Research Article

Physical vulnerability assessment and household preparedness of Buea Municipality to seismic hazards from Mount Cameroon Eruptions: A cause for concern

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ABSTRACT

Earthquakes associated with volcanic eruptions from Mount Cameroon can impact society and building infrastructures. This study therefore aimed to assess the following: i) the geological features (rock/soil types) and its characteristics in selected localities within Buea municipality; ii) past-eruption/earthquake impact assessment on buildings; iii) physical vulnerability of buildings infrastructure and iv) household preparedness to earthquake hazards. The study utilized a mixed-method approach, combining quantitative and qualitative techniques. Geological characteristics was assessed through site visits across the selected ten localities by physical observation and rock sample collection. Past-eruptions (1959, 1982, 1999, 2000) impacts assessment on buildings and household preparedness to earthquakes were evaluated using structured questionnaires. Building vulnerability was assessed using the ENSURE and the Building Vulnerability Index (BVI) methodology on the following parameters: building state, building materials, house position (single, row, clustered), house age, proximity to volcano and the surrounding soils/rocks. Findings revealed the rock types are predominantly made up of basaltic rocks/lava, pyroclastic deposits, tuff, lahar deposits and brownish to black loamy soils. Earthquake impact on buildings from the 4 eruptions revealed that localities around the epicenter were the most affected. Physical vulnerability assessment revealed that 35 % of the vulnerable buildings were < 5 years old and were residential buildings. Quantitative analysis of building vulnerability indicated moderate vulnerability to seismic hazards in 50 % of the assessed localities. For household preparedness to volcanic earthquakes: 32.0 % of households had first aid kits and 73.1 % had identified safe evacuation locations. The study revealed that the presence of tuff, soft and loose unconsolidated soils; the position and state of buildings; and the absence of evacuation plans significantly contributed to seismic vulnerability in Buea municipality.

Key words: Physical vulnerability, building infrastructure, seismic hazards, household preparedness, Mount Cameroon eruptions

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RÉSUMÉ

Les tremblements de terre associés aux éruptions volcaniques du Mont Cameroun peuvent avoir un impact sur la société et les infrastructures de construction. Cette étude visait donc à évaluer les éléments suivants : i) les caractéristiques géologiques (types de roches et de sols) et ses caractéristiques dans des localités sélectionnées au sein de la municipalité de Buea; ii) l'évaluation de l'impact des éruptions passées et des séismes sur les bâtiments; iii) la vulnérabilité physique des bâtiments et des infrastructures et iv) la préparation des ménages aux risques sismiques. L'étude a utilisé une approche mixte, combinant des techniques quantitatives et qualitatives. La géologie a été évaluée par des visites sur le terrain dans les dix localités sélectionnées, par l'observation physique et la collecte d'échantillons de roches. L'évaluation de l'impact des éruptions passées (1959, 1982, 1999, 2000) sur la préparation des bâtiments et des ménages aux tremblements de terre a été réalisée à l'aide de questionnaires structurés. La vulnérabilité des bâtiments a été évaluée à l'aide de la méthodologie ENSURE et de l'Indice de Vulnérabilité des Bâtiments (IVB) sur la base des paramètres suivants : état du bâtiment, matériaux de construction, position de la maison (simple, en rangée, groupée), âge de la maison, proximité du volcan et géologie environnante. Les recherches ont révélé une géologie principalement composée de roches basaltiques, de dépôts pyroclastiques, de tuf, de dépôts de lahar et de sols limoneux brunâtres à noirs. L'impact du tremblement de terre sur les bâtiments des 4 éruptions a révélé que les localités situées autour de l'épicentre étaient les plus touchées. L'évaluation de la vulnérabilité physique a révélé que 35 % des bâtiments vulnérables avaient moins de 5 ans et étaient des bâtiments résidentiels. L'analyse quantitative de la vulnérabilité des bâtiments a révélé une vulnérabilité modérée aux risques sismiques dans 50 % des localités évaluées. En ce qui concerne la préparation des ménages aux tremblements de terre volcaniques : 32,0 % des ménages disposaient de trousses de premiers secours et 73,1 % avaient identifié des lieux d'évacuation sûrs. En ce qui concerne la préparation des ménages aux tremblements de terre volcaniques : 32,0 % des ménages disposaient de trousses de premiers secours et 73,1 % avaient identifié des lieux d'évacuation sûrs. L'étude a révélé que la présence de tufs, de sols meubles et meubles ; la position et l'état des bâtiments ; et l'absence de plans d'évacuation ont contribué de manière significative à la vulnérabilité sismique de la municipalité de Buea.

Mots clés : Vulnérabilité physique, infrastructure des bâtiments, risques sismiques, préparation des ménages, éruptions du Mont Cameroun

1. INTRODUCTION

More than a dozen volcanoes erupt at any given time on Earth, and close to 100 erupt in any year (Loughlin *et al.*, 2015). Hazards from volcanic eruptions such as earthquakes can impact society and critical infrastructures (Brown *et al.,* 2015). Globally, volcanic eruptions caused about 80,000 deaths during the 20th century (Sigurdsson *et al.*, 2015). Earthquakes are amongst the most dangerous hazards associated with volcanic eruptions. However, earthquakes that are linked to volcanic eruptions are less dangerous when compared to those associated to tectonic events (movement of plates). Their occurrence during eruptions can cause major destruction of structures of any type, with the loss of human lives and material property in densely populated areas where the epicentre is located (Ayiris and Delmelle, 2012). Since a major part of human activities takes place in buildings, it is of utmost importance to ensure the structural safety of these buildings against earthquakes. Apart from buildings, other structures impacted by earthquakes include lifelines such as: transport networks, electricity cables, water and gas pipes, and bridges (Baxter and Ancia, 2002). These lifelines are vital for effective emergency response and recovery during volcanic eruptions (Grant, 2015). In the 20th century, both tectonic and volcanic earthquakes resulted to the death of more than 1,400,000 people, giving an average of 15,000 people per year (Tanguy *et al.*, 1998).

Mount Cameroon (MC) which is the largest active continental volcano along the Cameroon Volcanic Line (CVL) based on its recorded eruptive history (i.e. 7 eruptions in the last ~ 120 years), exhibits both mild explosive (Strombolian) and effusive eruptions (Ayonghe and Wantim, 2016). Eruptions from this volcano are usually characterized by pre-eruptive (before), syn-eruptive (during) and post-eruptive (after) episodes of earthquake swarms (Ateba and Ntepe, 1997). The geological setting of MC presents a complex interplay of volcanic activity and tectonic processes, making the region susceptible to seismic events such as earthquakes and volcanic eruptions. Earthquakes from its 1999 eruption for example was felt within a 100-km radius (Suh *et al.*, 2003) with the epicenter closest to the city of Buea (Wantim *et al.*, 2018). The 1999 earthquake destroyed ~63 houses in the Bokwaongo-Sasse neighbourhood within Buea municipality which rendered ~250 people homeless; displaced household items; cracked/broke walls and floors; caused land subsidence in the West Coast area; while surface fractures, shallow landslides and water turbidity were observed in communities that make up the 7 councils at the flanks of MC (Wantim *et al.*, 2018).

Recent studies by Mbida *et al.* (2023) highlighted the potential for hazardous events from MC's volcanic activity, including intense tremors, lava flows, tephra fallout, volcanic gas release and lahars (which are volcanic mudflows considered as one of the ancient hazards at MC), which can have far-reaching impacts on nearby communities. The geological characteristics of Buea municipality, situated at the base of MC, plays a crucial role in determining the susceptibility of buildings and infrastructure to seismic hazards (Mbida *et al.,* 2023). Different rock and soil types found within Buea have the potential to exhibit varying degrees of susceptibility to ground shaking and volcanic activity. Suh *et al.* (2001) established after the 1999 and 2000 eruptions from MC that concrete buildings within Buea municipality were constructed with disregard to appropriate building codes.

Previous work carried out for eruptions resulting from MC that centred on its seismicity focused on: its seismicity prior to, during and after eruptions used to determine the earthquake source (shallow or deep) (Ateba and Ntepe, 1997; Ubangoh *et al.*, 1997; Ateba *et al.*, 2009); the relationship that existed between its deep near-constant magnitude, low-frequency microearthquakes events and semidiurnal tidal waves (Ambeh and Fairhead, 2007); understanding the complex crustal structure beneath MC characterized with seismic activities as deep as 25 km along the Tiko and Ekona faults (Suh *et al.*, 2001; Nguiya *et al.,* 2019); and its tectonics (Nama, 2004; Matthieu *et al.*, 2011). Despite these earlier studies basic knowledge on the physical factors that made buildings vulnerable to earthquakes and household preparedness to this hazard has remained rudimentary. A large focus of volcanology research has been on characterizing the occurrence and dynamics of different volcanic hazards; but without a sound knowledge of seismic hazards, there is little point in planning and implementing risk reduction treatments (Brown *et al.*, 2015).

In periods of emergency as observed by Wantim *et al.* (2018), insufficient preparation can increase disaster damage in terms of injuries, health crisis and even deaths. For example, in the period that characterised the aftermath of the 1999 MC eruption, due to lack of household preparedness to volcanic hazards, the population living in the coastal communities (West Coast area) whose water sources were contaminated by ashfall, drank and bathe with it (Wantim *et al.,* 2018). This resulted to health impacts such as skin rashes, eye irritations (conjunctivitis) and abdominal diseases (e.g. typhoid, diarrhoea) caused by lack of household preparedness. Additionally, the devastating consequences of Mount Nyiragongo's 22 May 2021 eruption (which was accompanied by earthquakes, ash fallout and lava flows) on the population in the city of Goma in Democratic Republic of Congo (GVP, 2021), could also be attributed to inadequate community and household preparedness. This eruption which lasted for just one day, destroyed over 3,500 houses that included critical infrastructure such as schools, hospitals/ health centres, electricity supply lines that resulted to power outage in parts of Goma city; displaced approximately 234,000 people in the days following the eruption; and left over 200,000 people without access to safe drinking water that triggered a cholera outbreak (ECHO, 2021; IFRC, 2021; UNHCR, 2021). It should be noted that when disasters strike, governments and aid organizations are not always able to help communities immediately. Household and individuals usually act as first aid responders to victims, and they cannot execute this effectively if no community or household preparedness items are available.

To mitigate the impact of seismic hazards from MC eruptions, household preparedness plays a pivotal role in enhancing resilience and reducing disaster risks. Effective preparedness measures encompass various aspects, including early warning systems, evacuation plans, infrastructure reinforcement, and community education campaigns (Ngwene *et al.,* 2020). However, household preparedness is contingent upon access to resources, socio-economic status, cultural beliefs, and prior experiences with volcanic eruptions (Tchokossa *et al.,* 2022). Unfortunately, in the African continent and Cameroon in particular, more emphasis is paid to response rather than preparedness. With increased settlement at the flanks of MC, population influx, poverty, lack of awareness and sensitization there is a likelihood for an increase level of exposure and vulnerability amongst households to the accompanying hazards. It is therefore imperative to understand the characteristics of people, building infrastructure and the geology that enhances their vulnerability to volcanic earthquakes.

Ever since the creation of the University of Buea in 1993 which heralded the growth of other higher institutions of learning, the population increased.

The population in Buea municipality in the early 2000's stood at ~ 130,000 people (BUCREP, 2010); which increased to 300,000 people by 2013 (BUCREP, 2013) and today it is estimated at ~ 500,000 people. An additional reason for this increase is linked to the influx of internally displaced persons (IDPs) fleeing other parts of the SW and NW Regions of the country which are more affected by the on-going armed conflict. This has led to the influx of people who have never experienced any of the eruptions from MC and lack total awareness of the associated hazards this volcano is linked to. The population density in the vicinity of MC exacerbates the vulnerability of households, as settlements often extend into high-risk zones due to limited land availability and economic constraints (Nkongho *et al.,* 2021). It is believed that in the event of an eruption of similar magnitude and intensities (usually in the range 2-4 on the Richter's scale and IV-VIII on the modified Mercalli's scale respectively) as the 1999 and 2000 eruptions more chaos will ensure as the incoming population is not knowledgeable on the household preparedness measures to take to handle its resultant hazards. New houses are also built without following the guidelines of the recently developed earthquake building code and building regulations for municipalities within the Mount Cameroon area (Earthquake Building Code, 2019).

A key aspect of mitigating the impact of seismic hazards from MC eruptions is assessing the physical vulnerability of building infrastructure within the region, through structural evaluations using fragility analysis and vulnerability curves to quantify the susceptibility of buildings to seismic forces and volcanic hazards (Njome *et al.,* 2021). There is a slogan that says that '*Earthquakes don't kill but buildings do*.' The state of a building has a significant role to play in the way it responds to seismic waves. The way houses are constructed in Buea municipality urgently requires a detail physical vulnerability assessment to ascertain their strength against future eruptions. Prior to the design of this study, a poorly constructed supermarket collapsed in the Check Point neighbourhood of Molyko, in April of 2017 not linked to seismic activities from the volcano. Recently, in the month of February 2024, a poorly constructed two-storey building collapsed in the Dirty South neighbourhood of Molyko killing one person and injuring 5 others.

Over the years, vulnerability assessments have primarily targeted damage and occupant exposure with limited analysis of other physically relevant assets such as soils and building infrastructure and communities' preparedness levels. This study evaluated the factors that are critical in the improvement of physical vulnerability to volcanic earthquakes (seismic hazards) in Buea municipality and household preparedness to earthquake hazards. The aims of the present study were: i. to analyze the geological characteristics of selected localities within the municipality, ii. to assess the impact of past eruptions and earthquakes on buildings, specifically from the 1959, 1982, 1999, and 2000 events, iii. to evaluate the physical vulnerability of the built environment to earthquakes and iv. to examine household preparedness to earthquake hazards. This study considered early vulnerability research and previous fragility studies to address the current research knowledge gap, by developing a methodological framework to derive vulnerability function for building infrastructure impacted by volcanic hazards.

2.0 MATERIALS AND METHODS

2.1. Study Area

The city of Buea (4°102 03 N and 9°142 03 E) is located on the eastern slopes of MC, bounded to the north by lowland tropical forest (Fig 1). MC is an edifice, which is ~ 4100 m high, above sea level (a.s.l). The area is composed of undulating high and lowlands. The rocks are predominantly basaltic because of volcanic activities from MC. They weather to produce dark loamy soils ranging in age from 1 to 31 Ma without any clear spatial pattern (Suh *et al.,* 2003). The soils are well drained due to the generally hilly nature of the terrain. Volcanic activity has greatly altered and influenced the biophysical environment (Buea Communal Development Plan, 2012).

2.2 Research Design

The study made use of a mixed-method approach, combining quantitative and qualitative techniques. Field work was conducted in ten (10) localities within Buea municipality (Fig 1): Bolifamba, Bomaka, Muea, Molyko, Bokwai, Bonduma, Great Soppo, Buea Town, Bokwango and Small Soppo/Sasse/Tole area between 2018 and 2021. Out of these 10 localities, just 5 of them (Small Soppo, Bokwaongo, Molyko, Great Soppo and Buea town) were assessed for household preparedness to earthquake hazards. In these five localities, stratified and purposive sampling techniques (Patton, 2002), were used in selecting suitable respondents for the study. Intensive field observations were conducted to perform geological analysis and to complement the existing geologic map.

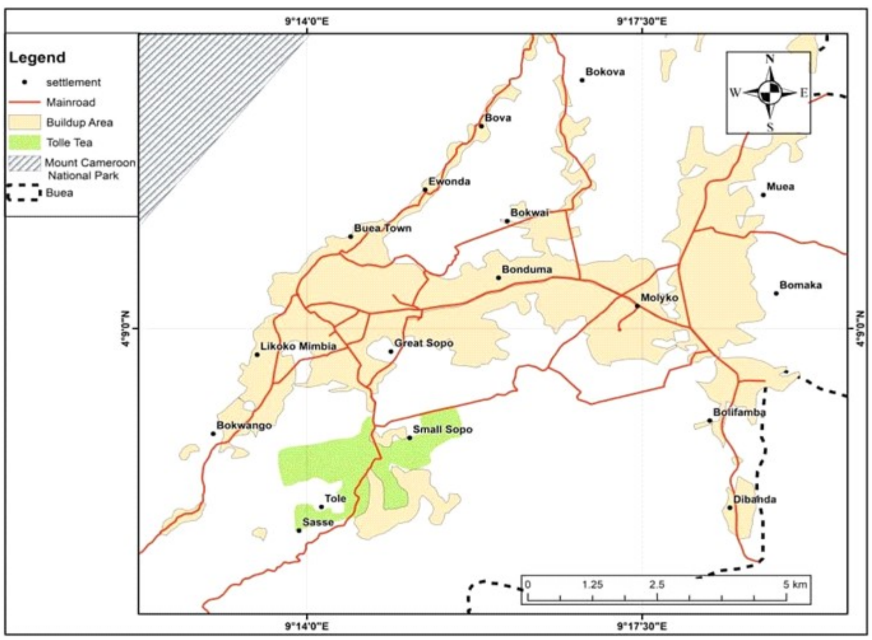

Fig. 1. Map of Buea Municipality showing the surface area covered by the built-up areas and the sampled localities

2.3. Data collection and sampling

2.3.1. Geology of the area

Physical observations and geological sampling

The geological characteristics of Buea Municipality was carried out through physical observation of outcrops in ten selected localities (Fig 2); geological analysis of the already existing map, and marking of outcrops. Rock samples were chipped off the outcrops using a sledge hammer for more detailed observation and description.

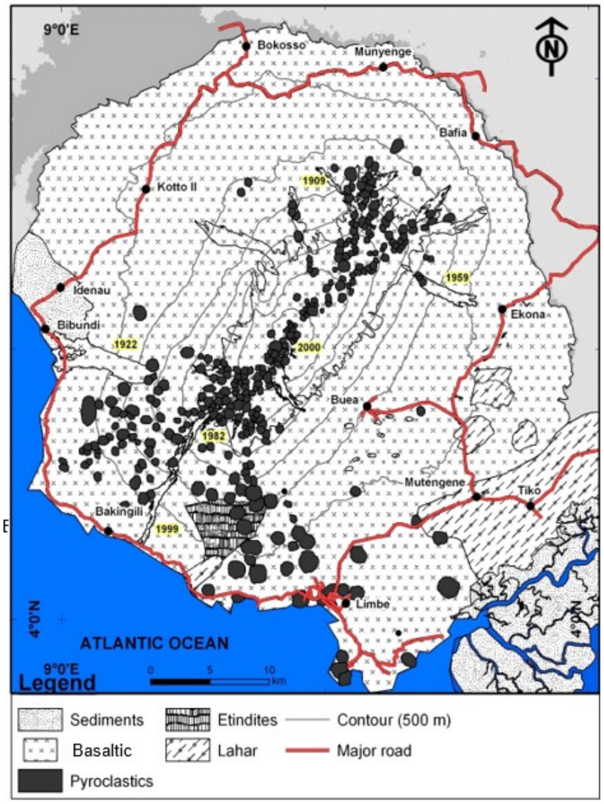

Fig. 2. The geology of Mount Cameroon and environs compiled from past dissertations and theses (Wantim, 2011) which was confirmed in this study for the ten localities within Buea Municipality

2.3.2. Physical Vulnerability Assessment Questionnaire Administration

A questionnaire was developed to assess the past-eruption/earthquake impact assessment on buildings from the 1959, 1982, 1999, 2000 eruptions. These eruptions/earthquake events were chosen because they were the most recent thus, some of those who witnessed them are still alive and can still remember some of the impacts it had on the built environment. The questionnaire was designed with structured close-ended questions for easy and precise response. The responses in relation to the damage caused to building infrastructure were **slight, medium, heavy and no effect**. Since the selection criterion was that the respondent should have witnessed at least one or more of these eruptions, there was no targeted/calculated sample size. Questionnaire administration was purposively done in the form of semi-structural interviews targeting traditional chiefs, quarter heads, traditional councillors, building operators or occupiers and house owners in the 10 localities. This gave a total of 300 respondents in the sampled localities.

ENSURE methodology

Physical vulnerability assessment of building infrastructure was carried out using the Enhancing Resilience of Communities and Territories facing Natural and Na-tech hazards (ENSURE) methodology developed by Menoni *et al.* (2012). This methodology incorporated advancements in structural engineering, utilizing performance-based seismic design principles to quantify the likelihood and extent of damage under different seismic intensities. The ENSURE methodology was designed to collect a sample of digital data within the time frame and facility limits of the research. Physical vulnerability assessment of at least 200 buildings within the 10 selected localities was carried out based on the following parameters: building age, building material (wood, concrete, masonry), construction state (quality & maintenance), position (single or in a row; isolated or clustered), rock/soil type, proximity to the volcano, alongside GPS coordinates of the surveyed houses (Table 1). This comprehensive data collection effort aimed to provide a detailed understanding of the infrastructure typology and vulnerabilities in the area. These parameters were qualitatively evaluated using the Building Vulnerability Index (BVI) adopted from the work of Hammar-Klose and Thieler (2001). For this study, vulnerabilities were qualified from **very low, low, moderate, high to very high** (1-5), for each parameter (see Table 1 for more details).

The quantitative analysis of building vulnerability following the ENSURE methodology incorporated aspects such as building materials, state, and position, each rated on a scale from 1 to 5 (Table 2). Buildings constructed with concrete were given a rating of 3, since they were considered to have moderate vulnerability compared to wood (rating of 2) or masonry (rating of 4-5). Additionally, factors like proximity to a volcano, rated from 1 to 5, also influenced vulnerability, with buildings located very close to the volcano (rating of 5) being at significantly higher risk compared to those farther away (rating of 1-2).

Another phase of data collection for physical vulnerability assessment involved the administration of semi-structured interviews to architects and a council official (a building construction Engineer). This was done to deepen and validate the analyses that made use of the ENSURE checklist, from a technical and professional perspective. The semi-structured interviews were designed to target similar issues as those that appeared in the ENSURE checklist.

Table 1: Building Vulnerability Index (BVI) to earthquake hazard for Buea Municipality following Hammer-Klose & Thierler (2001) methodology

Variables	**Very low**	**Low**	**Moderate**	**High**	**Very High**
Score	1	2	3	4	5
Aspect parameters	***Building material***	***Building state***	***Building position***	***Soil type***	***Proximity to the Volcano***

Table 2: Criteria for quantitative analysis of building vulnerability following ENSURE methodology (Menono *et al.,* 2012)

	Aspect parameters								
	1) Building Materials			**2) Building State**			**3) Building Position**		
VI	**Wood**	**Concrete**	**Masonry**	**Good**	**Moderate**	**Poor**	**Isolated**	**Row**	**Clustered**
	2	3	4-5	2	3	4-5	2-3	4	5
	4) Rock/Soil Type						**5) Proximity to volcano**		
	Lahar	**Ash**	**Aa aa lava**	**Pahoehoe lava**	**Blocky basalt**	**Pyroclastic**	**Very close**	**Close**	**Far**
VI	4	5	2	2	2	3	5	3	1-2

2.3.3 Household Preparedness

A structured- closed ended questionnaire was administered in 5 purposively selected localities: Small Soppo, Bokwaongo, Molyko, Great Soppo and Buea town. These localities were chosen based on the following criteria: i) they have been in existence since the advent of Buea municipality; ii) they had people who had witnessed past eruptions from MC; and lastly iii) some of them were significantly affected by earthquake hazards from the 1999 eruption. The questionnaires were administered to the selected population calculated using the Cai (2004) equation (Eqn 1) using stratified and purposive sampling techniques to identify suitable participants.

$$\frac{z_{1-\alpha/2}{}^2 P(1-P)}{d^2}$$

—Eqn 1

Where $Z_{1-á/2=}$ is standard normal variate (at 5% type 1 error (P< 0.05) it is 2.96 and at 1% type 1 error (P<0.01) it is 2.58). As in majority studies P values are considered significant below 0.05, hence 2.96 was used in the formula. P = expected proportion in population based on previous studies or pilot studies and d = absolute error or precision (= 0.05). Taking an estimated population of 300,000 people for Buea Municipality (Buea Council Report, 2020), it produced a sampled size of 300 participants. The utilized questionnaire had 3 sections: i) demographic characteristics of the respondents; ii) level of household vulnerability to volcanic hazard; and iii) level of household preparedness to earthquake hazards. The questionnaire was administered through semi-structural interviews for better outcome.

2.4 Data Analysis

Field data from questionnaire administration and physical vulnerability assessment were coded and uploaded into Microsoft excel for analysis. Results were presented in tables, diagrams, graphics, and thematic maps representing spatial aspect. Data were entered and treated using excel and transported to SPSS for analysis. A building vulnerability index was adapted from Hammar-Klose and Thieler (2001) and developed for Buea by qualitatively classifying and ranking susceptibility (Table 1). A vulnerability map was established from the physical vulnerability parameters in ArcGIS 10.8.1 for better visualization of vulnerability levels. Quantitative techniques such as scoring, correlation analysis, and comparative analysis of damages caused by eruptions over the past and recent eruptions was done (Table 2), followed by statistical analysis of physical vulnerability of building infrastructure using qualitative techniques.

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3.0 RESULTS

3.1 Geological Assessment

The study area primarily consisted of volcanic rocks and soils resulting from basaltic lava, pyroclastic deposits, lahars and underlying sediments (Fig. 2). These volcanic products are expected to exhibit varying characteristics under earthquake motion. The presence of the different soil/rock types enhanced vulnerability of the built environment to earthquakes (see Table 3). The presence of soft and saturated soils increased the potential of subsidence and liquefaction during earthquakes. Pyroclastic materials amplify vibrations, and jointed rocks serve as potential areas where slides or falls could be triggered. Understanding the diverse properties and behaviors of these materials was crucial for assessing and mitigating risks associated with seismic hazards in Buea municipality.

3.2 Physical vulnerability assessment of the built environment to earthquakes

3.2.1 Impacts of seismic hazards from four (1959, 1982, 1999, 2000) previous eruptions

The impacts of seismic hazards associated with eruptions from MC were studied across multiple events spanning several decades. The 1959 eruption stood out for its significant destruction, particularly affecting Muea where buildings suffered major damage (Fig. 3a). Most households in this locality were highly affected as per the respondents' perspective, underscoring the immediate and widespread impact of the seismic activity. Other localities such as Buea Town, Bolifamba (Mile 16), and Bokwaongo experienced moderate damage from earthquakes from the 1959 eruption, likely due to their distance from the epicenter. Interestingly, Bomaka, which was mostly an uninhabited farmland at the time, recorded no impact, highlighting the localized nature of the event.

The 1982 eruption brought about a different pattern of damage, with medium to heavy impacts primarily concentrated in selected areas like Tole/

Table 3: Classification of rocks/soils in the study area and their seismic reponse

Locality	Rock/soil type	Characteristics	Seismic response
Bolifamba Bomaka Muea	Lahar (volcanic mud flow) Deposit	- Lahar deposit made up of massive boulders with brown clayey soil - Presence of muscovite (whitish minerals in soil) - Soil is highly oxidized with high clay content - Massive rocks are porphyritic basalts (i.e. rocks made up of large crystals/phenocrysts (olivine mineral - greenish) within a fine grained matrix)	- Material becomes loose and collapses triggering a lahar avalanche 
Molyko Bonduma	Basalts (cooled lava)	- Highly weathered basaltic (grey) rocks - Moist weathered brownish soils	-Brittle failure (sudden breakage of rock characterised by little to no plastic deformation; rapid crack) 
Great Soppo	Aa aa lava (basaltic rock characterized with spiny surface)	▪ Massive greyish blocky aa lava with clinker surface ▪ Presence of black loamy soil with pebble sized rocks	- Brittle failure 

Sasse, Bokwai, Muea, and Buea Town (Fig. 3b). While some localities still experienced slight damages to no damage, the distribution was more widespread compared to the 1959 event. The localization of earthquake swarms within Buea municipality contributed to this variation, indicating the importance of understanding the specific dynamics of each eruption.

In 1999, the impact of seismic hazards escalated significantly, affecting Buea municipality more profoundly than previous eruptions (Fig. 3c; Fig. 4). Major and minor damages were observed across various neighbourhoods including Bokwaongo (specifically in Poto poto quarters; Fig. 4f), Buea Town, Small Soppo (even Sasse College was affected; Fig. 4gh), Bonduma, Molyko, Bomaka, and Muea. The epicenter being within the city of Buea heightened the overall impact, compounded by years of escalating seismic activity leading up to the eruption. The 1999 eruption marked a turning point, signifying a heightened vulnerability for Buea and its increasing population.

The 2000 eruption, considered a continuation of the 1999 event, displayed similar but relatively lower impacts across the city of Buea (Fig. 3d). Localities like Molyko, Muea, Bomaka, Bokwaongo, and Mile 16 were particularly affected, although some localities experienced minimal to no impacts due to the spread of earthquake effects beyond Buea. Overall, the trend indicated a gradual increase in the intensity of impacts over time, highlighting the evolving

Table 3: Cont'd

Locality	Rock/soil type	Characteristics	Seismic response
Tole/Sasse	Blocky basalts	- Highly weathered - Fractured - Presence of shallow cooling cracks	 - Displacement and breakage
Buea Town	Aa lava (Basalt)	▪ Porphyritic texture ▪ Black loamy soils with pebble and gravel sized fragments ▪ Grey to white in colour ▪ Forms small, irregular protrusions (cauliflower Aa) ▪ Poorly sorted angular to rounded blocks of massive lava and welded breccias	 - Brittle failure
Bokwango, Bokwai	Volcanic ash (tuff) Mud	▪ Brown clayey soils ▪ Rich ferromagnesian minerals (Fe^{2+} and Mg^{2+}) ▪ Presence of patches of weathered basaltic rocks ▪ Gravel to boulder sized particles ▪ Porphyritic basalts (grey) ▪ Unconsolidated sediments ▪ Spongy texture	-Foundation and bearing capacity failure. - loss of shear strength after saturation. - cyclic deformation - increased material's pore volume as the material dilates -amplification of motion 

vulnerability of Buea to seismic hazards associated with MC eruptions (Fig. 3).

Quantitative analysis further revealed that 50 % of the sampled localities had moderate vulnerability to seismic impacts (Table 4). Localities like Bokwaongo, Buea Town, and Bokwai exhibited high infrastructural vulnerability due to previous seismic swarms (Figs 3 & 4). Despite the recurring seismic hazards and escalating impacts, there was still a lack of awareness and a non-compliance attitude by the population towards respecting building regulations in this seismically active area. This was evident in the continued settlement on slopes and the construction of buildings without adequate precaution. Consequently, building infrastructure development, was inversely proportional to resilience; where indigenous and more resilient buildings which existed before the 1999/2000 eruptions (Fig. 5a) had been replaced by modern and less resilient buildings (non-engineered), which are mostly storey buildings (some up to 7 storeys high), clustered together especially in Molyko neighborhoods (Fig. 5b), and built with very fragile materials (glass, masonry).

3.2.2 Physical vulnerability of buildings to seismic hazards

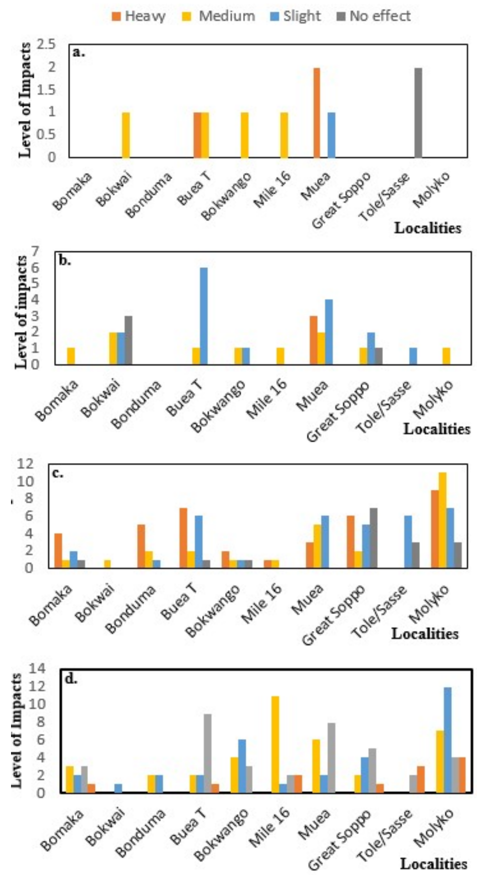

Fig. 3. Past eruption /earthquake impacts from the a. 1959, b. 1982, c. 1999 & d. 2000 eruptions for the sampled localities

Fig. 4. Photographs taken in 2018 (19 and 18 years after the 1999/2000 eruptions) showing the destruction caused on houses by the 1999/2000 earthquakes from MC in the following localities within Buea Municipality: a-b. cracked wall and foundation in Great Soppo; c-e. old poorly maintained residential buildings in Buea Town with cracked walls and floor; f. partially destroyed inhabited house at Poto-poto quarters in Bokwaongo; g-h. cracks on walls in buildings at Sasse college; and i. dilapidated wooden house in Tole village

Fig. 5. Photographs taken in the city of Buea a. before the year 2000 and b. in 2020, showing the evolution of settlement in the city over time (2000-2020)

A quantitative analysis of building fragility to earthquakes based on parameters such as building material, building state, proximity to the volcano, position, and soil type indicated moderate vulnerability for 50 % of the assessed localities considering the parameters qualified via the BVI (Fig. 6). The age distribution of buildings further elucidated vulnerability patterns, with buildings < 5 years old comprising 35 % of the vulnerable buildings (Fig. 6). The distribution of building ages highlighted the ongoing development and expansion within the area, as the newest constructions do not adhere to updated safety standards or consider the common recurring seismic hazards within the area.

Among the parameters used to evaluate vulnerability, building state emerged as the most critical factor, accounting for 32 % of vulnerability. Additionally, the proximity of buildings to the volcano played a significant role,

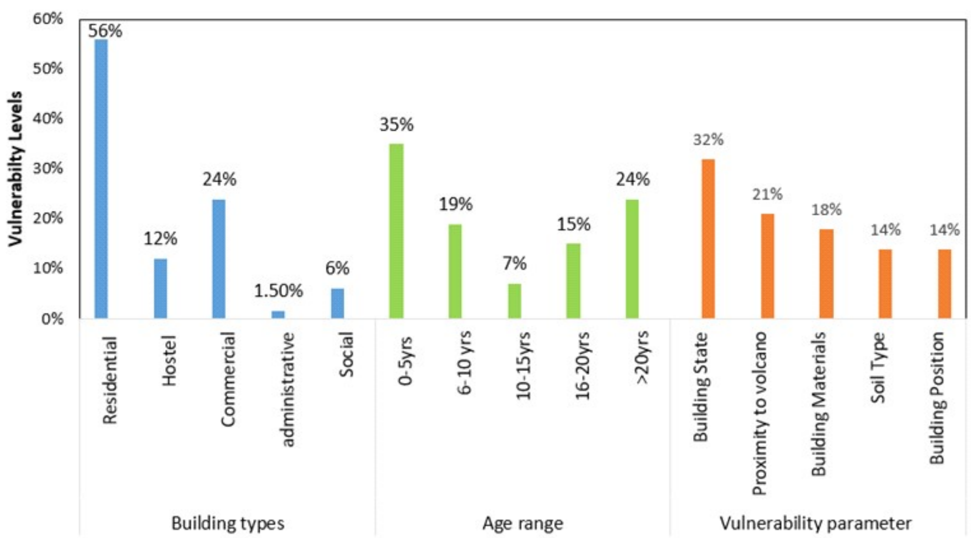

Fig. 6. Physical vulnerabilty assessment of building types, building age and the other vulnerability parameters assessed in this study

with 22 % of vulnerability attributed to this aspect, highlighting the heightened risk faced by communities such as Bokwaongo and Buea Town which are closest to MC (Table 4). The composition of building materials was observed to also influence vulnerability to earthquakes, as it contributed 18 % to the overall assessment (Table 4). Areas with structures constructed from less resilient materials were particularly susceptible to seismic events.

The quantitative estimates of the fragility of each parameter investigated in this study are summarized in Table 4. The building condition was identified as the most vulnerable parameter, accounting for 22%, particularly in the areas of Molyko, Great Soppo, Buea Town, Bokwango, Tole/Sasse, Bolifamba, Bomaka, Bokwai, and Bonduma. The second most significant factor was the proximity of buildings to the volcano, which accounted for 20.5%, affecting buildings in Bokwango, Buea Town, Bokwai, Bonduma, and Great Soppo. The third factor was the building materials, contributing to 19.5% of the vulnerability, notably in Molyko, Great Soppo, Bolifamba, Bonduma, and Bomaka. The fourth factor was the position of buildings in relation to their potential to affect or be affected by other infrastructure, which accounted for 19%, as seen in Buea Town, Molyko, Great Soppo, and Bokwango. The fifth parameter was geology (rock/soil type), which accounted for 19% of the vulnerability, with high levels observed in Bokwango and Bokwai due to volcanic ash and soft soils, and in Bomaka and Bolifamba due to lahar deposits.

From the analysis presented in Table 4, it is evident that a significant proportion of the assessed localities exhibit moderate vulnerability when all parameters are considered together. High vulnerability is concentrated in specific areas that have previously been affected by seismic swarms, such as Bokwango, Buea Town, and Great Soppo, as shown in the vulnerability map (Fig. 7). These findings highlight the complex interplay of various factors in determining the physical vulnerability of building infrastructure to seismic hazards.

3.3 Household preparedness to earthquake hazards

3.3.1 Perception and knowledge of past eruptions and hazards

Most of the respondents (64.0 %) were females with few males (36.0 %). Most of the respondents had spent between 1-9 years in the locality (30.7 %), were single (57.4%), had attained secondary education (40.7%) and had households of 5-9 occupants (43.3 %). Nearly all the respondents (99.6 %) did not witness the 1954 and 1959 (95.0 %) eruptions, unlike the 3 last eruptions: 1982,

Table 4: Physical vulnerability assessment of buildings in Buea Municipality

	Building Materials	Building State	Building Position	Soil Type	Proximity to volcano	Av. Vulnerability
Molyko	4	3	5	2	3	3.4
Bonduma	3	3	3	3	4	3.1
Great Soppo	4	4	4	2	5	4
Buea Town	3	5	5	2	5	4
Bokwango	3	5	4	5	5	4.4
Tole/Sasse	2	4	1	2	5	2.9
Bolifamba	5	4	3	4	1	3.4
Bomaka	3	2	2	4	1	2.7
Muea	2	4	4	4	2	3
Bokwai	3	5	2	5	4	3.9
Av. Vulnerability(%)	19.5% 3rd	22% 1st	19% 4th	19% 5th	20.5% 2nd	

1999 and 2000 (Fig. 8a). A good percentage of the respondents (44.0%) had experienced earthquake and discharge of volcanic ash (58.3 %) (Fig. 8b). Majority of the respondents (65.3 %) asserted to the fact that lava flow was a common hazard linked to these eruptions. Most of the respondents had witnessed the 2000 lava flow (Fig. 8c). As per the respondents, the 1982 eruption was characterized by high emission of volcanic gases (Fig. 8c); 1999 eruption characterized by the discharge of volcanic ash and gases with significant earthquakes when compared to the 2000 eruption; and lastly the 1954 and 1959 eruptions were also characterized by a high discharge of volcanic gases in addition to the other hazards.

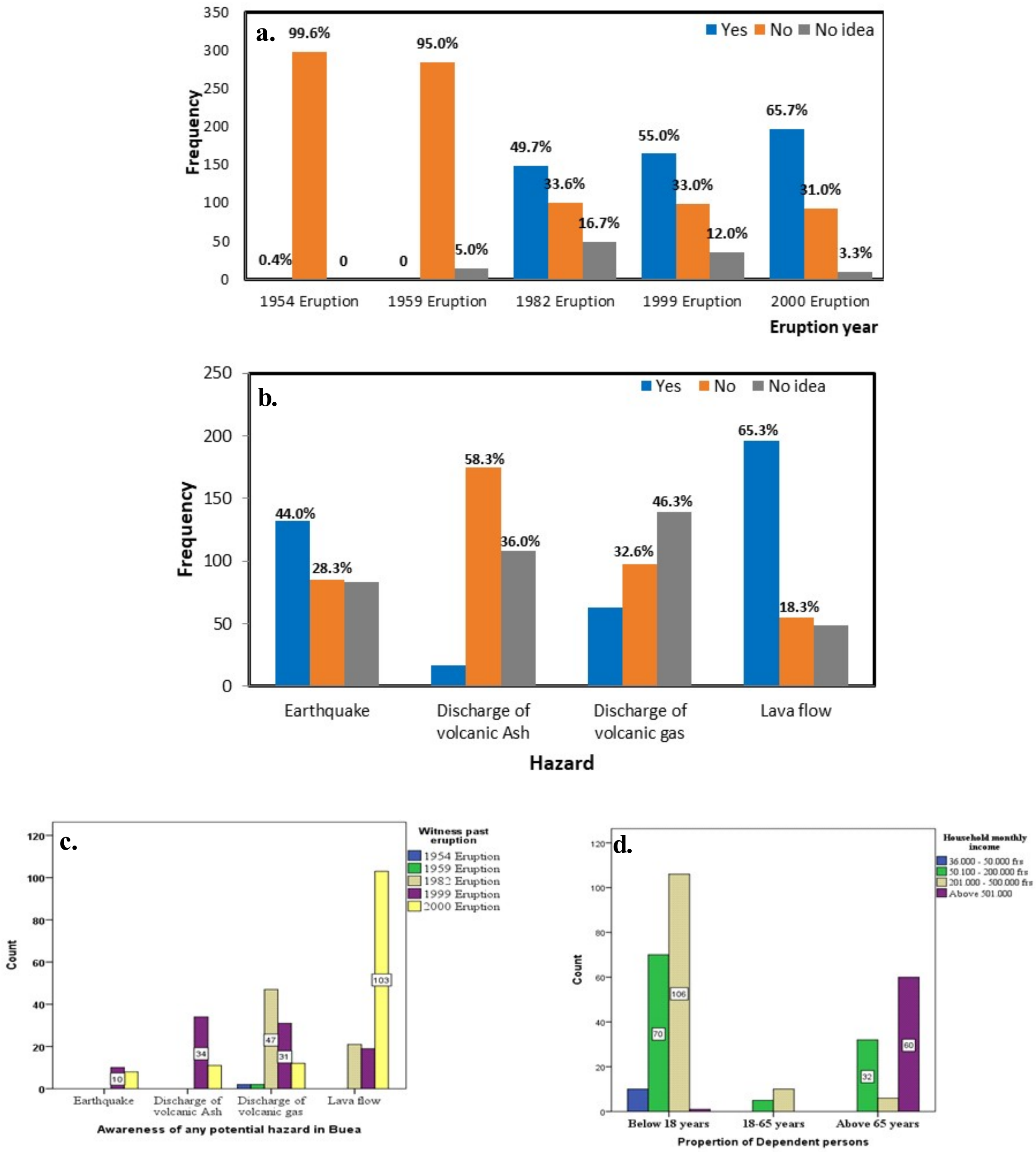

Fig. 8. Household preparedness to volcanic earthquakes showing respondents' perception on: a. occurrence of past eruptions (1954-2000); b. potential hazards from MC eruptions; c. potential hazards per eruption; and d. household income verse proportion of dependent personsFigure 4.5 Household income verse proportion of dependent persons

3.3.2 Household Disaster Preparedness

Most of sampled houses had no alarm system against any potential volcanic hazard (65.6%). However, 5.6 % of the respondents had installed fire alarm systems against household fires. In terms of household income, which is a significant preparedness measures, 40.67 % of households earned between 201,000-500,000 frs monthly. A cross tabulation between household income and age group of dependent persons in households showed that household members with ages below 18 years were most dependent (Fig. 8d). The income level of household with most dependent persons was between 201,000 frs and 500,000 frs. Household members above 65 years who were independent had income above 501,000 frs.

A total of 55.7 % of households in the 5 sampled localities were not aware of the notion of disaster communication and evacuation plans as relevant for earthquake preparedness (Table 5). Thus, 39.3 % of these households did not have personal communication and evacuation plans. However, 73.1 % of households reported that they had identified safe locations to evacuate to in times of disaster. Despite this, only 43.3 % of household members demonstrated knowledge of programs related to disaster preparedness, indicating a gap in education and awareness. Furthermore, 54.0 % of household members did not attend workshops or campaigns on earthquake preparedness, suggesting a lack of proactive engagement in preparedness efforts. Encouragingly, 72.0 % of households reported having transport means, such as emergency cars, available for evacuation in case of disaster (Table 5).

Regarding earthquake preparedness kits, 32.0 % of households had a first aid box as part of their preparedness measures. Approximately 18.3 % of households ensured their radios were equipped with spare batteries, potentially for receiving emergency broadcasts. A smaller proportion of households (15.0 %) had reserves of potable water, which is crucial for survival in the aftermath of a disaster. Similarly, 14.7 % of households had emergency food supply stocked, while 14.3% possessed walking flashlights. Only 5.7 % had cash reserve set aside as part of their earthquake preparedness efforts.

4. DISCUSSIONS

The identification and classification of rock/soil types within Buea aligned with research on building vulnerability in volcanic areas of Japan

Table 5: Levels of household preparedness

Categories	Variable	Percent (%)
Awareness of disaster community evacuation plan	Yes	44.3
	No	55.7
Household communication and evacuation plan	Yes	37.3
	No	39.3
Safe location in times of earthquake disaster	Yes	73.1
	No	26.6
Follow programs on disaster preparedness	Yes	43.3
	No	56.7
Attend workshops/ campaigns on earthquake preparedness	Yes	54.0
	No	46.0
Transport means available in case of disaster	Yes	72.0
	No	28.0

which emphasized the role of different soil/rock types in amplifying seismic effects and increasing building vulnerability (Yamazaki *et al.,* 2016). Similarly, studies on building vulnerability in volcanic regions of Ecuador highlighted the impact of volcanic soils and pyroclastic materials on building stability (Yepez *et al.,* 2019). When a soil supporting a building is characterised by loose unconsolidated material, it can liquefy (mixes with water and becomes saturated) and lose its bearing strength as observed in Japan (Yamazaki *et al.,* 2016). Seismic waves travel faster through hard rocks, reducing the amount of damage retained. However, when they meet soft soil or soft rocks such as tuff, they slow down and get bigger in amplitude as the energy piles up, thereby amplifying ground motion and causing more destruction (USGS, 2024) as was the case of Poto poto quarters in Bokwaongo which was hardest hit by the 1999 eruption. The large-scale destruction in the neighbourhood was attributed to the presence of very soft soil which was used to name the locality in Pidgin English *"Poto poto"* meaning muddy.

The significant vulnerability of households in Buea to volcanic hazards, particularly from MC eruptions, is consistent with findings from other volcanic regions. For instance, a study on household vulnerability to volcanic eruptions in Merapi, Indonesia, also highlighted the heightened vulnerability of households due to proximity to the volcano and inadequate awareness and preparedness measures (Marfai *et al.,* 2008). Similarly, research on household vulnerability in communities around Mount Vesuvius in Italy revealed similar trends of increased vulnerability with population growth and rapid urbanization (Mastrorillo *et al.,* 2014).

The quantitative analysis of building fragility in Buea reflected common vulnerabilities observed in volcanic areas of the Philippines, with similar findings regarding building vulnerability factors such as building material, state, and proximity to volcanic hazards (Suarez *et al.,* 2018). Also, research in volcanic regions of Guatemala identified similar vulnerabilities related to building codes and regulations, exacerbating building vulnerability (Williams *et al.,* 2020). By addressing factors such as building state, proximity to the volcano, construction materials, building position, and geological considerations, major stakeholders in Buea municipality like the council, can develop tailored interventions to enhance resilience and mitigate the potential impacts of seismic hazards on the built environment.

The assessment of household preparedness for earthquake hazards in Buea municipality was similar with research on household preparedness in seismic regions of California characterised with similar gaps in awareness, communication plans, and preparedness measures among households (Peacock *et al.,* 2010). Similarly, studies on household preparedness in earthquake-prone regions of Japan underscored the importance of education and awareness programmes in enhancing household preparedness (Paton *et al.,* 2001). While the specific context of Buea and MC presents unique challenges, the findings regarding volcanic earthquakes in relation to household vulnerability, building vulnerability, and earthquake preparedness align with broader trends observed in studies conducted in other volcanic and seismic regions globally.

5. CONCLUSIONS

The study identified a range of rock and soil types in Buea municipality, including basalts, tuff, lahar deposits, loamy soil, and underlying sediments, all contributing to building vulnerability, especially in areas with soft soils, pyroclastic materials, and jointed rocks. The impact of past eruptions (1959, 1982, 1999, and 2000) showed damage directly proportional to the epicenter's location. Physical vulnerability assessment revealed moderate to high vulnerability in areas like Bokwaongo, Buea Town, and Bokwai; with building state, proximity to the volcano, and construction materials being critical factors. Common issues included narrow foundations, heavy roofs, poorly maintained buildings, and lack of environmental consideration in construction. Household preparedness was notably lacking in disaster communication and evacuation plans. Unless appropriate measures are taken, Buea municipality is a disaster waiting to happen due to its extreme vulnerability to seismic hazards and lack of preparedness.

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