ 400 per m^2 while replacement cost per m^2 of MUR buildings ranges between US$240 and US$275 in rural and urban settlements respectively. Overall, the exposure model estimates approximately 9.62 million residential buildings valued at over US$ 171 billion. In addition, the building stock includes more than 198,000 commercial buildings, and 85,000 industrial facilities valued more than US$ 11.9 billion and US$ 6.6 billion, respectively. As per Uganda's nominal gross domestic product (GDP), estimated at US$ 40.53 billion (UBoS 2022), the building stock amounts to approximately 4.7 times of nominal GDP.

6 Fragility and vulnerability models

To minimise uncertainties and achieve accurate predictions of seismic risk, a rigorous selection of suitable fragility models for the area of interest is required (Riga et al. 2017; Sianko et al. 2023). In this regard, fragility curves benchmarked against post-earthquake damage data and specifically developed for the building stock in the region in question should be used (Sianko et al. 2023; Villar-Vega and Silva 2017). For instance, Giordano et al. (2023) derived a set of analytical fragility curves for informal and code-conforming unreinforced

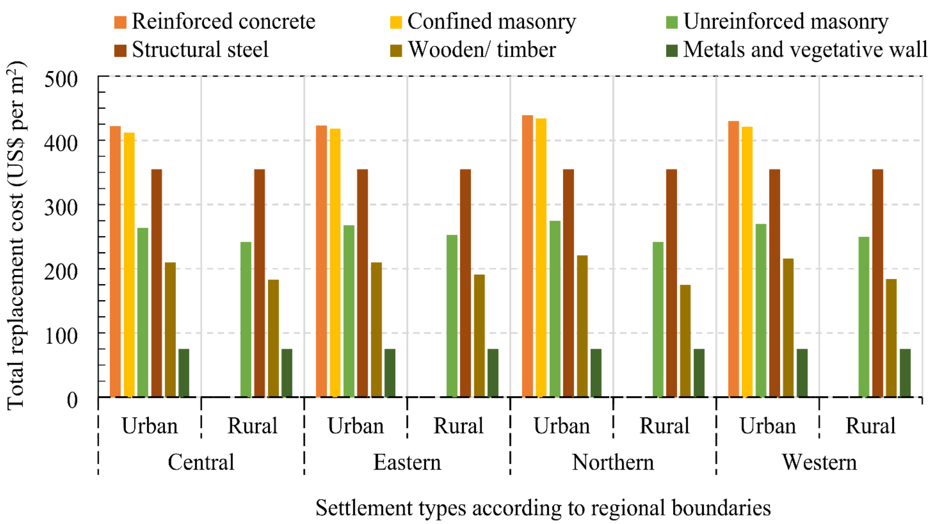

Fig. 9 Total replacement cost per area in urban and rural settlements for different building types located in each of the four regions of Uganda

fired brick masonry buildings constituting the Malawian housing stock. Moreover, in the probabilistic seismic collapse risk assessment of non-engineered masonry buildings in Malawi, Goda et al. (2024) based on different static pushover curves to propose fragility functions for geometric instability, limited ductility, and strength degradation vulnerability classes. However, the substantial lack of fragility models developed with holistic considerations of buildings in many African countries, except for some building typologies in Ghana (Adom-Asamoah 2012) and Malawi (Giordano et al. 2021, 2023), poses huge challenges towards more accurate seismic risk analyses. Although the building stock may be similar across Sub-Saharan African countries, post-earthquake damage data vary extensively; and as such, fragility curves for a particular region can give more representative and accurate results. Unfortunately, distinct fragility curves published for Uganda do not exist.

Vulnerability curves for estimating the distribution of economic losses can be derived through the straightforward convolution of fragility curves and consequence models (e.g., Bal et al. 2008; Crowley et al. 2005; Hazus-MH 2003 and Smyth et al. 2004) whereas the distribution of the human loss ratios can be described using casualty models. Consequence and casualty models can be defined by specifying parameters of the continuous distribution of loss ratios for each damage/limit state (Pagani et al. 2023). The plausible lack of fragility, consequence and casualty models for Uganda is amongst the dominant limitations of this study. In that respect, analytical vulnerability curves derived for equivalent single degree of freedom models of different typologies analysed using non-linear time history analysis (D'ayala et al. 2014; Martins and Silva 2021; Rao et al. 2020) are selected from the GEM global vulnerability database (Martins and Silva 2023) and adopted in this study. Although the exposure model adopted in this study includes some buildings of medium ductility, the taxonomy mapping herein assigns vulnerability curves developed for buildings of low ductility level which is essentially more representative of Uganda's building stock. Depending on the number of storeys, various building taxonomies across Uganda are mapped to their corresponding conversion of vulnerability models as shown in Table 3. The nomenclature and corresponding plots for each vulnerability curve in the taxonomy mapping above can be obtained from GEM Foundation vulnerability database (Martins and Silva 2023) which is hosted within: https://github.com/gem/global_vulnerability_model/.

7 Results

7.1 MC-based probabilistic seismic hazard

In stochastic event-based earthquake loss assessment, the high computational demand of MC simulations renders the evaluation of seismic risk for each logic tree branch combination impracticable. Following a branch sampling strategy (e.g., Porter et al. 2017 and Rao et al. 2020) which relies on sensitivity analysis to trim an intractable logic tree whilst minimising the propagation of the associated epistemic uncertainties, 100 terminal branches are sampled from the overall logic tree and 100 sets of stochastic events are simulated for each logic tree path. The rupture geometries shown in Fig. 10 are then generated by sampling ground motion intensity values using the GMMs assigned for each tectonic sub-region. As expected, the largest earthquake ruptures strike along the two geo-tectonic and seismically active branches of the EARS. Whereas the Precambrian basement of Uganda is largely

Table 3 Mapping of the various building taxonomies to the GEM global vulnerability curves

Building taxonomy	Corresponding conversion of the vulnerability model
1. Low-medium code reinforced concrete with:	
(a) Infill walls	CR/LFINF + CDL + DUM/H1;CR/LFINF + CDL + DUM/H2; CR/LFINF + CDL + DUM/H3; CR/LFINF + CDL + DUM/H5; CR/LFINF + CDL + DUM/H8
(b) Shear walls	CR/LWAL + CDL + DUM/H1; CR/LWAL + CDL + DUM/H2; CR/LWAL + CDL + DUM/H3; CR/LWAL + CDL + DUM/H5; CR/LWAL + CDL + DUM/H8
2. Non-ductile un-reinforced masonry consisting of:	
(a) Adobe blocks	MUR + ADO/LWAL + DNO/RWO/H1; MUR + ADO/LWAL + DNO/RWO/H2;MUR + ADO/LWAL + DNO/RWO/H3
(b) Concrete blocks	MUR + CBH/LWAL + DNO/H1; MUR + CBH/LWAL + DNO/H2; MUR + CBH/LWAL + DNO/H3; MUR + CBH/LWAL + DNO/H4
(c) Fired clay bricks	MUR + CLBRH/LWAL + DNO/H1; MUR + CLBRH/LWAL + DNO/H2; MUR + CLBRH/LWAL + DNO/H3; MUR + CLBRH/LWAL + DNO/H4
(d) Dressed stone masonry	MUR + STDRE/LWAL + DNO/H1; MUR + STDRE/LWAL + DNO/H2; MUR + STDRE/LWAL + DNO/H3; MUR + STDRE/LWAL + DNO/H4
(e) Rubble stone masonry	MUR + STRUB/LWAL + DNO/H1; MUR + STRUB/LWAL + DNO/H2; MUR + STRUB/LWAL + DNO/H4
3. Confined masonry of low-medium ductility	MCF/LWAL + DUL/H1; MCF/LWAL + DUL/H2; MCF/LWAL + DUL/H4
4. Structural steel buildings of low-medium ductility	S/LFM + CDL + DUM/H1; S/LFM + CDL + DUM/H2
5. Wooden, wattle and daub, metal and vegetative exterior walled buildings	W/LFM + CDL + DUM/H1; W/LFM + CDL + DUM/H2; W/LFM + CDL + DUM/H3; W + WWD/LWAL + DNO/H1; W + WWD/LWAL + DNO/H2

stable and inactive, several earthquake ruptures have been recorded along the Rwenzori fold belt: especially around the Lake Victoria microplate, Utimbere, Nyanza and Speke rifts at the Uganda-Kenya-Tanzania border.

Within an investigation period of 50 year, the seismic hazard maps on reference rock site conditions with $V_{s,30}$ = 760 *m/s* and site-dependent hazard maps estimating 10% POE (475-year return period) and 2% POE (2475-year return period) in terms of peak ground acceleration (PGA) in g are shown in Figs. 11a-b and 12a-b, respectively.

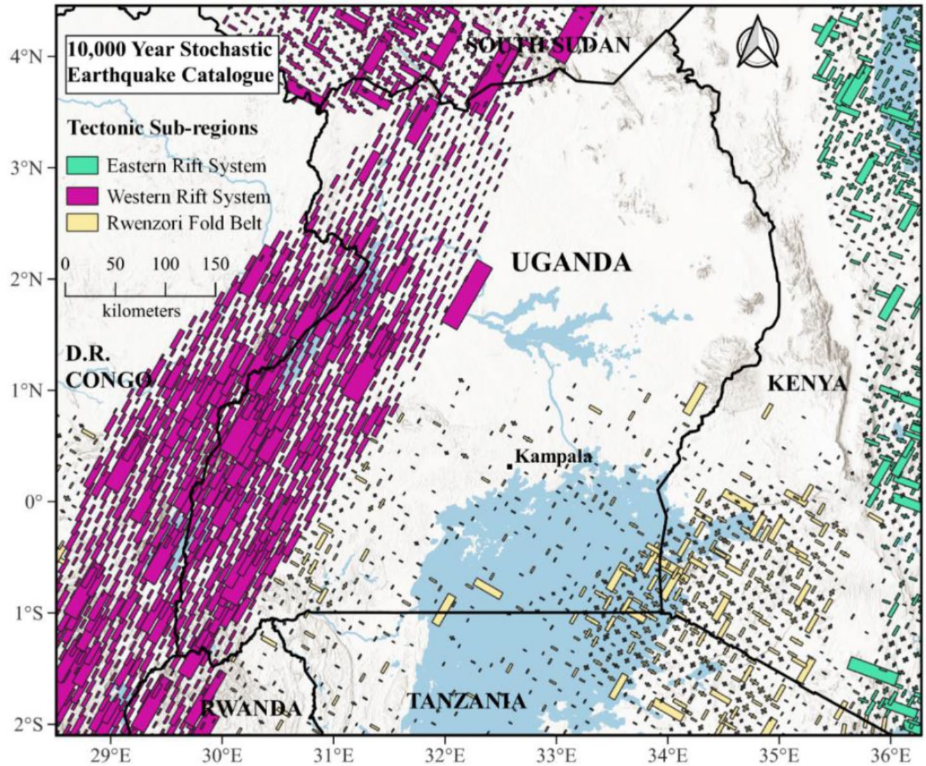

Fig. 10 Earthquake rupture geometries illustrating a 10,000-year subset of stochastic event catalogue striking each tectonic regime, following the major earthquakes ($M_w \geq 4.0$) in Uganda

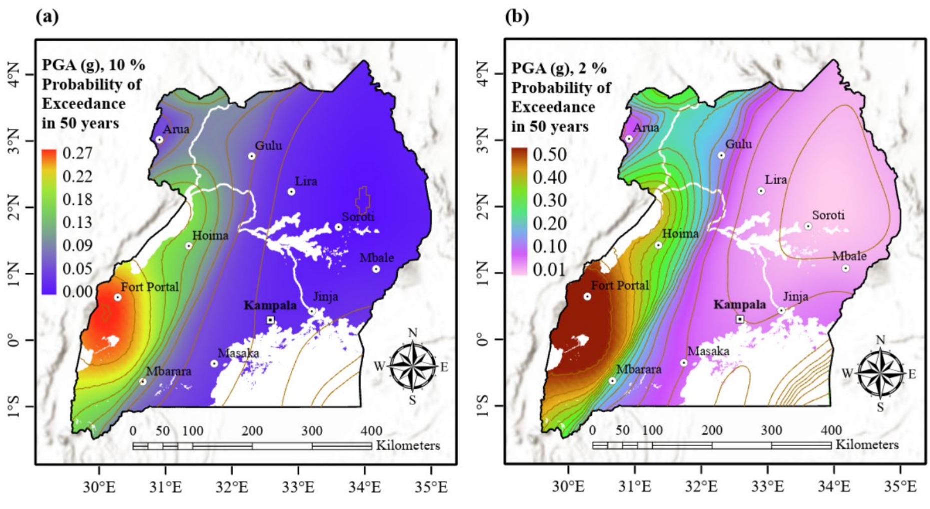

Fig. 11 Earthquake hazard maps of Uganda on reference rock site conditions with a 0.03 g contour interval investigated in terms of PGA (g) and presented for: **a** 475-year return period (10% POE in 50 years), and **b** 2475-year return period (10% POE in 50 years) (Oleng et al. 2024b)

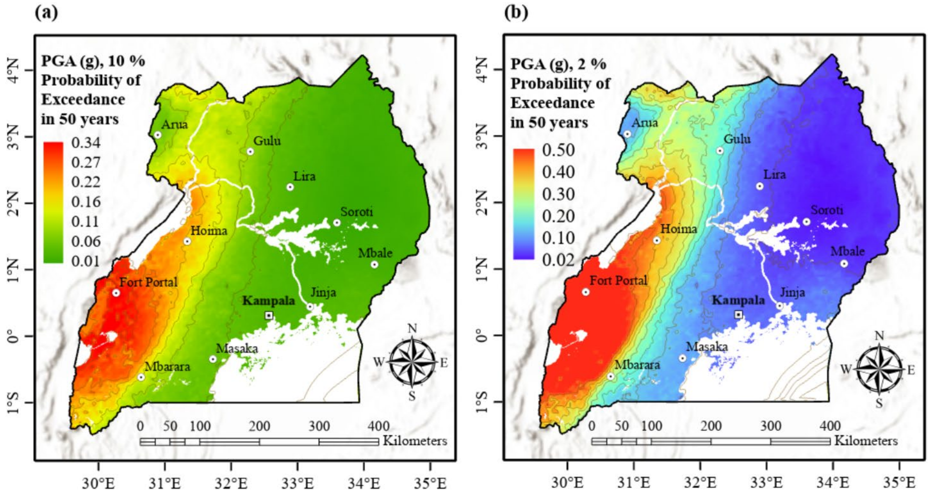

Fig. 12 Site-dependent seismic hazard maps of Uganda investigated over 50 years, in terms of PGA (g) and computed for: **a** 10% POE (475-year return period), and **b** 2% POE (2475-year return period). Contour lines are imposed on the maps at 0.05 g contour interval (Oleng et al. 2024b)

The seismic hazard estimate presented herein is largely consistent with previous national and regional studies and further confirms that the highest level of seismicity is concentrated in western Uganda. The Rwenzori and Kigezi regions that can expect maximum PGA values ranging between 0.24 and 0.27 g, respectively, on Type A (rock) ground for a 475-year return period are prone to the worst level of seismicity. Additional discussions into the findings and implications of the earthquake hazard model presented in this work can be found in the study by Oleng et al. (2024b).

7.2 Probabilistic seismic risk

7.2.1 Loss exceedance curves

Alongside the Uganda's nominal GDP estimate of US$ 40.5 billion (UBoS 2022) which is used to display loss values relative to the national GDP on the secondary vertical axis, mean and quantile loss exceedance curves estimating economic losses over several return periods are presented in Fig. 13. On the other hand, loss exceedance curves predicting the likely number of deaths over various return periods are shown in Fig. 14.

7.2.2 Mean annual loss maps

By associating losses between buildings of similar vulnerability classes (Jayaram and Baker 2009), the aggregated loss maps derived in this work are more representative of the entire exposure model (Carvalho et al. 2008; Park et al. 2007). The economic loss maps of Uganda showing mean annual loss values which are aggregated according to municipality/county, sub-county, parish, and grid-based exposure levels are shown in Fig. 15a-d. On the other hand, mean annual human fatalities are computed for night-time occupancy in all residential

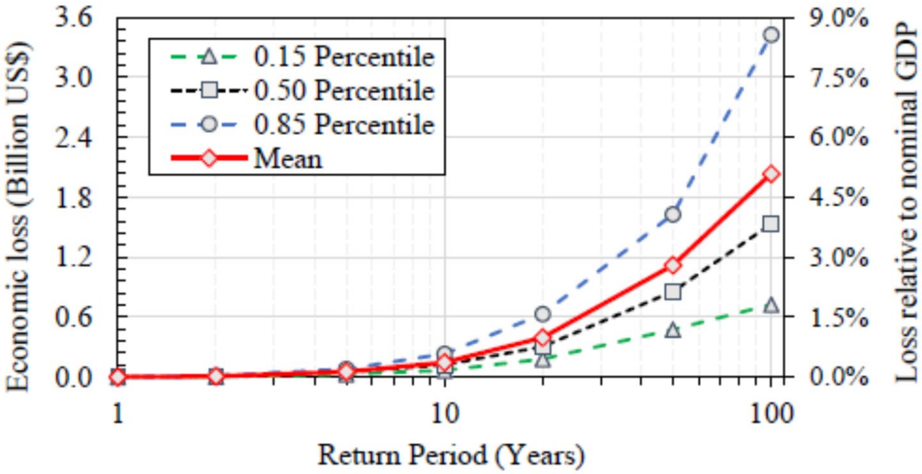

Fig. 13 Mean and quantile economic loss exceedance curves showing losses relative to the country's nominal gross domestic product

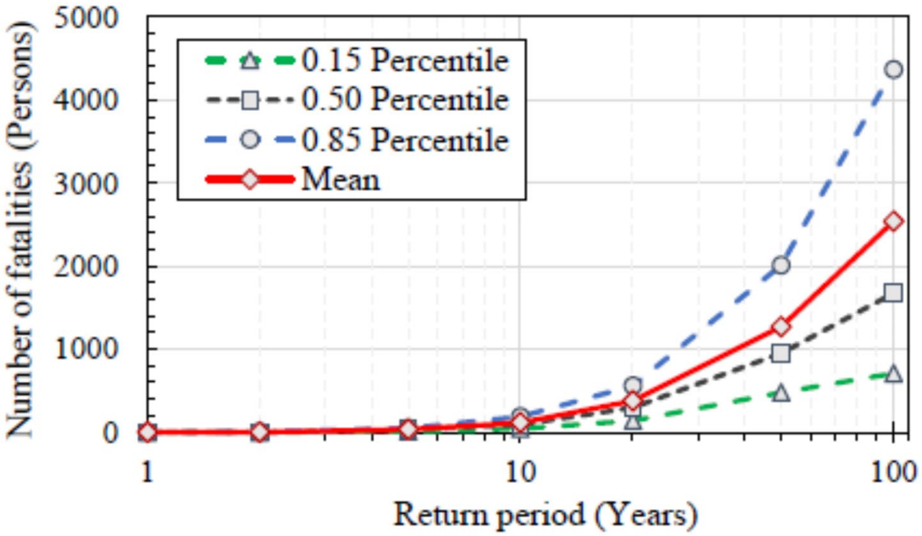

Fig. 14 Mean and quantile loss exceedance curves for number of deaths that are likely to occur in various return periods

buildings comprising Uganda's building stock and their spatial distribution aggregated at various levels as portrayed in Fig. 16a-d.

In order to ascertain the spatial distribution of mean annual economic losses and average yearly fatalities across rural and urban settlements in each region of Uganda, seismic risk calculations are aggregated, and results plotted as shown in Fig. 17a-b. It is observed that, mainly due to its active seismicity yet comprising many substandard buildings coupled with

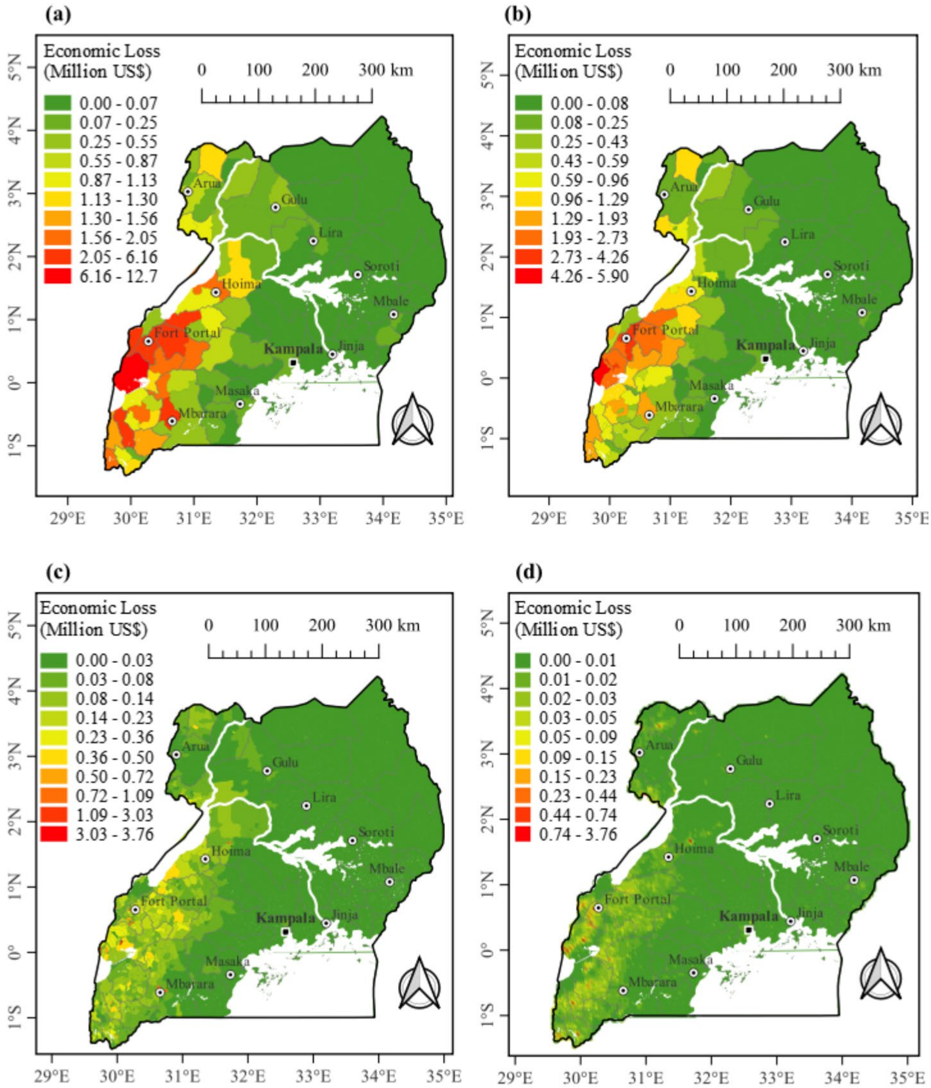

Fig. 15 Economic loss maps of Uganda indicating the average annual loss values for all occupancy types and aggregated at various exposure categories corresponding to: **(a)** municipality/county boundaries, **(b)** sub-county level, **(c)** parish extents, and **(d)** grid cell-based exposure model

a highly escalating population growth, western Uganda is exposed to the highest level of seismic risk.

For purposes of providing a more accurate picture of the real impacts of earthquakes, especially on more socially vulnerable sectors within the community of those living in highly vulnerable assets characterized by low replacement values, average annual economic loss ratios aggregated at municipality and sub-county levels are mapped in Fig. 18a-b. Considering the same administrative boundaries, mean loss ratios for annual fatalities are shown

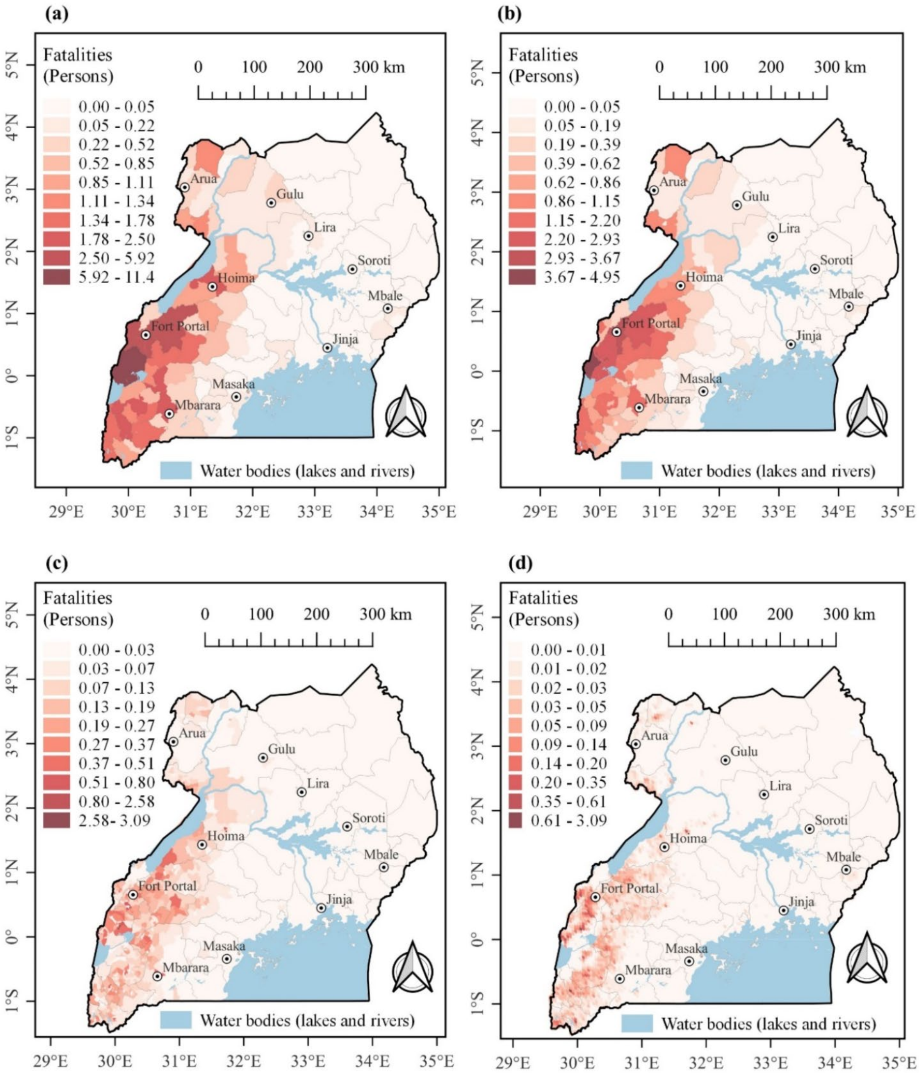

Fig. 16 Loss maps of Uganda showing the mean annual fatalities for night-time occupancy in residential buildings, aggregated for exposure categories corresponding to: **a** municipality/county boundaries, **b** sub-county level, **c** parish extents, and **d** grid cell-based exposure model

in Fig. 18c-d. The largest loss ratios are concentrated in the western Uganda, particularly in Rwenzori region.

Considering that recordings for a given earthquake event are available at a number of sites, knowledge of various ground-motion fields can be used whilst incorporating their spatial correlation to constrain shaking intensity for sites neighbouring the recording stations (Crowley et al. 2008). Spatial correlation model (e.g. Esposito and Iervolino 2012; Goda and Hong 2008; Jayaram and Baker 2009; and Wang and Takada 2005) can be used to obtain inter-event and intra-event residuals at each site when modelling ground-motion fields for

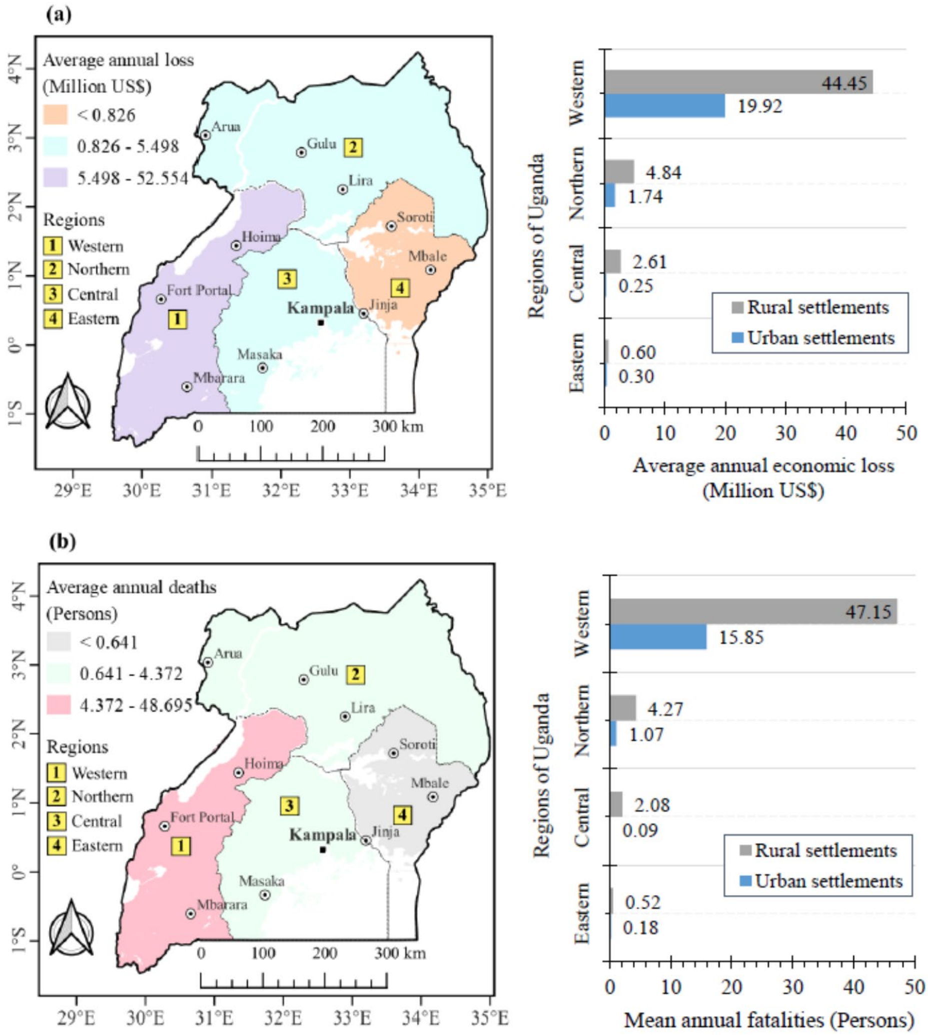

Fig. 17 Loss maps of Uganda and the distribution of losses across rural and urban settlements, aggregated on a regional basis and presented for: **a** economic (structural) average annual losses for all occupancy categories, and **b** mean annual fatalities for night-time occupancy in residential buildings comprising the country's housing stock

scenario earthquakes (Erdik 2021). Even though the inclusion of the spatial correlation of ground motion intensities into the earthquake risk analysis can result in more representative estimates (Weatherill et al. 2015), the present study does not consider the inclusion of spatial correlation of intra event residuals as it increases computational complexity (Sianko et al. 2023). Moreover, the spatial correlation of intra event residuals does not influence the average annual loss and has insignificant impact on the losses for large-scale risk assessment (Crowley et al. 2008).

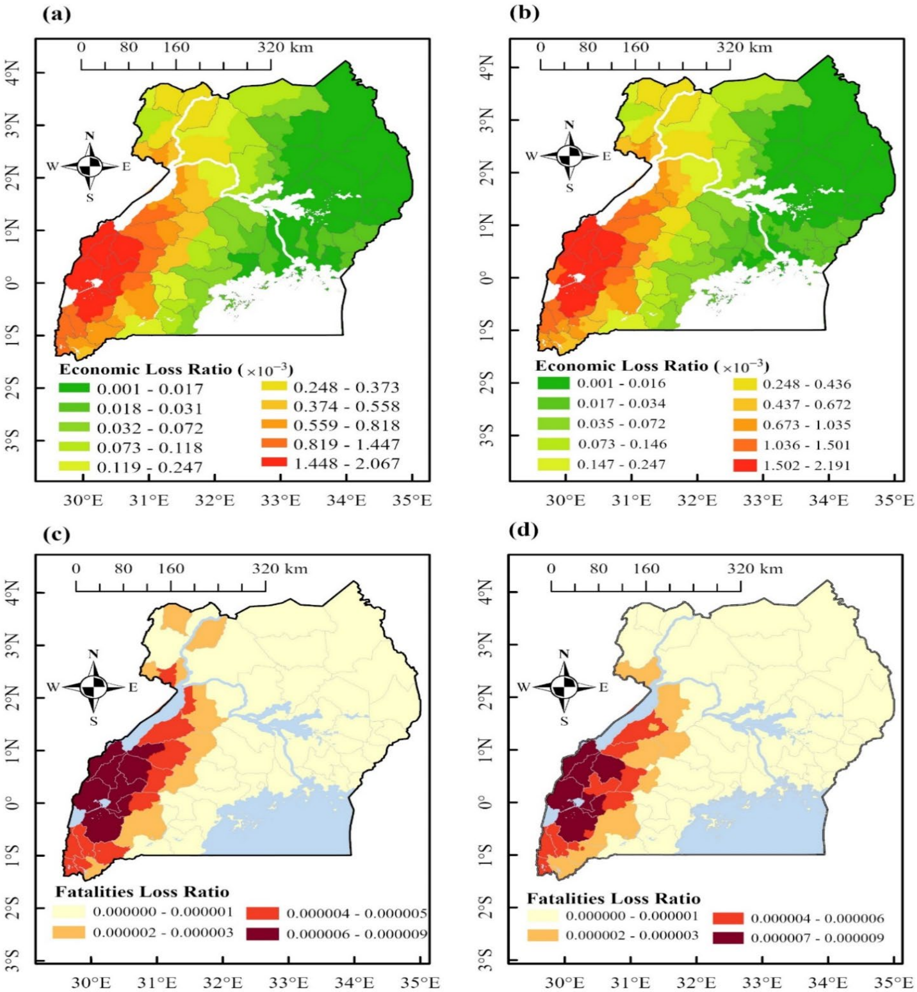

Fig. 18 Average annual economic loss ratios obtained for all occupancy types and aggregated at **a** municipality/county, **b** sub-county; and mean loss ratio maps showing the annual fatalities for night-time occupancy in residential buildings comprising Uganda's building stock and aggregated at **c** municipality/county, and **d** sub-county

7.3 Comparison with previous regional predictions

This work considers three lines of business (residential, commercial, and industrial) whose risk indicators are compared with the global earthquake risk model estimated by Silva et al. (2023) as presented in Table 4. Whilst the present study estimates a total average annual loss value in excess of US$ 74.7 million, Silva et al. (2023) predicted lower average annual losses due to damaged buildings of US$ 64.7 million across the whole country. Furthermore, average economic loss values obtained for all occupancy types are computed for return periods of 1, 2, 5, 10, 20, 50, and 100 years and compared with the overall previous estimates by GEM Foundation (Silva et al. 2018, 2023) as shown in Fig. 19. Whereas

Table 4 Comparison of seismic risk indicator obtained in the present study with previous estimates of the global earthquake Model seismic risk map derived by Silva et al. (2023)

Occupancy type	Silva et al. (2023)		Present study	
	Average annual loss (Thousand US$)	Mean annual loss ratio (%)	Average annual loss (Thousand US$)	Mean annual loss ratio (%)
Residential	59,134	0.376	67,385	0.339
Commercial	4,699	0.400	5,555	0.405
Industrial	906	0.165	1,782	0.235
Total	64,739	0.371	74,722	0.340

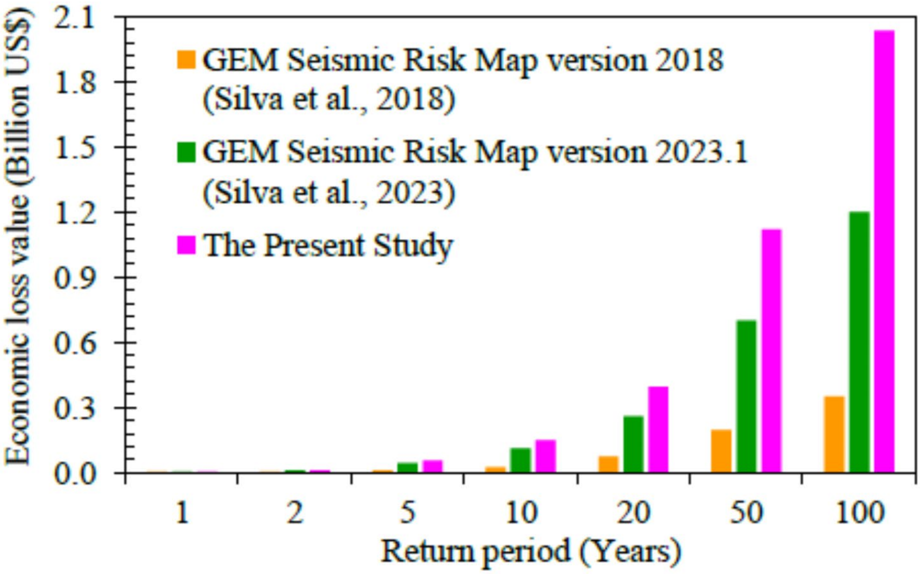

Fig. 19 Average economic loss curves derived for all occupancy types estimated in the present study, compared with the predictions from GEM Seismic Risk Models

there are insignificant differences in economic loss values at lower return periods, larger variations are observed for long return periods. In general, the present study predicts higher losses compared with GEM Foundation (Silva et al. 2018, 2023) estimates. For instance, compared with the GEM seismic risk map version 2023.1 (Silva et al. 2023), a difference of more than approximately US$ 25.3 million, US$ 195.4 million and US$ 349.4 million is estimated over 10, 50 and 100-year return periods respectively.

Although Silva et al. (2023) relied on the global seismic hazard map of Johnson et al. (2023) from which a maximum PGA raising to 0.35 g is predicted, this study adopts the hazard model by Oleng et al. (2024b) in which lower PGA values increasing to a maximum of 0.27 g are estimated over a 475-year return period across Uganda. Whereas a lower earthquake risk is expected on the basis of the present seismic hazard model, the current study generally estimates a higher risk partly due to higher total building replacement costs which are adjusted to reflect current market rates of construction. Moreover, as opposed to Silva et al. (2023) who mapped some building taxonomies to vulnerability curves developed for buildings of medium ductility, this study maps all building taxonomies to analytical vulnerability curves for non-ductile and low code buildings which typically represent the bulk of Uganda's housing stock.

According to the disaster risk profile of Uganda (WorldBank 2019), an earthquake capable of causing strong ground shaking is expected to occur at least once in a person's lifetime, especially for the exposed population in high hazard regions. Uganda's disaster risk profile (WorldBank 2019) further indicates that the highest contribution to the national seismic risk, in terms of average annual population affected, is generated within Ntoroko, Kabarole, Kasese and Nebbi districts. In that regard, mean annual economic losses are determined for some high risk districts in western Uganda and compared with the net present value (NPV) of the previous GEM Foundation estimates by Silva et al. (2018) as presented in Fig. 20. It is observed that the seismic risk model herein, which relies on non-ductile and low code vulnerability models for building exposure projections as of 2024, estimates higher economic mean annual losses.

7.4 Aggregated asset loss statistics

Mean annual economic losses per building taxonomy are disaggregated to understand the contribution of each building type to the overall economic losses incurred as shown in Fig. 21a-d. In general, the largest average annual economic losses are generated by non-ductile unreinforced masonry buildings consisting of adobe blocks, which comprise the main proportion of Uganda's building stock.

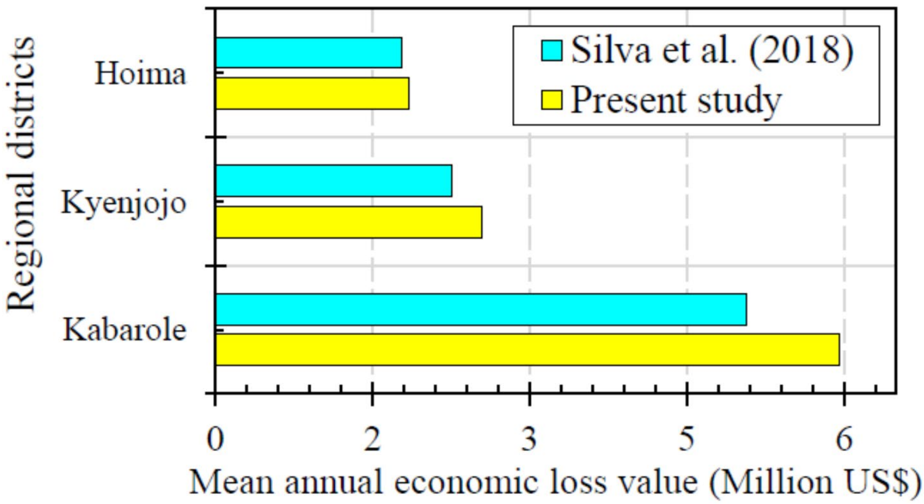

Fig. 20 Comparison of mean annual economic losses estimated in the present study with the net present value of the predictions by Silva et al. (2018) projected to 2024 for major high-risk districts in western Uganda

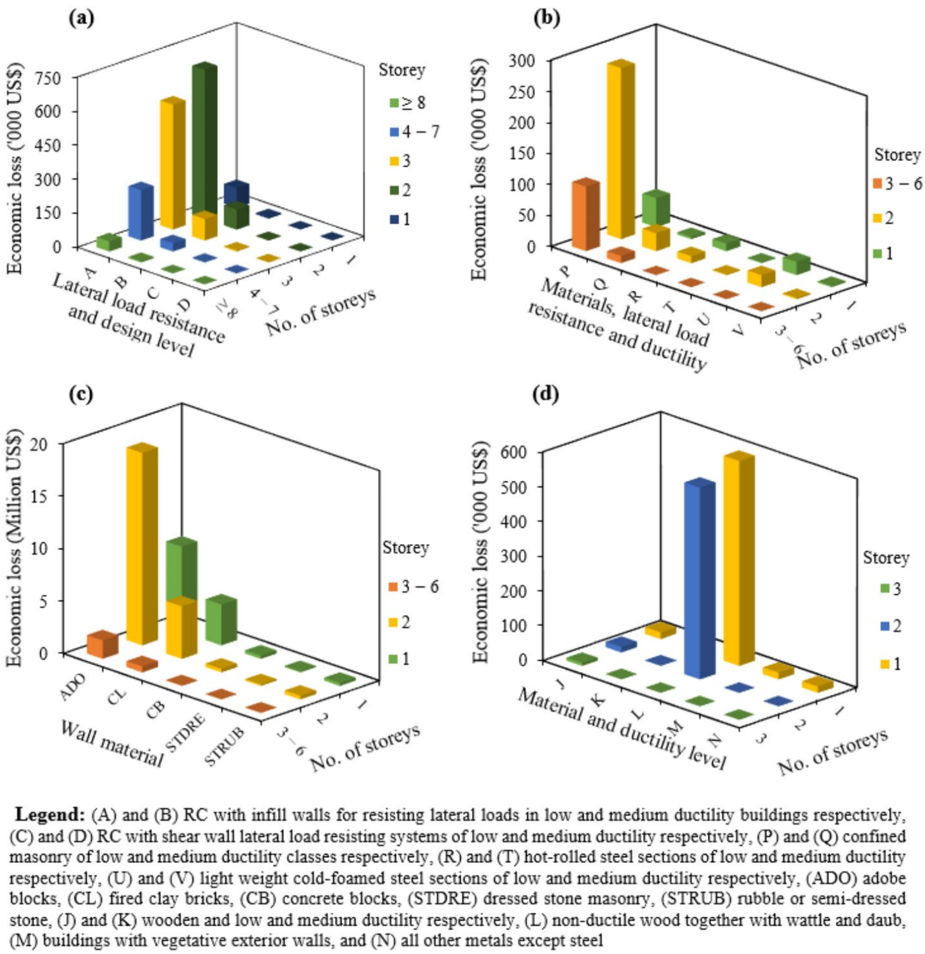

Fig. 21 Average annual economic losses computed for: **a** reinforced concrete, **b** confined masonry and steel, **c** non-ductile unreinforced masonry, and **d** wooden and other building types. (A) and (B) RC with infill walls for resisting lateral loads in low and medium ductility buildings respectively, (C) and (D) RC with shear wall lateral load resisting systems of low and medium ductility respectively, (P) and (Q) confined masonry of low and medium ductility classes respectively, (R) and (T) hot-rolled steel sections of low and medium ductility respectively, (U) and (V) light weight cold-foamed steel sections of low and medium ductility respectively, (ADO) adobe blocks, (CL) fired clay bricks, (CB) concrete blocks, (STDRE) dressed stone masonry, (STRUB) rubble or semi-dressed stone, (J) and (K) wooden and low and medium ductility respectively, (L) non-ductile wood together with wattle and daub, (M) buildings with vegetative exterior walls, and (N) all other metals except steel

8 Discussion

Despite the lack of a national earthquake risk assessment conducted for Uganda, the stochastic event-based seismic risk framework derived herein is largely consistent with previous global estimates. To begin with, the mean economic loss exceedance curve showing the losses relative to nominal GDP (see Fig. 13) indicates that the mean economic losses for 10, 50 and 100-year return periods are in excess of US$ 148 million (0.36% GDP), US$ 1.12 billion (2.72% GDP) and US$ 2.04 billion (4.94% GDP) respectively. Similarly, the mean loss exceedance curve showing likely fatalities (see Fig. 14) indicates average death estimates of 113, 1270 and 2537 persons over a 10, 50 and 100-year return periods, respectively. On the other hand, the mean annual loss maps presented in Fig. 15a-d indicate that the economic loss is largely concentrated in Kigezi, Rwenzori and Albertine regions of western Uganda; where for instance a maximum mean annual economic loss of US$ 12.7 million can be incurred at a given county or municipality as illustrated in Fig. 15a. In terms of the average annual population affected by earthquakes, the districts (e.g., Kasese, Kabarole, Bundibugyo, Ntoroko, Hoima, and Mbarara) located near the western branch of the EARS have the highest contribution to seismic risk in Uganda. High economic losses are attributed to the high seismicity and a growing population of the districts of western Uganda (Oleng et al. 2024b).

It is worth noting that damages of more than US$ 1.13 million per year is anticipated in a given municipality located the north-eastern part of the country, near Arua city. In addition, Kampala capital city and its immediate environs can expect a maximum mean annual economic loss of US$ 0.55 million. Although Kampala is situated in an area of low seismicity, the associated relatively high absolute damage costs can be attributed to the high concentration of exposed assets (Mujugumbya et al. 2006). Although the seismic hazard across the rest of Uganda is very low, substantial economic losses are still expected to increase owing to the presence of many substandard buildings located in soft soils, notwithstanding the already high rate of urbanisation and population growth across the region. By and large, the seismic risk model derived in this work estimates an overall economic mean annual loss of US$ 74.7 million across the whole country. This value is fairly realistic compared with economic losses indicated in past earthquake damage reports (e.g., Balikuddembe and Sinclair 2018; Kahuma et al. 2006 and USGS 2016), where for instance economic losses worth US$ 60 million were incurred in the aftermath of the catastrophic 1994 Kisomoro earthquake which struck Kabarole, Bundibugyo and Kasese districts (NEDC 1994). Furthermore, the mean annual fatalities map for night-time occupancy in residential buildings (shown in Fig. 16a) indicates that, within a county/municipality, up to 11 deaths could be incurred on average per year in western Uganda. Across the whole country, the mean annual death toll due to seismic activity is estimated to increase to a maximum value of 71 persons.

Following the mean annual economic losses and average annual fatalities aggregated by region and settlement type (see Fig. 17a-b), mean annual economic loss of US$ 64.4 million and average fatalities of 63 persons can be incurred per year across rural and urban settlements in western Uganda. This indicates that over 86.2% of Uganda's total seismic risk originates from its western territory. Whereas about 8.8 and 3.8% contribution of mean annual economic losses are generated from the northern and central territories respectively, eastern Uganda is exposed to the lowest level of seismic risk with less than US$ 900,000 likely to be incurred on average, per year. It is worth noting that, in addition to over 75.8% likely deaths, more than 70.2% of mean economic annual losses originate from the widely spread rural settlements in Uganda: partly due to the high vulnerability of most substandard buildings.

The asset loss statistics shown in Fig. 21a indicate that low ductility RC buildings that rely on infilled walls for resisting lateral loads can suffer mean annual economic losses of over US$ 655,000, US$ 550,000, and US$ 220,000 for 2, 3, and 4–7 storeyed buildings, respectively. More than US$ 275,000 and US$ 103,000 are respectively calculated for 2-

and 3-storeyed confined masonry buildings of low ductility (see Fig. 21b). Whereas most typologies generate low losses, possibly due to their lower likelihood of damage due to ground shaking and the fact that they represent only a small fraction of Uganda's building stock, the largest disaggregation of economic losses comes from non-ductile unreinforced masonry buildings (see Fig. 21d). For instance, the mean annual loss for single and double storeyed comprising adobe block wall construction material is estimated at over US$ 8.1 million and US$ 18.4 million, respectively.

Although the framework presented in this study provides a fundamental basis for practical seismic risk appraisals across Uganda, the major challenge faced in this work is lack of detailed information regarding assets contained in the exposure model. Uganda Bureau of Statistics and National Planning Authority should conduct a thorough population and housing census (supplemented by quick walkthrough and detailed surveys of individual buildings, satellite images and remote street surveys) to specifically derive a more elaborate building classification scheme that describes different building attributes in a more refined manner. Government agencies (e.g., the National Building Review Board in conjunction with Uganda Institution of Professional Engineers, Institution of Surveyors of Uganda and Uganda Society of Architects) endeavour to establish actual building construction costs which will inform more detailed and refined seismic risk analyses. Another challenge faced in this study is the lack of casualty, consequence, fragility and vulnerability models which are developed with holistic considerations of the building stock in Uganda. Hence there is a need to derive fragility and vulnerability curves specific for the building stock in Uganda. Realistic finite element models of selected building types in Uganda should be developed to derive fragility curves that satisfactorily reflect the corresponding capacity, demand and limit state uncertainties. In this regard, the relevant government institutions like the Directorate of Geological Survey and Mines and Ministry of Relief, Disaster Preparedness and Management ought to improve earthquake monitoring and recording of post-earthquake damage data.

Considering that mitigation of seismic risk at a national level largely requires the formulation and implementation of appropriate earthquake design codes, there is an urgent need to identify key deficiencies and make recommendations toward performing an in-depth review and update of Uganda's seismic code of practice for structural design (US 319:2003). Further to aligning US 319:2003 to modern seismic design standards, there is need to explore the use of locally sourced timber as a structural material for post-disaster relief housing. Earthquake-resistant timber houses which suit the social and cultural practices of the communities living in in Uganda's earthquake-prone zones can be designed and tested under earthquake loads through numerical simulations. On the other hand, scenario-based analyses (e.g., Opabola and Galasso 2024 and Goda et al. 2022) can be employed to comprehensively revise the policies stipulated in the National Policy for Disaster Preparedness and Management (NPDPM 2010). Moreover, gross insurance premiums and a government insurance scheme should be determined for various types of construction in each region based on the seismic risk levels.

Succinctly, strengthening public awareness of earthquake-induced disaster is critical and can be achieved through promoting risk education, universal access to disaster risk information, building social demand for risk mitigation and encouraging individual safety as well as public responsibility. Information campaigns towards creating earthquake awareness can be instigated through the preparation of videos and maps based on the findings of the present study. Moreover, a participatory approach is critical for local communities to adopt mitigation measures that fully or partially change their lifestyle. For the strongest possible earthquake in scenario cities (e.g., Fort Portal), emergency plans catering for the number of buildings likely to be damaged and require immediate inspections, number of people required to stay away from buildings and provisions to be made for temporary accommodation, water and food should be set in place. In addition, the number of people likely to be injured and the number of field hospitals equipped with beds to be deployed within 24 h can be determined based on the framework presented in this study. Finally, efficient and effective coordination of emergency response resources at local and national levels should be planned at both civil and military levels.

9 Conclusions

Seismic risk in Uganda is intensifying due to its rapidly growing population and urbanisation coupled with a highly vulnerable substandard building stock caused by lack of building control and out-of-date seismic design guidelines. As a pioneering step towards building seismic risk and resilience for the country, the present study employs the probabilistic event-based risk calculator of *OpenQuake*-engine to holistically assess potential losses resulting from future earthquakes. Uganda's exposure model estimates approximately 9.62 million residential buildings, 198,000 commercial buildings and 85,000 industrial facilities respectively valued in excess of US$ 171.45 billion, US$ 11.9 billion and US$ 6.6 billion. Globally calibrated analytical vulnerability curves derived for equivalent single degree of freedom models of various building typologies in various tectonic regimes are combined with the event-based probabilistic seismic hazard model for Uganda. The seismic hazard map computed for a 475-year return period indicates a maximum reference PGA of 0.27 g on rock ground in western Uganda. In general, over 86.2% of the total earthquake risk originates from western Uganda (particularly within the districts of Kasese, Kabarole, Bundibugyo, Ntoroko, Hoima, and Mbarara) and only about 8.8, 3.8 and 1.2% contribution of mean annual losses are generated from the northern, central and eastern territories, respectively. Overall, mean annual losses worth US$ 74.7 million coupled with a mean annual death toll of up to 71 persons can be expected to be instigated by seismic activity nationwide. On average, economic losses worth 0.36, 2.72, and 4.94% of the country's nominal GDP can be expected over 10, 50 and 100-year return periods, respectively. Partly due to their high vulnerability and the fact that they represent the bulk of Uganda's building stock, the largest disaggregation of the losses originates from non-ductile unreinforced masonry buildings comprising adobe blocks. However, seismic risk in Uganda is not very high and could be easily dealt with via compulsory building insurance such as a National Insurance Scheme (NIS) that allows for fixed compensation per square-metre. The seismic risk assessment framework proposed in this work presents a huge step towards providing practitioners, policymakers, insurance companies and government stakeholders with practical seismic risk appraisals towards risk-informed decision making, especially at a national policy level.

Acknowledgements The authors are entirely responsible for the contents herein. This paper represents a chapter from Dr Morris Oleng's PhD thesis, and he appreciates the highly constructive contribution of his external examiner, Professor Carmine Galasso (Department of Civil and Environmental Engineering, University College London). The authors are grateful to the US. Geological Survey and World Bank for providing preliminary data. Special thanks go to the Department of Relief, Disaster Preparedness and Management, Office of the Prime Minister in Uganda who provided the National Risk and Vulnerability Atlas of the country. In addition, the notable support from National Building Review Board, Uganda Institution of Professional Engineers, Uganda Engineers Registration Board, and Uganda National Bureau of Standards is highly appreciated.

Author contributions All authors contributed to the study conception and design. Material preparation and data collection was performed by Dr Morris Oleng. The development of codes and analysis were performed by Dr Morris Oleng, and Dr Zuhal Ozdemir and Professor Kypros Pilakoutas checked the results. The first draft of the manuscript was written by Dr Morris Oleng and Dr Zuhal Ozdemir and Professor Kypros Pilakoutas commented on previous versions of the manuscript. All authors read and approved the manuscript.

Funding The authors declare that this study been made possible by the funding from the United Kingdom Commonwealth Scholarship Commission (CSC) and the University of Sheffield. Scholar ID: UGCS-2020-760.

Declarations

Conflict of interest The authors declare no competing interests. The authors have no relevant financial or non-financial interests to disclose.

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