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Geotechnical Assessment of Seismic Vulnerability in the Built Environment of Fako Division, South West Region of Cameroon

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Authors' contributions

This work was carried out in collaboration among all authors. Author NLW designed the study, performed the statistical analysis, and drafted the protocol, the first draft of the manuscript. Authors MNW and SNA headed the geological survey, determined sample collection points, predicting high-risk areas, and facilitating sample collection. All authors read and approved the final manuscript.

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ABSTRACT

Introduction: Volcanic earthquakes may trigger severe hazards with considerable impact on the natural and built environment and the surrounding population.
Aim: Evaluate the geotechnical characteristics of soils in Fako division to estimate their seismic vulnerability and recommend suitable stabilization techniques to enhance the safety and resilience of built environments.

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Place and Duration of Study: This study was conducted over a period of 12 months beginning from June 2022 to May 2023.
Methodology: It employed a multi-criteria geotechnical approach, involving soil sampling, laboratory analysis, and seismic risk analysis. Soil samples collected from various locations within the study area, were subjected to laboratory tests to determine their plasticity (Atterberg limits) and load-bearing capacity (California Bearing Ratio - CBR). Historical data analysis and seismic hazard mapping were used to assess seismic vulnerability which helped to identify highly susceptible and unstable areas that may require engineered interventions.
Results: The findings revealed significant variations in soil plasticity and load-bearing capacity, correlating with observed settlement and instability issues in the region. Historical seismic events, highlighted significant structural damage in areas with high plasticity and low CBR values, underscoring the necessity for robust soil stabilization measures (geotechnical interventions) to mitigate seismic risks and enhance the resilience and safety of structures, reducing the risk of settlement and instability within the Mount Cameroon area, particularly Fako Division.

Keywords: Seismic susceptibility; geotechnical assessment; Mount Cameroon; seismic hazard; Fako division.

1. INTRODUCTION

The presence of volcanoes in inhabited areas presents a complex scenario, offering benefits such as fertile soil and construction materials, but also posing significant risks due to volcanic and seismic activities [1]. Mount Cameroon, for example, holds cultural significance for local populations, complicating efforts to deter settlement in these areas [2]. Moreover, urbanization in developing nations exacerbates exposure to natural hazards, including seismic risks associated with volcanic activity [3]. Despite historical disasters, populations continue to settle in vulnerable areas due to socio-economic factors, highlighting the intricate relationship between human settlement patterns and risk perception [4]. Earthquakes cause a multitude of accompanying and subsequent phenomena with considerable impact on the natural and built environment and consequently on the people who live and operate within them [5].

Mount Cameroon is situated on the Cameroon Volcanic Line (CVL), a major tectonic feature extending from the Gulf of Guinea into the African continent. The CVL is a zone of crustal weakness, facilitating the ascent of magma and associated seismic activity [6]. Historical records indicate that the region has experienced earthquakes with magnitudes up to 6.0 on the Richter scale, with periods of increased activity correlating with volcanic eruptions [7]. Local soil conditions, particularly geology, play a crucial role in the seismic vulnerability of built infrastructures [8]. Geological characteristics influence soil-structure interaction, impacting the safety and stability of buildings. The soils in the Mount Cameroon area are primarily volcanic in origin, with significant variability in composition and properties. These soils are often fertile but can pose challenges for construction due to their potential for instability under seismic loading [9]. The predominant geological formations are basaltic and trachytic volcanic rocks, resulting from numerous eruptions over thousands of years, creating a stratovolcano that rises approximately 4,040 meters above sea level [10].

Despite the inherent uncertainties in seismic risk assessment, it is essential to design structures capable of withstanding earthquake loads safely [11]. Pre- and post-earthquake upgrading of buildings remains a challenging issue, requiring comprehensive public policy decisions [12]. The region experiences frequent seismic events, ranging from minor tremors to significant earthquakes. These events are often associated with volcanic activity, including magma movement and eruptions [13]. The intensity of ground shaking during seismic events can be severe, particularly in areas with soft or loose soil [14]. Soil liquefaction, where saturated soils temporarily lose strength and behave like a liquid, is a significant concern in the region, especially in areas with high water tables [15].

Understanding these geological features is imperative for mitigating building collapse risks during earthquakes [16]. Studies in similar volcanic regions emphasize the importance of considering soil properties in construction design to mitigate seismic risks effectively [17]. This study, therefore, aims to conduct a geotechnical assessment of seismic vulnerability in the built environment in Fako. The region's susceptibility to seismic hazards due to its geological characteristics and historical seismic activity necessitates a thorough understanding of local soil conditions to ensure the safety and stability of structures [18].

Despite the potential for devastating seismic events, there is a dearth of research addressing the seismic risks faced by structures and communities in this area. Rapid urbanization exacerbates the situation, underscoring the urgent need for analytical approaches to assess seismic risk comprehensively [19]. There is a lack of comprehensive geotechnical assessments focused on mitigating seismic vulnerability in the Fako. Comprehensive geotechnical assessments are essential for identifying areas of high seismic risk and implementing mitigation measures. This includes mapping seismic hazards, monitoring ground movements, and developing emergency response plans [20].

2. MATERIALS AND METHODS

2.1 Description of Study Area

This study was carried out in Fako division (covering all the seven council areas), nestled in the Southwest Region of Cameroon, which occupies a strategic geographical position marked by diverse landscapes and unique features. Located along the Atlantic coastline (Fig. 1), Fako benefits from its proximity to maritime resources, influencing its economic activities [21]. The division's coastal stretch extends from the Limbe Bay in the south to the Bakingili Beach in the north, providing access to the Gulf of Guinea. Inland, Fako Division encompasses the eastern slopes of Mount Cameroon, Africa's highest peak and an active volcano (about 4100 m above sea level) bounded to the north by the tropical forest on the slope of mount Cameroon.

The mountain range extends to the beautiful sandy beaches of Atlantic Ocean. Fako Division covers major towns like Buea Municipality to the North, the City of Limbe to the South West, Tiko municipality to the South East, Muyuka Municipality to the East and Idenau district to the West. The fertile volcanic soils around Mount Cameroon support agricultural endeavors, including the cultivation of crops like cocoa, oil palm, and rubber.

Moreover, Fako Division is bordered by Meme Division to the north and Manyu Division to the east, while its western boundary extends to the Southwest Region's coastline. This strategic positioning facilitates trade and connectivity with neighboring regions, contributing to Fako's economic significance within the broader Cameroonian context [22].

The division's administrative center is Buea, which serves as a focal point for governance, education, and commerce within Fako Division, further emphasizing its central role in the region's dynamics.

2.2 Methodology

2.2.1 Study design

This study made use of a descriptive research design where a case study approach was adopted to address all the seven councils at the flanks of Mount Cameroon. This involved a full desktop review of current building vulnerability, along with the review of statutes and various journals on potential volcanic hazards, geology and building vulnerability in Fako. This study covered the seven councils of Mount Cameroon area: Buea, Tiko, Muyuka, Limbe I, Limbe II, Limbe III and West Coast (Idenau Council) (Fig. 1), which were randomly sampled within a period of 3 months, for spatial analysis.

2.2.2 Data collection methods and procedure

An attempt was made to characterize the site, the seismic hazard analysis considering the local site effects, and to develop micro-zonation maps for the Mount Cameroon area. Geotechnical seismic risk assessment for the Mount Cameroon area was addressed through; site characterization using geotechnical methods, estimation of seismic hazard using seismic intensities (modified Mercalli intensity scale) and geology of the terrain.

Having researched the literature described above, a framework for assessing seismic risk within Mount Cameroon area is schematically represented (Fig. 2).

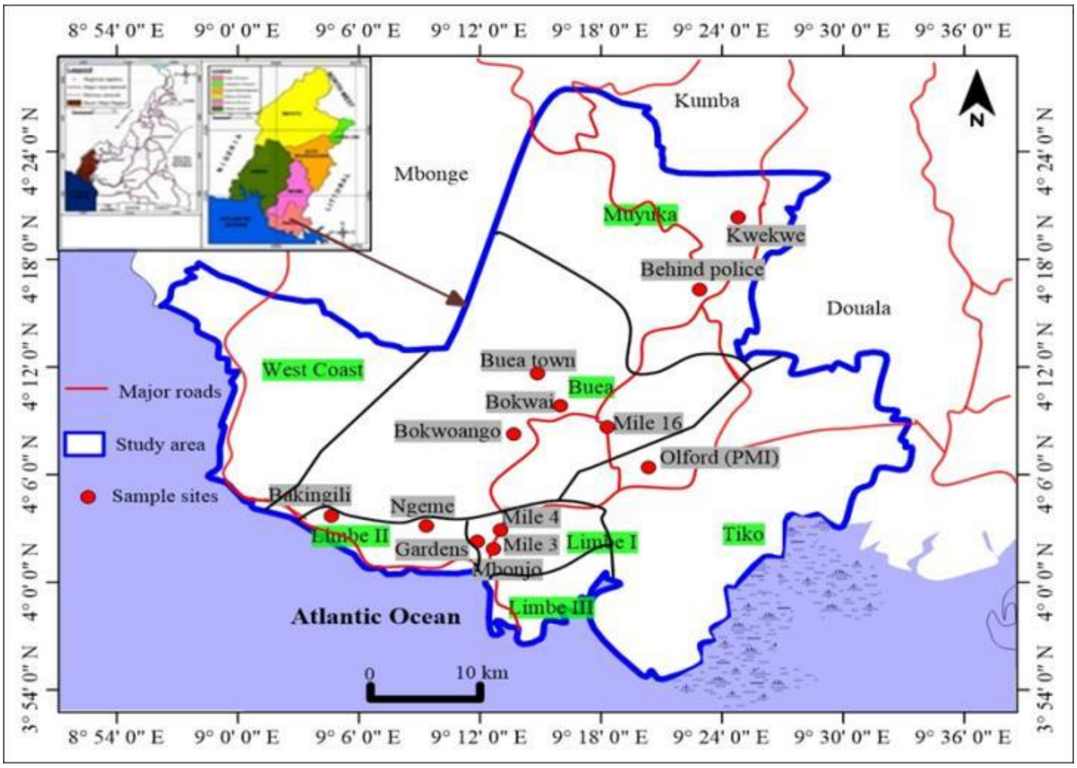

Fig. 1. Adapted base map for the Mount Cameroon area (7 councils of Fako Division)

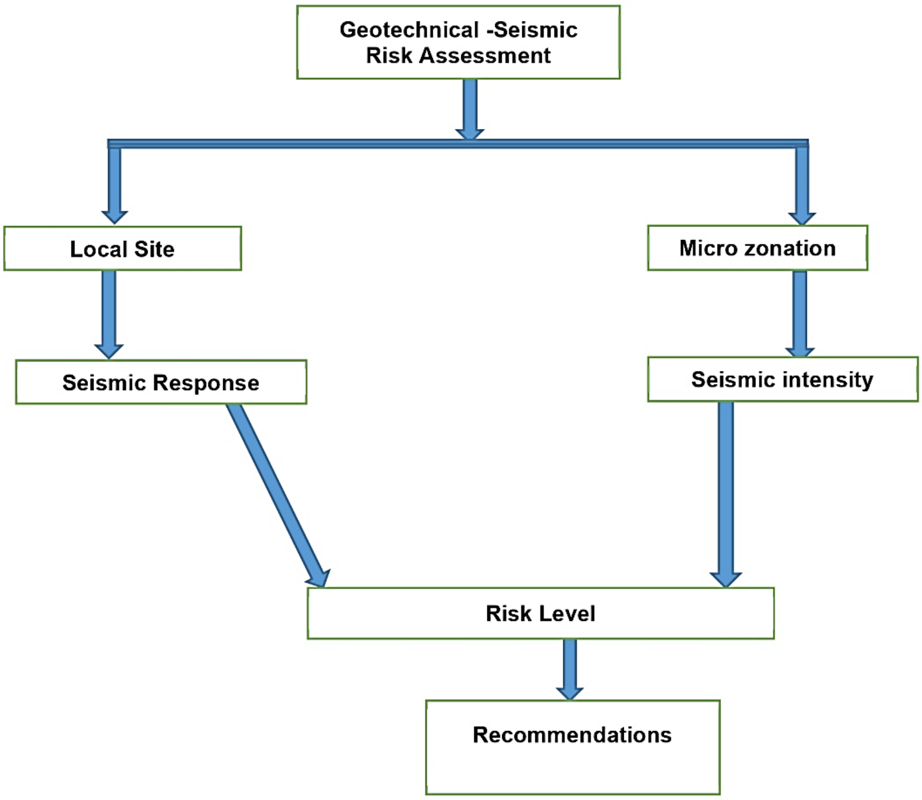

Fig. 2. Risk assessment framework for Mt Cameroon Area

2.2.2.1 Geologic survey and soil sampling

Reconnaissance survey was conducted in various localities to gather crucial information about the study area, develop survey strategies, and overcome potential shortcomings. The survey involved physical observation, geological descriptions, and marking outcrops for geological analysis prior to soil sample collection from sixteen sample points. Detailed descriptions including the name of the locality, rock/soil type, and soil characteristics were recorded during this phase for all the 16 points. GPS points and photographs were taken to produce a geologic map and provide a true depiction of the area's geology (Fig. 3).

The field survey comprised a multidisciplinary team including a volcanologist, civil engineer, disaster risk expert, and PhD research students. Each member had specific roles such as describing the geology, determining sample collection points, predicting high-risk areas, and facilitating sample collection respectively.

Soil sampling was carried out meticulously to ensure the accuracy of geotechnical analyses. Samples were collected from specific depths relevant to the study objectives, considering laboratory test calibration. Depending on soil type and analysis purpose, samples were gathered from appropriate depths (at least 2M deep), often from exposed outcrops. Each sampling point yielded at least 40 kg of soil to ensure sufficient material for various analyses. Equipment for soil sampling included basic tools like soil augers, spades, and trowels for collection, mixing, and storage, alongside items for data documentation and transportation. Clean buckets and soil bags lined with plastic were used for mixing and storing samples respectively. Marking tools, tags, and sample information sheets aided in proper labeling and documentation. Field data including GPS coordinates and photographs were captured for comprehensive record-keeping and analysis (Fig. 3.). Additionally, accessories like hammers for rock sampling, portable water, and vehicles for transportation ensured the efficiency and smooth execution of the sampling process.

This particular approach to soil sampling and handling highlights the importance of accurate evaluation in generating reliable geologic recommendations and also, facilitates informed decision-making and the development of effective risk mitigation strategies. Moreover, it minimizes costs and reduces the potential impact of disasters by providing precise geologic data.

The fresh samples collected were moist, and were air-dried immediately before being bagged and sent to a soil-testing lab. The drying was done by spreading each sample on farm bags, trays and plastic bags to air dry at room temperature.

2.2.2.2 Seismic intensities associated within this area

Post-seismic earthquake damage data from the 1999 eruption was acquired using the Modified Mercalli Intensity (MMI) Scale, as most researchers have used for different studies and regions. Notably, the Intensity observed by an area due to a volcanic earthquake, widely depends upon the geology, building nature and volcanic properties of the area. The scale was used to evaluate hazard and risk impacts, with respect to the 1999 eruption (most recent and most severe events).

The purpose of this, was to establish the nature of impact and level of volcanic risk; population and building exposure to volcanic hazards and to consider the factors that are necessary for risk reduction and mitigation, through sustainable urban planning based on public perception and recommendations.

2.2.3 Laboratory analysis

Various analyses were carried in the lab to address the objectives of the study;

2.2.3.1 Test for compaction

The modified Proctor test determines the dry density and optimum moisture content for compacted soil, crucial for safely transmitting structural forces. It involves mixing approximately 8kg of air-dry soil with water, compacting it in layers within a mold using a manual hammer, and measuring the wet soil's weight and moisture content to find the optimal conditions. The test shows that increasing water content up to the Optimum Moisture Content (OMC) enhances density, beyond which further increases in water content (W_c) reduces density; the dry unit weight ($\boldsymbol{Y_{dry}}$) is calculated from the wet unit weight and moisture content. Increasing W_c will increase $\boldsymbol{Y_{dry}}$ up to a certain limit (Optimum moister Content, OMC) after this limit, Increasing W_c will decrease $\boldsymbol{Y_{dry}}$;

Fig. 3. Field survey and sample collection showing: a. GPS Points recording and marking of outcrops, b. geologic description & c. sample collection

Knowing the wet unit weight and the moisture content, the dry unit weight can be determined from Eqn 1

$$\boldsymbol{\gamma}_{dry} = \frac{\gamma wet}{1+\frac{Wc\ (\%)}{100}} \text{...Eqn (1)}$$

2.2.3.2 Californian Bearing Ratio Test (CBR)

The Californian Bearing Ratio (CBR) test assesses soil's load-bearing capacity, by using specific equipment; CBR molds, a proctor hammer, and a hydraulic press to establish soil classification and determine optimal road layer thickness based on compaction levels.

The test involves preparing, compacting, and weighing soil samples in molds, followed by immersion, drainage, and hydraulic press testing to measure settlements at various displacements (Eqn 2).

γd_{max} **=2.03,**

W_{opt}**=13.2%,**

V=**2300cm^3**

$$\boldsymbol{Pmat} = \frac{\gamma d(w\%+100)V}{100} \text{...... ....Eqn (2)}$$

For compaction energy at 100%, i.e. 55blows we have:

$$\boldsymbol{P_{55}} = \frac{2.03(11.4+100)2300}{100} = \mathbf{52830.8kg}$$

For compaction energy at 95%, i.e. 25 blows we have:

$$P_{25} = P_{55} * .95 \Longrightarrow 52830.8 * .95 = \mathbf{502104.26}\boldsymbol{kg}$$

For compaction energy at 90%, i.e. 10blows we have:

$$P_{10} = P_{55} * .90 \Longrightarrow 52830.8 * .90 = \mathbf{475677.72}\boldsymbol{kg}$$

Summing all these values we have the approximated $\mathbf{P_{mat}}$**=16kg**

The quantity of water needed is deduce as $\mathbf{P}_{\boldsymbol{eau}} = \frac{\mathbf{P}_{mat} * w\%}{100} = \mathbf{2.112}\boldsymbol{l}$

In the analysis phase, the Californian Bearing Ratio (CBR) test calculated soil's dry density from its humid weight and water content, and determined the CBR from stresses at 2.5 and 5.0 mm settlements (70 and 105 bars), providing crucial data for evaluating soil suitability for construction and informing layer thickness and structural integrity decisions. Knowing the humid weight, water content and the volume of the mold, we then calculated the dry density ($\boldsymbol{\gamma}$d) (Eqn 3).

$$\gamma d = \frac{Ws}{V} = \frac{\text{dry weight}}{\text{Volume}}, \ldots \qquad \textbf{Eqn (3)}$$

With $Ws = \frac{\mathbf{100xP_h}}{\mathbf{100+w}}$

The CBR was calculated from stresses corresponding to settlement values of 2.5 and 5.0 mm i.e. 70 and 105bars of pressure (Eqn 4).

Therefore,

$$\mathbf{CBR} = \text{Max}\left[\frac{\mathbf{P(2.5mm)X100}}{\mathbf{7o}}, \frac{\mathbf{P(5mm)X100}}{\mathbf{105}}\right] \text{......} \mathbf{Eqn\ (4)}$$

where **P** is piston penetration or settlement.

2.2.3.3 Atterberg limits test

The Atterberg's limits test determines the water content at various soil consistency stages using; a grooving tool and Cassagrande's apparatus, where the liquid limit was found by plotting the relationship between water content and the number of drops needed to close a groove in the soil. This analysis provided essential data on soil behavior under different moisture conditions, and can aid engineering decisions for construction projects.

Plastic limit: The plastic limit test determines the water content at which soil transitions from a plastic to a semisolid state by rolling a soil sample into a thread until it crumbles at a diameter of 3.2 ± 0.5 mm, indicating the soil's plastic limit. This process involves reducing the soil's water content, forming it into an ellipsoidal mass, and repeatedly rolling it on a glass plate until it reaches the specified diameter and crumbles (Fig. 4).

Plasticity index: The plasticity index (PI) measures a soil's plasticity by calculating the range of water contents over which the soil remains plastic, determined as the difference between the liquid limit (LL) and the plastic limit (PL), with higher PI values indicating more clay content. Additionally, the liquidity index (LI) scales a soil sample's natural water content to its plastic and liquid limits, computed as the ratio of the difference between the natural water content and the plastic limit to the difference between the liquid limit and the plastic limit (Eqn 5).

$$LI = \frac{(W-PL)}{(LL-PL)} \text{..........................} \quad \text{Eqn (5)}$$

Where W is the natural water content.

2.2.3.4 Systematic analysis of geotechnical data

The soil strength and susceptibility levels were determined by analyzing the plasticity, California Bearing Ratio (C.B.R.), and load-bearing capacity, with high values indicating greater soil strength and low values suggesting higher susceptibility to deformation and settlement. The susceptibility levels, which range from low to moderate for soils with low to medium plasticity, low C.B.R., and low load-bearing capacity, were then qualified using a susceptibility index (S.I.) depicted by different colors, adapted from [23].

Soil Strength is a qualitative measure based on C.B.R. and Load Bearing Capacity. If both C.B.R. and Load Bearing Capacity are low, Soil Strength is low.

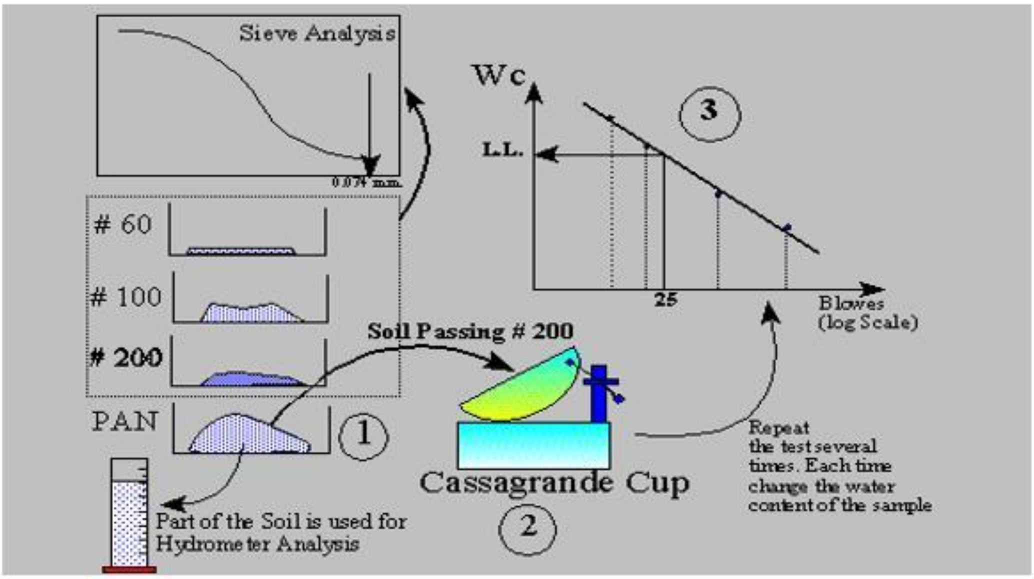

Fig. 4. Steps in carrying out the Atterberg's limits tests and presentation of results

$$\text{Soil Strength} = \begin{pmatrix} \text{low} \\ \text{high} \\ \text{moderate} \end{pmatrix} \begin{pmatrix} \text{if C. B. R. and Load Bearing Capacity are low} \\ \text{if C. B. R. and Load Bearing Capacity are high} \\ \text{other wise} \end{pmatrix}$$

Plasticity, C.B.R., and Load Bearing Capacity influence susceptibility Level.

$$\text{Susceptibility Level} = \{ \begin{matrix} \text{high} \\ \text{low to moderate} \\ \text{moderate} \end{matrix}$$

$$\begin{matrix} \text{if plasticity is high and . B. R. and Load Bearing Capacity are low} \\ (\text{if plasticity is low} - \text{mediwm C. B. R. \& Load Bearing Capacity is low} \\ \text{if plasticity is medium and CBR is Moderate} \end{matrix}$$

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Geology of Mount Cameroon Area

Mount Cameroon's geology across the seven council areas reflects a complex volcanic landscape with a variety of volcanic rocks and deposits, including lahar deposits, basaltic lava flows, pyroclastic materials, and weathered volcanic soils. This geological diversity influences the soil properties and susceptibility to hazards (Fig. 5).

The geology of the Buea Council area displays a range of volcanic deposits and formations associated with Mount Cameroon eruptions. Campsic, one of its localities is characterized by lahar deposits, which are volcanic mudflows consisting of a mixture of pyroclastic materials and water, often carrying boulders and debris. Federal Quarters features lava flow, specifically blocky aa lava, known for its rough, broken surface typical of more viscous basaltic lava flows. Buea Town is composed mainly of vesicular basalt with reddish-brown clay soils, indicative of highly porous rock due to trapped gas bubbles during solidification. Bokwango has dark brown clay soils derived from volcanic ash, pointing to significant weathering processes. Soppo consists of massive blocky porphyritic basalts (aa lava), which have large, visible crystals (phenocrysts) in a finer-grained groundmass, suggesting slower cooling lava flows. Bokwai contains dark brown clay soils rich in ferromagnesian minerals (Fe^{2+} and Mg^{2+}), interspersed with patches of weathered basaltic rocks and varying particle sizes from gravel to boulders. The presence of grey porphyritic basalts and unconsolidated sediments contributes to the spongy texture of the soil. Basalts from cooled lava, typical of volcanic eruptions where lava has solidified to form dense, hard rock, dominate Molyko. Mile 16 and Mile 14 feature lahar deposits with boulders containing muscovite, a mica mineral, indicating a mix of volcanic material with metamorphic influences. Blocky basalts, formed from solidified lava into large, angular blocks, characterize tole/Sasse.

In Limbe I, the geology reflects volcanic activity and pyroclastic processes. Mile 4 comprises porphyritic basalt, which has large crystals set in a finer matrix, indicative of complex cooling histories. Mile 3 is characterized by columnar basalts, formed from the cooling and contraction of lava into hexagonal columns. Gardens is dominated by a pyroclastic cone made of scoria, a highly vesicular volcanic rock formed from explosive eruptions. In Limbe III, Mbonjo is represented by weathered basalts, showing significant alteration from the original basaltic lava due to weathering processes. Limbe II has a mix of pyroclastic and basaltic materials, with Ngeme composed of porphyritic basalts indicating slow cooling and crystallization of lava, Mukundange containing lapilli-sized pyroclastic materials from explosive eruptions, and Batoke dominated by a scoria cone formed from pyroclastic fragments due to volcanic activity (Fig. 5).

Tiko's geology features various volcanic and sedimentary materials. Olford (PMI) includes pyroclastic materials and sediments mixed with vesicular basalts, indicative of both explosive volcanic deposits and quieter lava flows. Police School area has similar geology with pyroclastic materials and vesicular basalts. Mutengene is characterized by loamy soil with patches of porphyritic basalts, suggesting fertile soil with scattered volcanic rocks. Washing Point and Limbe Road also have loamy soil with porphyritic basalts, indicating mixed volcanic influences. The West Coast Council Area showcases a variety of basaltic formations. Bakingili features weathered massive basaltic rocks, indicative of significant alteration and soil formation processes. Debundscha and Idenau are dominated by massive basaltic lava and rocks, suggesting solidified lava flows. The Chocolate Brown Loamy Soils in the region are fertile, well-drained soils derived from volcanic parent material (Fig. 5).

Muyuka Council Area also presents diverse volcanic influences. Behind Police features sandy clay, a mix of finer and coarser volcanic materials. Kwekwe is characterized by interbedded basalts, indicating alternating layers of solidified lava flows. This diverse geology across the seven council areas of Mount Cameroon reflects a complex volcanic landscape which highlights the need for localized geotechnical assessments for construction and land use planning.

3.1.2 Geotechnical characteristics of Soils in the Mount Cameroon Area

The plasticity of soil, indicated by its Atterberg limits, varies significantly across the different localities in the Buea Council Area and other regions listed. Plasticity, which measures the soil's ability to deform without breaking, ranges from low to high across the table. Molyko has low to medium plasticity with an Atterberg limit of 15.0%, suggesting it is less prone to significant volume changes compared to areas like Bokwai and Mile 16, which have high plasticity (Att. Limits of 34.3% and 30.1% respectively). Higher plasticity soils, such as those in Bokwango and Bokwai, are more susceptible to volume changes and related hazards like settlement (Table 1).

The C.B.R. values, which indicate the soil's load-bearing capacity, also exhibit a broad range, from very low to high. Localities like Molyko, Bokwango, and Mile 16 have low C.B.R. values (around 11.0%), reflecting a low load-bearing capacity and consequently lower soil strength. In contrast, Buea Town and Mutengene have significantly higher C.B.R. values (55.0% and 29.5% respectively), suggesting a high load-bearing capacity and stronger soil (Table 1). These differences imply that while some areas can support construction and heavy loads effectively, others may require additional stabilization measures to prevent settlement and instability.

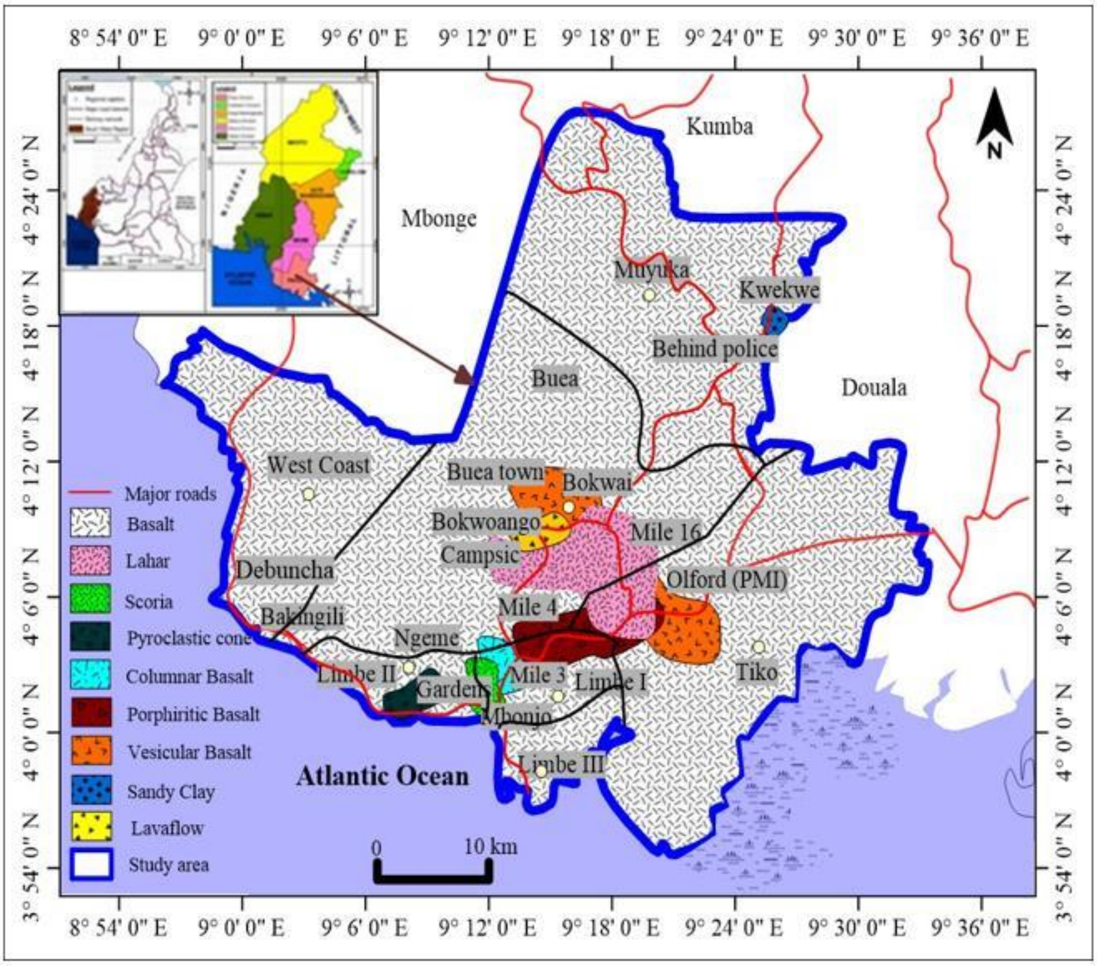

Fig. 5. Geology of Fako showing localities from which samples were collected for geotechnical analyses

Table 1. Geotechnical characteristics of soils in the Mount Cameroon area

Council Area	Locality	Att. Limit (%)	Plasticity	C.B.R (%)	Load Bearing Capacity	Soil Strength	Susceptibility Level
Buea	Molyko	15.0	Low to medium	11.0	Low	Low	Low to moderate
Buea	Soppo	24.8	Medium	22.0	High	High	Moderate
Buea	Campsic	19.1	Medium	19.0	Moderate	Moderate	Moderate
Buea	Bokwango	33.9	High	11.0	Low	Low	High
Buea	Buea Town	16.6	Medium	55.0	High	High	Low
Buea	Bokwai	34.3	High	11.0	Low	Low	High
Buea	Mile 16	30.1	High	11.0	Low	Low	High
Tiko	Tiko	29.2	Moderate	23.4	High	High	Moderate
Tiko	Mutengene	28.3	High	29.5	High	High	Moderate
Limbe 1	Mile 4	19.4	High	11.0	Low	Low	High
Limbe II	Batoke	25.7	Medium	11.0	Low	Low	Moderate
Limbe III	Mbonjo	16.8	Higher	28.4	High	High	Low
Muyuka	Behind Police Station	15.0	Moderate	8.3	Very Low	Very Low	High
Muyuka	Kwekwe	30.5	High	29.5	high	High	Moderate
West coast	Bakingili	20.3	High	11.0	Low	Low	High
West coast	Debundscha	33.8	High	11.0	Low	Low	High

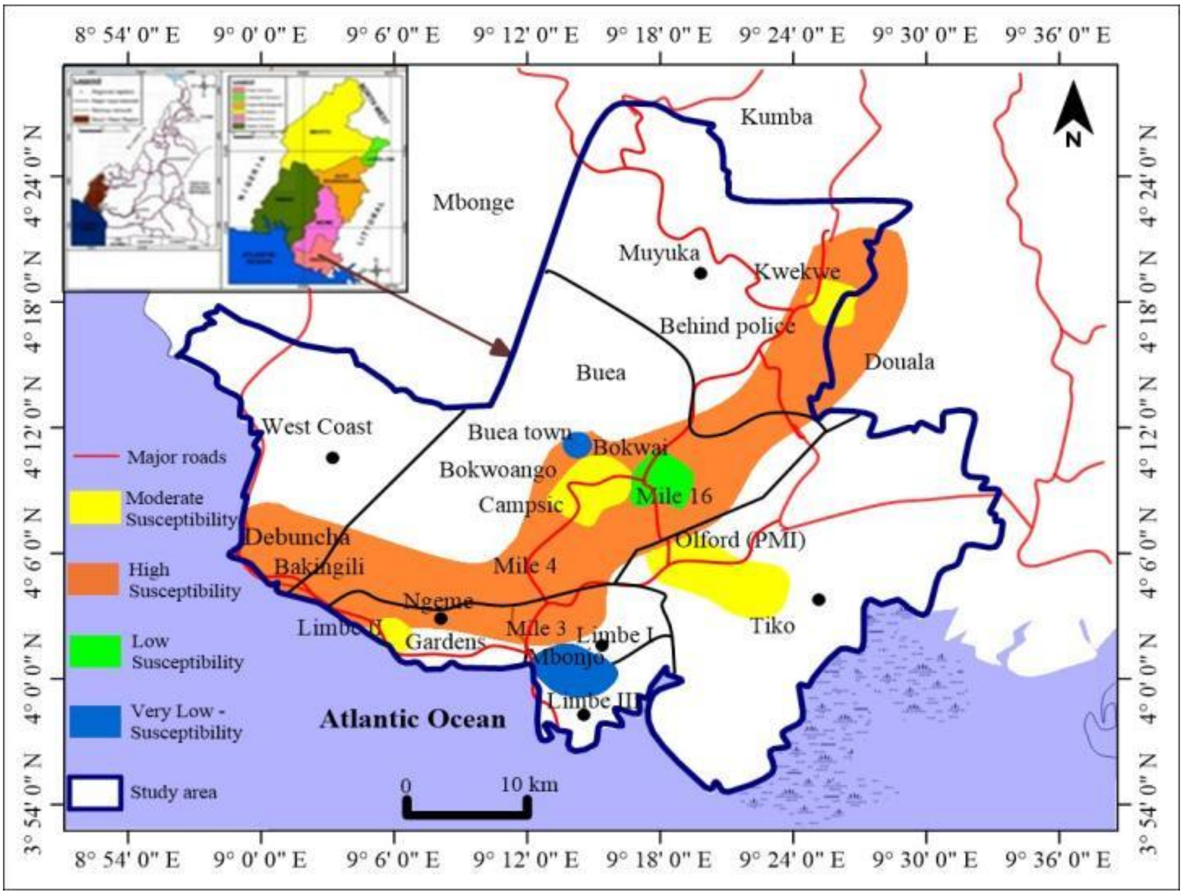

Fig. 6. Susceptibility map for Mount Cameroon Area (Fako)

Table 2. Seismic Intensities and associated impacts within Fako from previous eruptions

Year	Felt intensities (MMI)	Localities	Nature of felt intensities	Nature of impact
1959	VII	Ekona Muyuka Buea	Very strong	Strong shaking, significant damage to buildings
1982	VII	Limbe Buea Tiko	Very strong	Falling of objects, cracking of walls, and damage to buildings
1999	**VI**	**Buea** **Limbe** **Tiko**	**Moderate**	**Shaking of buildings, rattling noises, and minor damage**
2000	IV	Buea limbe Tiko	Light	Vibrations felt by people, rattling of doors and windows

3.1.3 Susceptibility to hazards and soil strength

The soil strength, derived from C.B.R. values and load-bearing capacity, directly influences the susceptibility to various hazards. Soils with high C.B.R. and load-bearing capacity, such as those in Buea Town and Mutengene, exhibit high strength and low susceptibility to deformation. Conversely, areas like Behind Police in Muyuka and Mile 4 in Limbe I have very low soil strength due to low C.B.R. values, making them highly susceptible to settlement and soil instability. The susceptibility level across the localities ranges from low to moderate in areas with high C.B.R. and low plasticity to high in areas with low C.B.R. and high plasticity (Table 1 and Fig. 6).

The combined analysis of Atterberg limits, plasticity, C.B.R., and load-bearing capacity provides a comprehensive understanding of soil behavior in these regions (Table 1 and Fig. 6). For areas like Molyko and Batoke, where the susceptibility level is low to moderate, standard construction practices may suffice. However, in high susceptibility regions like Bokwango, Bokwai, and Behind Police, enhanced geotechnical interventions such as soil stabilization, reinforcement, and careful load management are crucial to mitigate risks associated with settlement and instability. These findings highlight the importance of localized soil assessments to inform safe and sustainable construction practices.

3.1.4 Seismic intensities associated with Mount Cameroon area

The findings presented in this section targeted recorded eruptions, with attention on the most recent eruptions of 1959, 1982, 1999 and 2000. This information was obtained from Published Journals and responses from residents living in the studied localities using the Modified Mercali Intensity scale (MMI). These were used to assess the impact of seismic motion from the targeted eruptions on the built environment in these localities (Table 2).

In 1959, a significant seismic event with an intensity of VII on the Modified Mercalli Intensity (MMI) scale was felt in Ekona, Muyuka, and Buea. This event was characterized by very strong shaking, resulting in considerable damage to buildings, indicating the severity of the seismic activity.

In 1982, another event with an intensity of VII on the MMI scale impacted Limbe, Buea, and Tiko. The shaking was very strong, leading to the falling of objects, cracking of walls, and damage to buildings, reflecting a substantial impact on the infrastructure.

In 1999, a moderate seismic event with an intensity of VI on the MMI scale was experienced in Buea, Limbe, and Tiko. This event caused moderate shaking of buildings, rattling noises, and minor damage, showing a relatively lower but still notable level of impact compared to the previous events.

Finally, in 2000, a light seismic event with an intensity of IV on the MMI scale affected Buea, Limbe, and Tiko. People, causing rattling of doors and windows, felt the vibrations but there was no significant damage reported, indicating the mild nature of the event.

The 1999 eruption had a higher impact in Buea as a whole than other areas (Figs. 7& 8) when compared to the 1959 and 1982 events with major and minor damages greatly felt in Bokwango, Buea Town, Small Soppo, Bonduma, Molyko, Bomaka and Muea. However, some houses experienced no effects. This high impact within the city of Buea could be linked to the fact that the epicentre of the quake was within the city.

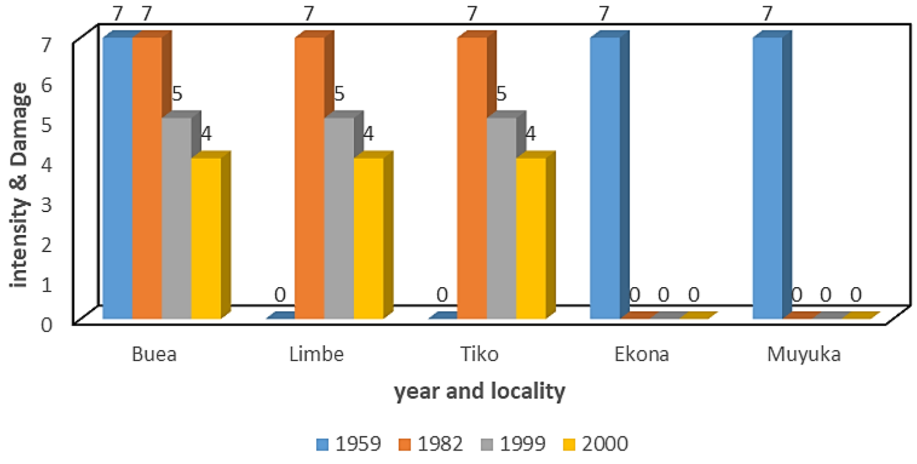

Fig. 7. Intensities and associated impacts (damages) from the 1959. 1982, 1999 & 2000 eruptions

Fig. 8. Damaged buildings in Buea during the 1999 eruption at: a. Small Soppo, b. poto-poto quarter-Bokwango, c. Buea Town and d. Small Soppo

In addition, seismic activities for this eruption started as far back as 1986 and gradually built up and accumulated over a period of 13 years before the eruption in 1999.

3.2 Discussion

The geological diversity of the Buea, Limbe, Tiko, West coast (Idenau), and Muyuka Council areas around Mount Cameroon precisely within Fako Division, underscores a complex volcanic history with distinct formations such as lahars, blocky basalts, and scoria cones. This aligns with findings from studies in other volcanic regions like Hawaii and Iceland which have identified comparable volcanic materials such as basaltic lava flows, scoria cones, and pyroclastic deposits, which influence local geology and land use suitability [24,25].

Moreover, the presence of varied volcanic and sedimentary materials in Tiko and Muyuka Council areas reflect a diverse geological composition, similar to findings in regions like the Andes and the Cascades, where volcanic activities have shaped landscapes and soil characteristics [26]. This diversity influences soil fertility, land stability, and the susceptibility to volcanic hazards, highlighting the need for tailored geotechnical assessments and land use planning to mitigate risks and harness resource potentials sustainably [27].

In the Mount Cameroon area, soil plasticity, assessed through Atterberg limits, varies significantly across different localities within the seven council areas. For instance, Molyko exhibits low to medium plasticity with an

Atterberg limit of 15.0%, indicating less susceptibility to volume changes compared to Bokwai and Mile 16, where higher values (34.3% and 30.1% respectively) suggest greater potential for settlement hazards [28]. Concurrently, the California Bearing Ratio (C.B.R.) values highlight varying load-bearing capacities, with Molyko, Bokwaongo, and Mile 16 showing low values around 11.0%, necessitating careful construction planning to manage potential settlement and instability risks. In contrast, Buea Town and Mutengene demonstrate higher C.B.R. values (55.0% and 29.5% respectively), indicating stronger soil and greater suitability for heavy construction loads [29].

Research in the Limbe area, for instance, echoes findings from Mount Cameroon, revealing that high plasticity soils with low C.B.R. values are prone to significant settlement and structural instability [30]. Such insights emphasize the need for tailored geotechnical interventions across regions with diverse soil characteristics to ensure safe and sustainable construction practices. This comprehensive approach, integrating Atterberg limits, C.B.R., and soil strength assessments, informs effective strategies for soil stabilization and load management to mitigate hazards associated with soil deformation and settlement [30].

The analysis of Atterberg limits, plasticity, C.B.R., and load-bearing capacity offers crucial insights into soil behavior in the Mount Cameroon area and similar regions. Areas characterized by low to moderate susceptibility levels, such as Molyko and Batoke, may benefit from standard construction practices, whereas high susceptibility regions like Bokwaongo and Bokwai require enhanced geotechnical interventions. These include soil stabilization, reinforcement, and careful load management to mitigate risks associated with settlement and instability, aligning with established principles in geotechnical engineering and soil mechanics [31,32].

The findings from this study highlight the varying impacts of seismic events on built environments across several eruptions in the Mount Cameroon area, ranging from significant damage in 1959 and 1982 to milder effects in 1999 and 2000. Similar studies in volcanic regions globally have also documented varying intensities of seismic activity and their corresponding impacts on infrastructure. For instance, research in volcanic regions like Japan and Iceland has shown comparable patterns of increasing or decreasing damage relative to the intensity of seismic events, underscoring the importance of local geological conditions and building resilience strategies in mitigating these impacts [33,34].

4. CONCLUSION

The diverse geology across the Buea, Limbe, Tiko, and Muyuka Council areas of Mount Cameroon illustrates the complex volcanic history and its profound influence on local landscapes and soil compositions. The presence of various volcanic deposits, from lahars and scoria cones to basaltic lava flows and weathered basalts, necessitates tailored approaches to infrastructure development and environmental management.

Given Mount Cameroon's geological characteristics, including volcanic rocks, pyroclastic deposits, and alluvial deposits, the area is highly susceptible to seismic hazards. The findings underscore the importance of localized soil assessments to inform safe construction practices and enhance disaster resilience.

The plasticity of soils within the seven Council area varies significantly. Localities in the Buea Council area like Molyko exhibit low to medium plasticity, indicating lower susceptibility to volume changes, whereas areas like Bokwai and Mile 16 show high plasticity, making them more prone to volume changes and related hazards such as settlement. The C.B.R. values, indicating soil's load-bearing capacity, range from very low to high across different localities. Areas like Buea Town and Mutengene have high C.B.R. values, suggesting strong soil and high load-bearing capacity, whereas Molyko and Mile 16 have low C.B.R. values, indicating lower soil strength and higher need for stabilization measures during construction.

The seismic events recorded in Buea from 1959 to 2000 illustrate varying degrees of intensity and impact on local infrastructure, reflecting the dynamic geological activity of Mount Cameroon. The significant damage observed in 1959 and 1982 due to intense shaking underscores the vulnerability of built environments to volcanic seismicity. The concentration of higher impacts within Buea during the 1999 eruption suggests localized factors such as proximity to the epicenter influencing severity. This historical data underscores the importance of continuous monitoring and preparedness strategies for volcanic seismic hazards in urban planning and disaster resilience efforts.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

We hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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