Scientific Research Publishing

Open Journal of Geology, 2025, 15(9), 537-548
https://www.scirp.org/journal/ojg
ISSN Online: 2161-7589
ISSN Print: 2161-7570

Assessment of Unrecorded Intraplate Seismicity: Empirical Magnitude Determination of the Shaki Earthquake, Southwest Nigeria

Ayodeji Adekunle Eluyemi[1*], Peter Adetokunbo[2], Imuetinyan Aigbogun[3], Michael Ayuk Ayuk[4], Segun Aguda[5], Mako Sitali[6], Fisayo Mayowa Adegbemi[7], Akintunde Olanrewaju Olorunfemi[8], Musa Olufemi Awoyemi[7], Saurabh Baruah[9]

[1]Centre for Energy Research and Development (CERD), Obafemi Awolowo University (OAU), Ile-Ife, Nigeria
[2]Boone Pickens School of Geology, Oklahoma State University, Stillwater, USA
[3]School of Biological Sciences and Applied Chemistry, Seneca Polytechnic, Toronto, Canada
[4]Department of Applied Geophysics, Federal University of Technology, Akure, Nigeria
[5]Department of Project Management, Missouri State University, Springfield, USA
[6]Ministry of Mines and Energy (Geological Survey of Namibia), Windhoek, Namibia
[7]Department of Physics and Engineering Physics, Obafemi Awolowo University (OAU), Ile-Ife, Nigeria
[8]Department of Earth and Environmental Sciences, University of Minnesota, Duluth, USA
[9]Geosciences and Technology Division, CSIR-North East Institute of Science and Technology (CSIR-NEIST), Jorhat, India
Email: *ay_dot2006@yahoo.com

How to cite this paper: Eluyemi, A.A., Adetokunbo, P., Aigbogun, I., Ayuk, M.A., Aguda, S., Sitali, M., Adegbemi, F.M., Olorunfemi, A.O., Awoyemi, M.O. and Baruah, S. (2025) Assessment of Unrecorded Intraplate Seismicity: Empirical Magnitude Determination of the Shaki Earthquake, Southwest Nigeria. *Open Journal of Geology*, **15**, 537-548.
https://doi.org/10.4236/ojg.2025.159026

Received: June 18, 2025
Accepted: September 8, 2025
Published: September 11, 2025

Abstract

Recent seismic events at Shaki, an old town in Southwest Nigeria, have generated concern regarding the possible reactivation of old fault lines in the area. Two events of note occurred on August 21, 2016 and September 8, 2021, both of which were followed by a sequence of aftershocks lasting several weeks. Unfortunately, the events were not instrumentally recorded, restricting data for hazard characterization. To resolve this problem, we carried out a study to estimate the local magnitude (ML) of the events through an integration of site visitations and questionnaires administered to the residents of the localities. The study adopted a systematic method founded on the Modified Mercalli Intensity (MMI) scale that relates instrumental intensity to perceived shaking, object movement, and possible building damage. One hundred respondents were interviewed in the areas where the tremors were most strongly felt. The data collected were processed with a weighted statistical approach, and the magnitude was computed from the empirical relations obtained. The results gave a consistent magnitude estimate of 4.7 ML for both events, with a narrow 95% confidence limit of 4.6 - 4.8 ML. The results offer useful information on the seismic hazard in Shaki and the need for instrumental monitoring and additional investigations to clarify the geological and tectonic processes responsible for the seismic activity in the area. The research contributes to seismic risk assessment and the formulation of proper hazard mitigation strategies in Shaki and the surrounding areas.

Keywords

Shaki, Intraplate Earthquake, Magnitude Estimation, Modified Mercalli Intensity, Seismic Hazard Assessment

1. Introduction

Intraplate seismicity has attracted heightened interest because of its potential implications and unique challenges in seismic hazard estimation and risk reduction [1] [2]. These seismic events have the characteristics of unpredictability, lower frequency, and occurrence in areas often assumed to be stable, and thus are of specific importance for risk reduction in areas lacking large seismic monitoring networks [3] [4]. An old town of Shaki in Southwest Nigeria was struck by a succession of seismic events on September 16, 2016, which continued for some months, resulting in extensive panic and confusion among the populace. These operations were also accompanied by continuous vibrations and earth tremors that rocked buildings and structures, dislodging individuals from their residences, farms, and businesses [5].

Intraplate earthquakes in stable continental areas like Shaki are generally attributed to the reactivation of ancient fault lines or local stress concentrations [6]. The Nigeria Geological Survey Agency (NGSA) has conducted some monitoring and assessment to determine the level of damage in the area. However, the shortage or absence of instrumental records of these events has impeded the scientific investigation and assessment of the seismic hazard in the area.

When instrumental data are unavailable, indirect approaches like the Modified Mercalli Intensity (MMI) scale and empirical relations can be utilized for earthquake magnitude estimation [7]. The MMI scale can be related to instrumental magnitude, felt or perceived shaking, movement of objects, and potential building damage [8] [9]. Using this relationship, researchers can establish the intensity of the seismic events and approximate the local magnitude (ML) via empirical relations using eyewitness reports and field observations [10].

This study aims to determine the magnitude of the seismic activities in Shaki through field visits, questionnaires, and statistical analysis. By relating the MMI scale to Peak Ground Acceleration (PGA), velocity, and perceived shaking, we hope to determine the local magnitude (ML) of seismic activities. The findings of this research will be useful for seismic risk assessment and designing suitable mitigation strategies in the area.

2. Tectonic Setting

Shaki is situated in the Southwestern Nigerian Basement Complex, which is part of an extensive Pan-African mobile belt separating the West African Craton and the Congo Craton [11] [12]. It is situated in a stable Precambrian basement complex that has experienced multiple cycles of deformation with attendant metamorphism. The geology of the basement here is largely made up of migmatites, gneisses, and related metamorphic units, which have been intruded by various types of granitoid intrusives of the Pan-African age [13] [14]. The Shaki tectonic fabric is dominated by the Pan-African orogeny that led to the development of major structural features such as folds, faults, and fracture systems. These geological structures all have a predominantly NNE-SSW trend, which is the overall structural trend of the Nigerian basement complex [15]. The region is also marked by a suite of deep-seated fractures and lineaments that can act as potential conduits for stress build-up and release [16].

Tectonic evolution in the area has been largely affected by the northward movement and counterclockwise rotation of the African plate over the last 90 million years [17] [18]. The translation led to a regime change from peripheral compression to one of peripheral extension as the functional mechanical center of Africa moved across the equator. The contemporary stress regime, characterized by extensional tectonics, could potentially account for the reactivation of the pre-existing structures in the basement complex. Although situated in a relatively stable intraplate area, far from active plate boundaries, the Shaki region exhibits features of neotectonic activity. The existence of such deep-seated geological structures in the basement rocks may be the reason for the sporadic seismic activity in this apparently stable continental area. Reactivation of these old fault systems in the current extensional regime may be the cause of the observed seismicity.

3. Methodology

Shaki town in the southwest of Nigeria (**Figure 1**) has, in recent years, been faced with unprecedented land tremors that were not recorded instrumentally. In an attempt to establish the magnitude of these seismic events, a systematic procedure via field surveys, statistical treatment, and established empirical relationships was adopted.

The research utilizes the Modified Mercalli Intensity (MMI) scale [9] in **Table 1**, which correlates instrumental intensity with peak ground acceleration, ground motion velocity, perceived/felt shaking, and possible structural damage. The scale forms the basis for the estimation of earthquake parameters where instrumental records are lacking.

A structured questionnaire was prepared and distributed among 100 respondents in the areas where the tremors were most felt. The sample included residents from various building types (single-family homes, apartments, and commercial structures) and encompassed diverse demographic groups by age, occupation, and socioeconomic status. Respondents were selected from multiple neighborhoods that experienced the earthquake to ensure the survey adequately represents the geographic and social diversity of the affected population. The questionnaire contained three general sections to obtain detailed information about the seismic activity. The initial section measured the strength of ground motion felt, ranging from "not felt" to "very strong shock". The second section recorded the movement and displacement of objects within the houses during the incidents. The third section aimed to collect data regarding possible damage to building structures, ranging from slight cosmetic damage to severe structural effects.

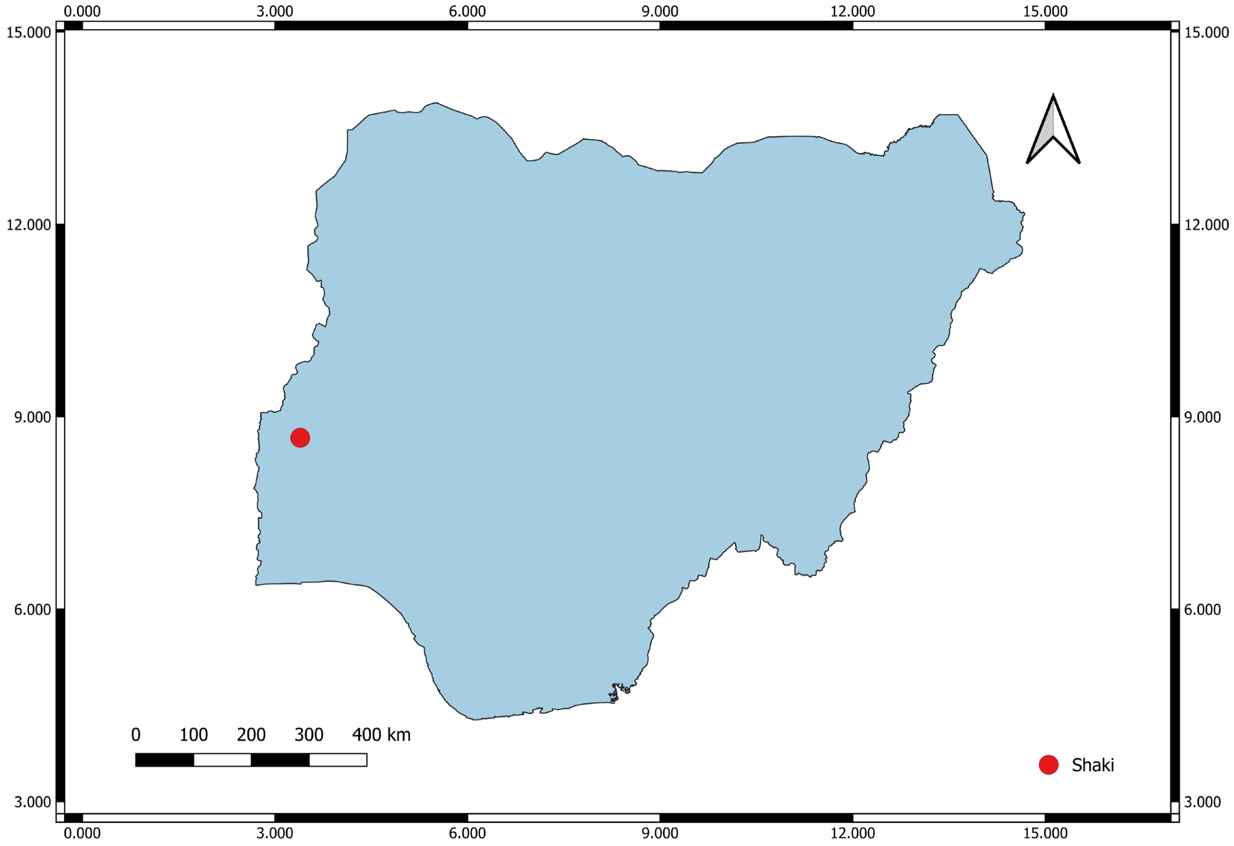

Figure 1. The map of Nigeria showing the geographic position of Shaki-town (study area).

Table 1. Modified Mercalli Intensity (MMI) scale [9].

Instrumental Intensity	Acceleration (g)	Velocity (cm/s)	Perceived Shaking	Potential Damage
I	<0.0017	<0.1	Not felt	None
II - III	0.0017 - 0.014	0.1 - 1.1	Weak	None
IV	0.014 - 0.039	1.1 - 3.4	Light	None
V	0.039 - 0.092	3.4 - 8.1	Moderate	Very light
VI	0.092 - 0.18	8.1 - 16	Strong	Light
VII	0.18 - 0.34	16 - 31	Very Strong	Moderate
VIII	0.34 - 0.65	31 - 60	Severe	Moderate to heavy
IX	0.65 - 1.24	60 - 116	Violent	Heavy
X+	>1.24	>116	Extreme	Very heavy

The magnitude estimation technique uses a weighted statistical process in which each intensity observation is given an MMI value. A weighted average MMI value is derived from the frequency distribution of the observations. The MMI-earthquake magnitude relation is derived from two empirical equations. The Richter relation [9] (Equation (1)) connects magnitude and MMI through:

$$M = 1 + \left(2/3\right) \times MMI \tag{1}$$

while the Murphy-O'Brien relationship [19] (Equation (2)) provides an alternative estimation:

$$M = 1.3 + 0.6 \times MMI \tag{2}$$

where M is the local magnitude and MMI is the Modified Mercalli Intensity value. These relations are used separately with the computed average MMI to cross-validate the magnitude values. The confidence intervals are calculated using the standard deviation of the two magnitude estimates. Because the survey was done close to the epicenter of the earthquake, the values are given in terms of local magnitude (ML). The application of Richter and Murphy-O'Brien intensity-magnitude relations to West African crustal conditions assumes that the stable continental crust characteristics are similar to those of regions where these relations were originally calibrated. This assumption is reasonable given that West Africa is part of the stable continental regions where crustal earthquakes show similar characteristics to other cratonic regions.

4. Results

Figure 2 illustrates the distribution of total structural damage across the various building elements. The most damage occurred in collapsed ceiling trim/lamps at 68%, followed by cracked windows at 56% and exterior wall cracking at 46%. Cracks in interior plaster and collapsed wall/ceiling plaster recorded comparatively lower damage percentages of 18% each. Note that there was no damage at all occurring in the chimneys. This trend indicates that the impact of the earthquake was particularly marked on lighter structural elements and ceiling members, but it had little impact on more robust structural elements.

The heatmap plot (**Figure 3**) showed definite patterns of intensity, with windows/doors showing the most intense effects (66% strong, 15% very strong), followed by dishes (57% strong, 4% very strong). The distribution is obviously graded from light to heavy objects, with an abrupt transition in the middle range. Smaller objects, such as pictures and small items, were predominantly exhibiting small intensity effects at 60% - 63%, whereas slamming doors were showing low to moderate effects (31% low, 16% moderate). Larger objects, such as furniture, showed minimal displacement, with less than 2% showing strong effects. Statistical analysis revealed a high level of correlation between object mass and displacement intensity ($p < 0.001$), with smaller objects tending to have higher frequencies of displacement.

The pattern of distribution of perceived/felt shaking intensity (**Figure 4**) revealed a tendency towards greater effects. Statistical analysis revealed that 86% of respondents experienced moderate to very strong ground shaking. Among these respondents, 31% reported moderately strong shaking with a 95% confidence interval of 22.1% - 39.9%, 29% reported strong shaking with a 95% CI of 20.3% - 37.7%, and 26% reported very strong shaking with a 95% CI of 17.6% - 34.4%.

Table 2. Distribution of perceived shaking intensity and corresponding MMI levels with their contributions to the weighted sum for magnitude estimation.

Observation	Percentage	MMI Level	Contribution
Heard noise but felt no vibration.	3	2	6
Very weak vibration	1	3	3
Weak vibration	10	4	40
Moderately strong shock	31	5	155
Strong shock	29	6	174
Very strong shock	26	7	182

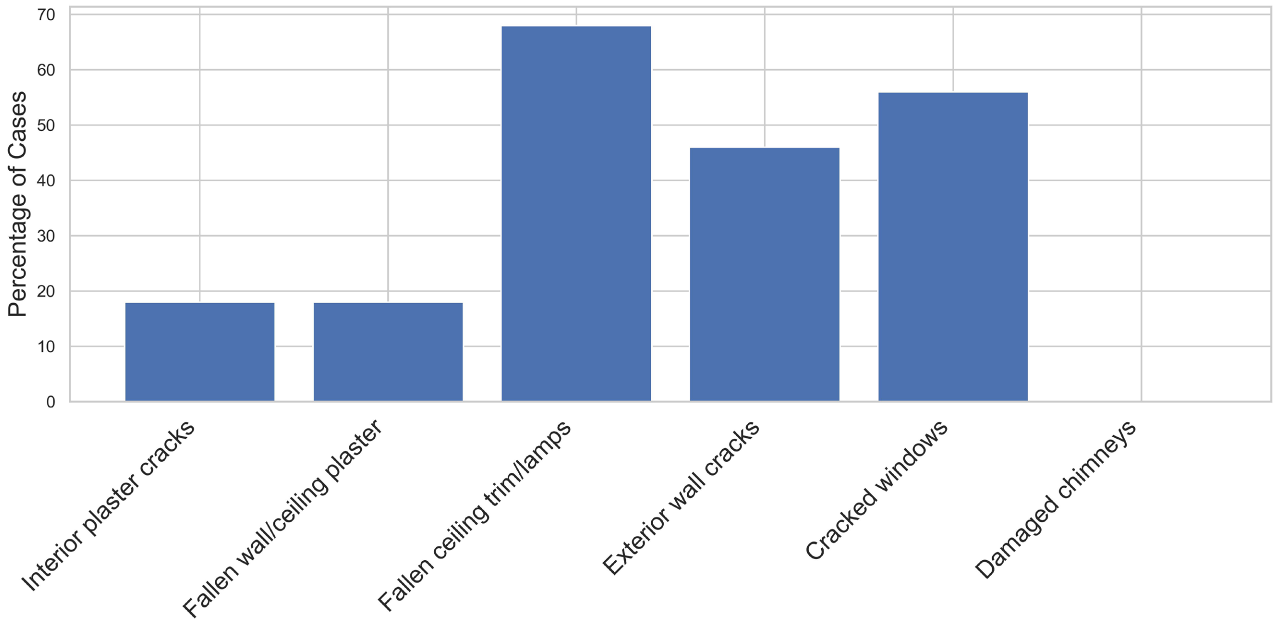

Figure 2. Distribution of structural elements damaged during the seismic activity.

Just 14% of interviewees described weak or very weak vibrations, with few reports (3%) of noise heard without vibration, suggesting general perception of the seismic event.

Analysis of structural damage (**Figure 5**) showed patterns in line with moderate seismic activity. Cracked windows accounted for the highest incidence at 17%, followed by cracks in exterior walls at 14%, while cracks in interior plaster and ceiling trim/lamps that had fallen accounted for 8% and 12%, respectively. The distribution of severity (**Figure 6**) showed a strong skew towards the lower levels of structural impact, with 145 instances of very low damage, 38 instances of low damage, 12 instances of moderate damage, and fewer than 5 instances of strong or very strong damage. This is typical of a moderate-sized earthquake that is capable of producing widespread minor damage but relatively limited severe structural effects.

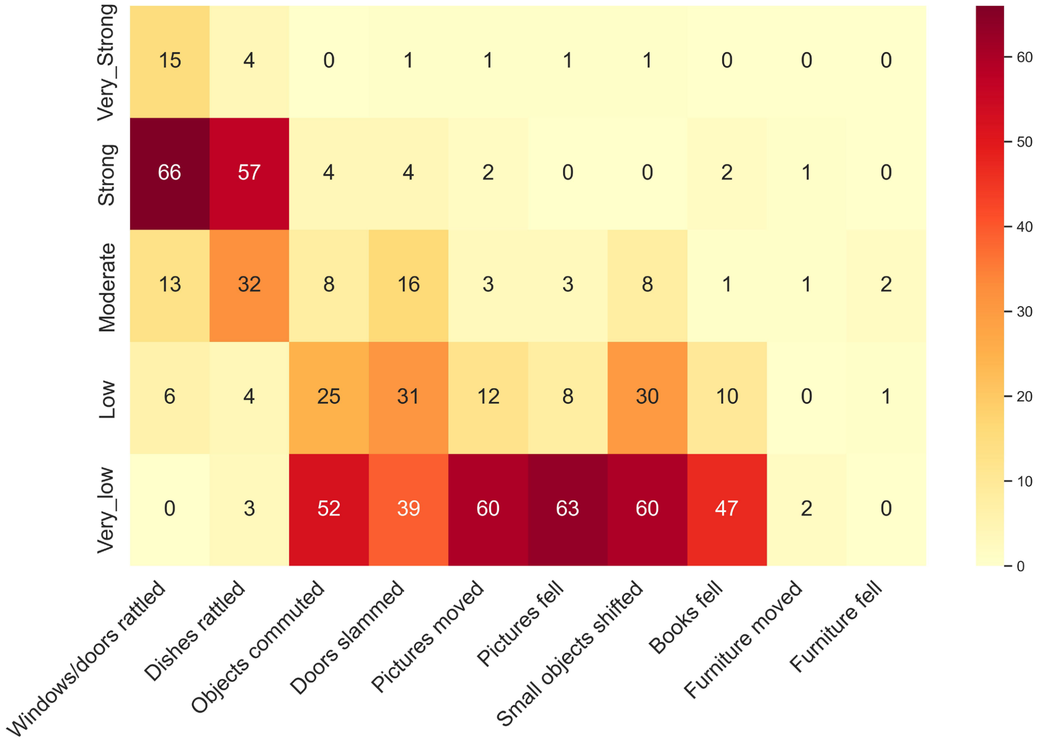

Figure 3. Heat map analysis of the object displacement intensity during the earthquake.

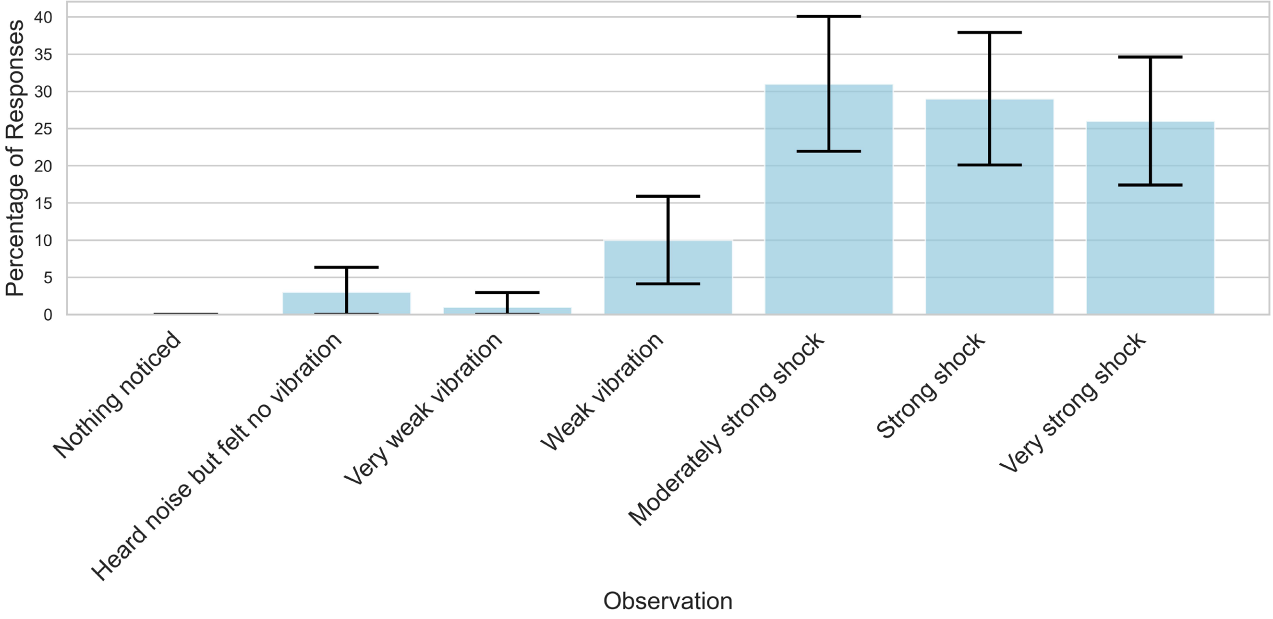

Figure 4. Distribution of perceived shaking intensity among survey respondents with a 95% confidence interval.

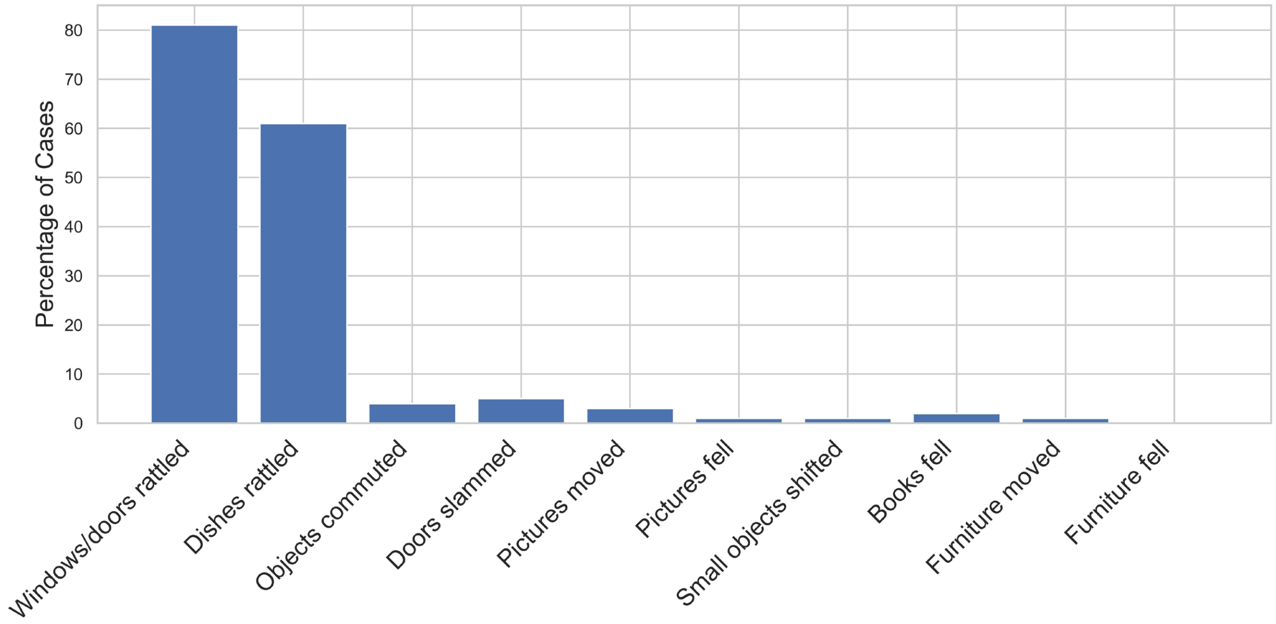

Figure 5. Frequency distribution of object displacement during the earthquake events.

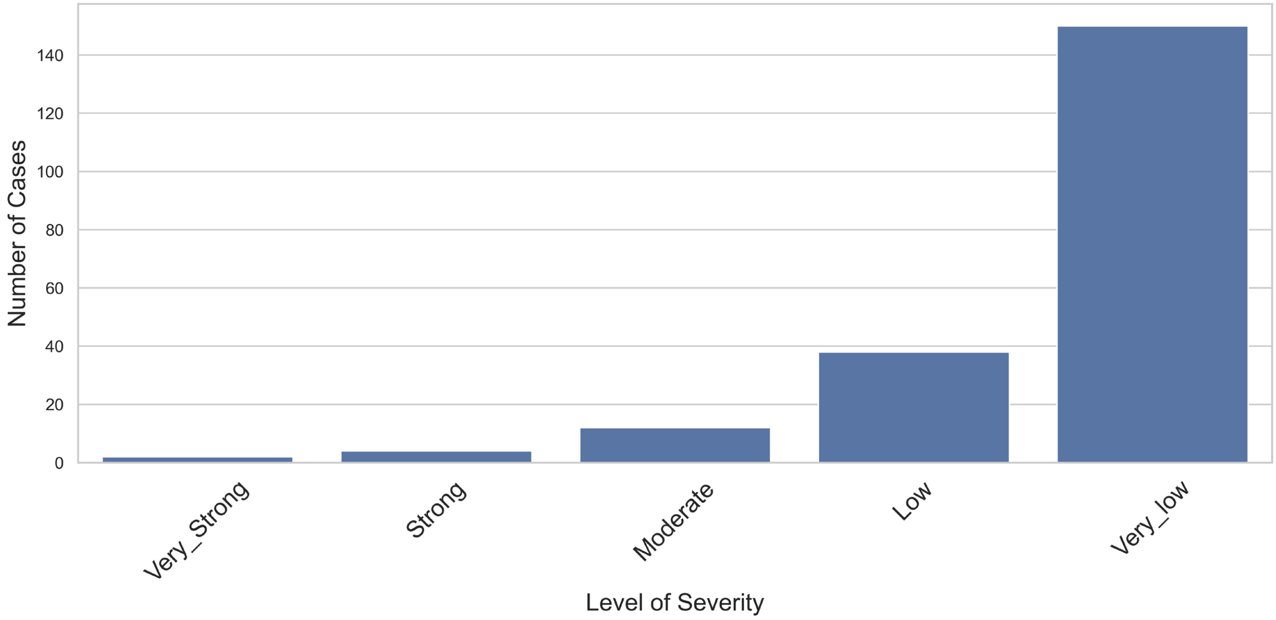

Figure 6. Classification of structural damage by severity levels of the earthquake event.

The MMI analysis (Table 2) provided the foundation for magnitude determination. The weighted average MMI was calculated by multiplying each intensity observation's percentage by its corresponding MMI value, then dividing by the total percentage of responses. Very strong shock (MMI VII) accounted for the largest contribution (182.0 from 26% of responses), followed by strong shock (MMI VI, contributing 174.0 from 29% of responses) and moderately strong shock (MMI V, contributing 155.0 from 31% of responses). The cumulative weighted sum of 560.0

divided by the total response percentage (100.0) yielded an average MMI of 5.6. Magnitude estimation was extremely reproducible across methods, with both the Richter and Murphy-O'Brien methods yielding 4.7 ML. The overall magnitude estimate of 4.7 ML, with the very tight 95% confidence interval of 4.6 - 4.8 ML, indicates very high reliability in the estimate.

5. Discussion

This work provides a comprehensive evaluation of the extent and impact of recent earthquakes in Shaki town, Nigeria, based on a systematic examination of perceived shaking intensity, object motion patterns, and building damage observations. The findings validate the use of the Modified Mercalli Intensity (MMI) scale and empirical relationships in estimating the magnitude of earthquakes where instrumental records are lacking.

The general impression of moderate to strong shaking, as noted by the majority of the participants (86%), shows that the seismic events were largely felt by the community. The high percentage implies that the events were of enough magnitude to be discernible. The consistency in the shaking intensity reports throughout the area surveyed also adds to the credibility of the data and the existence of a local seismic source. The behavior of object displacement in response to earthquake activity gives great insight into the nature of ground motion. The high degree of correlation between object mass and displacement magnitude, where lighter objects are displaced more frequently, aligns with expected behavior when there is seismic activity. This pattern suggests that the seismic waves generated by the events had sufficient energy to cause noticeable movement in light objects. The well-defined intensity patterns seen for windows, doors and dishes also support the fact that there was a seismic event capable of causing vibrations over a range of frequencies.

Analysis of the structural damage shows a pattern consistent with moderate seismic activity. Minor damages, like shattered windows and fissures in outside walls, did take place, which shows that the magnitude of the events was sufficient to produce surface harm to the structures. Nonetheless, the sporadic incidence of extreme structural damage implies that the magnitude of the events was not strong enough to cause widespread major structural failure. The spread of observed damage is in agreement with the estimated magnitude of 4.7 ML, a size often found to be associated with moderate earthquakes capable of inducing light to moderate structural damage, especially to poorly constructed or older structures.

The concordance between magnitude estimates derived from the Richter and Murphy-O'Brien techniques and the narrow confidence interval enhances the reliability of the MMI-based method. The agreement between these independent methods of estimation enhances the validity of the results and corroborates the description of seismic events as moderate earthquakes. The magnitude estimate is further reinforced by a detailed study of shaking intensity, movement of objects, and damage to structures, which together present a multi-faceted view of the earthquake's effects.

6. Conclusions

This study investigated two unrecorded seismic events that occurred in Shaki town in August 2016 and September 2021, using macroseismic intensity analysis based on questionnaire data from 100 respondents. Through the application of the Richter and Murphy-O'Brien intensity-magnitude relations, the analysis yielded an average Modified Mercalli Intensity (MMI) of 5.6, corresponding to an estimated magnitude range suitable for the stable continental region characteristics of West Africa. The study successfully demonstrated the utility of systematic macroseismic assessment in areas lacking instrumental seismic monitoring infrastructure.

The findings have significant implications for seismic risk assessment and mitigation strategies in Shaki town and surrounding areas. The confirmation of moderate seismic activity is consistent with previous studies [20]-[22] and necessitates enhanced awareness, preparedness, and resilience initiatives among residents. This includes implementing appropriate building codes, retrofitting vulnerable structures, and developing early warning systems. The study underscores the critical importance of establishing seismic monitoring networks and maintaining comprehensive instrumental records to improve the understanding of regional seismic hazards and inform evidence-based risk reduction measures.

Several limitations must be acknowledged. The absence of instrumental recording equipment in the study area necessitated complete reliance on questionnaire data, which introduces inherent uncertainties in magnitude estimation. Additionally, potential recall bias exists as questionnaires were administered in 2021, which may not accurately reflect the intensity of shaking experienced during the 2016 event due to memory degradation over the five-year interval. Future research should focus on establishing instrumental monitoring capabilities in the Shaki area and investigating the underlying geological and tectonic processes driving local seismic activity to better characterize the seismic hazard profile of this region.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Gangopadhyay, A. and Talwani, P. (2003) Symptomatic Features of Intraplate Earthquakes. *Seismological Research Letters*, **74**, 863-883. https://doi.org/10.1785/gssrl.74.6.863

[2] Holford, S.P., Hillis, R.R., Hand, M. and Sandiford, M. (2011) Thermal Weakening Localizes Intraplate Deformation along the Southern Australian Continental Margin. *Earth and Planetary Science Letters*, **305**, 207-214. https://doi.org/10.1016/j.epsl.2011.02.056

[3] Stein, S., Liu, M., Camelbeeck, T., Merino, M., Landgraf, A., Hintersberger, E., *et al.* (2015) Challenges in Assessing Seismic Hazard in Intraplate Europe. *Geological Society, London, Special Publications*, **432**, 13-28. https://doi.org/10.1144/sp432.7

[4] Levandowski, W., Zellman, M. and Briggs, R. (2017) Gravitational Body Forces Focus North American Intraplate Earthquakes. *Nature Communications*, **8**, Article No. 14314. https://doi.org/10.1038/ncomms14314

[5] Akpan, A.E., Ilori, A.O. and Essien, N.U. (2015) Geophysical Investigation of Obot Ekpo Landslide Site, Cross River State, Nigeria. *Journal of African Earth Sciences*, **109**, 154-167. https://doi.org/10.1016/j.jafrearsci.2015.05.015

[6] Mooney, W.D., Ritsema, J. and Hwang, Y.K. (2012) Crustal Seismicity and the Earthquake Catalog Maximum Moment Magnitude (M_{cmax}) in Stable Continental Regions (SCRs): Correlation with the Seismic Velocity of the Lithosphere. *Earth and Planetary Science Letters*, **357**, 78-83. https://doi.org/10.1016/j.epsl.2012.08.032

[7] Musson, R.M.W., Grünthal, G. and Stucchi, M. (2009) The Comparison of Macroseismic Intensity Scales. *Journal of Seismology*, **14**, 413-428. https://doi.org/10.1007/s10950-009-9172-0

[8] Gutenberg, B. and Richter, C.F. (2012) Magnitude and Energy of Earthquakes. *Annals of Geophysics*, **9**, 1-15. https://doi.org/10.4401/ag-5590

[9] Richter, C.F. (1958) Elementary Seismology. W.H. Freeman and Company, 768.

[10] Grünthal, G., Stromeyer, D., Bosse, C., Cotton, F. and Bindi, D. (2018) The Probabilistic Seismic Hazard Assessment of Germany—Version 2016, Considering the Range of Epistemic Uncertainties and Aleatory Variability. *Bulletin of Earthquake Engineering*, **16**, 4339-4395. https://doi.org/10.1007/s10518-018-0315-y

[11] Black, R., Caby, R., Moussine-Pouchkine, A., Bayer, R., Bertrand, J.M., Boullier, A.M., *et al.* (1979) Evidence for Late Precambrian Plate Tectonics in West Africa. *Nature*, **278**, 223-227. https://doi.org/10.1038/278223a0

[12] Reijers, T.J.A., Petters, S.W. and Nwajide, C.S. (1997) Chapter 7: The Niger Delta Basin. *Sedimentary Basins of the World*, **3**, 151-172. https://doi.org/10.1016/s1874-5997(97)80010-x

[13] Oyawoye, M.O. (1972) The Basement Complex of Nigeria. In: Dessauvagie, T.F.J. and Whiteman, A.J., Eds., *African Geology*, University of Ibadan Press, 67-99.

[14] Ajibade, A.C., Woakes, M. and Rahaman, M.A. (1987) Proterozoic Crustal Development in the Pan-African Regime of Nigeria. In: Kroner, A., Ed., *Geodynamics Series*, American Geophysical Union, 259-271. https://doi.org/10.1029/gd017p0259

[15] Rahaman, M.A. (1976) Review of the Basement Geology of Southwestern Nigeria. In: Kogbe, C.A., Ed., *Geology of Nigeria*, Elizabethan Publishing Company, 41-58.

[16] Odeyemi, I.B. (1981) A Review of the Orogenic Events in the Precambrian Basement of Nigeria, West Africa. *Geologische Rundschau*, **70**, 897-909.

[17] Fail, J.P., Montadert, L., Delteil, J.R., Valery, P., Patriat, P. and Schlich, R. (1970) Prolongation des zones de fractures de l'ocean atlantique dans le golfe de guinee. *Earth and Planetary Science Letters*, **7**, 413-419. https://doi.org/10.1016/0012-821x(70)90083-x

[18] Neev, D., Hall, J.K. and Saul, J.M. (1982) The Pelusium Megashear System across Africa and Associated Lineament Swarms. *Journal of Geophysical Research*: *Solid Earth*, **87**, 1015-1030. https://doi.org/10.1029/jb087ib02p01015

[19] Murphy, J.R. and O'Brien, L.J. (1977) The Correlation of Peak Ground Acceleration Amplitude with Seismic Intensity and Other Physical Parameters. *Bulletin of the Seismological Society of America*, **67**, 877-915. https://doi.org/10.1785/bssa0670030877

[20] Eluyemi, A., Baruah, S., Sharma, S. and Baruah, S. (2019) Recent Seismotectonic Stress Regime of Most Seismically Active Zones of Gulf of Guinea and Its Kinematic Implications on the Adjoining Sub-Sahara West African Region. *Annals of Geophysics*, **62**, SE564. https://doi.org/10.4401/ag-7877

[21] Eluyemi, A.A., Baruah, S. and Baruah, S. (2019) Empirical Relationships of Earthquake Magnitude Scales and Estimation of Guttenberg-Richter Parameters in Gulf of Guinea Region. *Scientific African*, **6**, e00161. https://doi.org/10.1016/j.sciaf.2019.e00161

[22] Eluyemi, A.A., Ibitoye, F.I. and Baruah, S. (2020) Preliminary Analysis of Probabilistic Seismic Hazard Assessment for Nuclear Power Plant Site in Nigeria. *Scientific African*, **8**, e00409. https://doi.org/10.1016/j.sciaf.2020.e00409