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Site-Specific Seismic Ground Response and Liquefaction Potential Analysis of Ranau, Sabah

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Abstract: The 6.0 moment magnitude scale (Mw) earthquake that struck Ranau, Sabah, on June 5, 2015, resulted in seismic intensities of VI to VII, significantly increasing the seismic vulnerability of buildings in the region. This study presents an analysis of the site-specific seismic ground response and liquefaction potential for the Ranau District, East Malaysia. Ground response spectra were generated for 15 borehole sites, applying a 5% damping factor at ground level using both global and local input ground motions. Seven global and five local seismic records were processed using a one-dimensional equivalent linear approach via DEEPSOIL software. The LiqIT software, based on the Boulanger and Idriss method, was employed for the liquefaction analysis. Ground amplification in Ranau was found to range between 1.281 and 5.132, with peak ground acceleration (PGA) reaching an average maximum of 0.314 g at the surface. Soil periods across the region varied from 0.05s to 1s, consistent with the specifications outlined in the Malaysian National Annex for Sabah (MS EN 1998-1:2015). The results confirmed that the Ranau District is not prone to liquefaction, offering valuable insights for the structural design of future constructions in the area.

Keywords: Design response spectra; Equivalent linear; Peak ground acceleration; Site amplification; Soil liquefaction potential; Ranau District, Sabah

1 Introduction

Earthquakes are natural phenomena caused by the sudden release of energy in the Earth's crust, resulting from tectonic movements, volcanic activity, or human-induced events [1]. This release generates seismic waves that propagate through the earth, producing ground shaking. Earthquake magnitude, typically measured on Mw, quantifies the energy released, while intensity scales, such as the Modified Mercalli Intensity (MMI), describe the effects of shaking at specific locations. These seismic events pose significant risks to human life, infrastructure, and the environment, particularly in regions near active fault lines [2]. Recent advances in seismology have improved people's understanding of earthquake mechanisms, ground motion characteristics, and the potential for secondary hazards such as liquefaction, landslides, and tsunamis [1]. Seismic hazard assessments, which evaluate the probability of earthquake occurrence and its likely impacts, are crucial for designing earthquake-resistant structures and improving disaster preparedness [1, 2]. Ground response and liquefaction analyses, in particular, provide essential insights into soil behaviour during seismic events, aiding in mitigating structural damage [1]. As urban areas expand and seismic vulnerability increases, these studies are vital for minimizing earthquake-related risks and enhancing community resilience in seismically active regions [1, 2].

East Malaysia consists of Sabah and Sarawak, which have a huge potential for future local earthquakes, as both of them are associated with existing ancient faults [1]. The potential active faults which could be triggered by the low to moderate earthquakes that occurred in East Malaysia since years ago [2]. In Sarawak, the potential active faults located close to Niah, Selangau and Sri Aman have been associated with a few ancient faults, such as Tubau Fault Zone, Mersing Fault Zone and Sungai Lupar Fault Zone, respectively [3]. Based on the study by Tongkul [4], the reason for the reactivation of ancient faults in Sarawak is the stress from the subduction of the Philippine Sea Plate under the Sunda Plate [5]. Sabah is particularly susceptible to earthquake activities and experienced moderate seismicity throughout the years generated by intra-plate active faults [6]. The potential active faults mostly concentrate in Ranau, Lahad Datu, Sandakan and Kunak regions because the westward movement of the Philippines

Sea Plate leads to the crust shortening of Sabah [4]. The location of potential active faults in Sabah is illustrated in Figure 1. The local earthquake events, such as the 1991 Ranau earthquake, 2008 Kunak earthquake and the latest 2015 Ranau earthquake, have caused considerable structural damage where the brick walls collapsed, and few cracks appeared in several parts of the building [1, 5]. The strong felt intensities have resulted in partial damage to a few buildings and roads, including minor cracks in masonry walls and narrow fissures in the ground.

Moreover, the minor ground movement has been clearly observed due to the active faults, especially in Lahad Datu and Kundasang areas [1]. One of the fault lines was found near Kundasang town area, which was produced by active normal fault and left-lateral horizontal displacement of the Mesilou River at Mesilou Quarry, as illustrated in Figure 2.

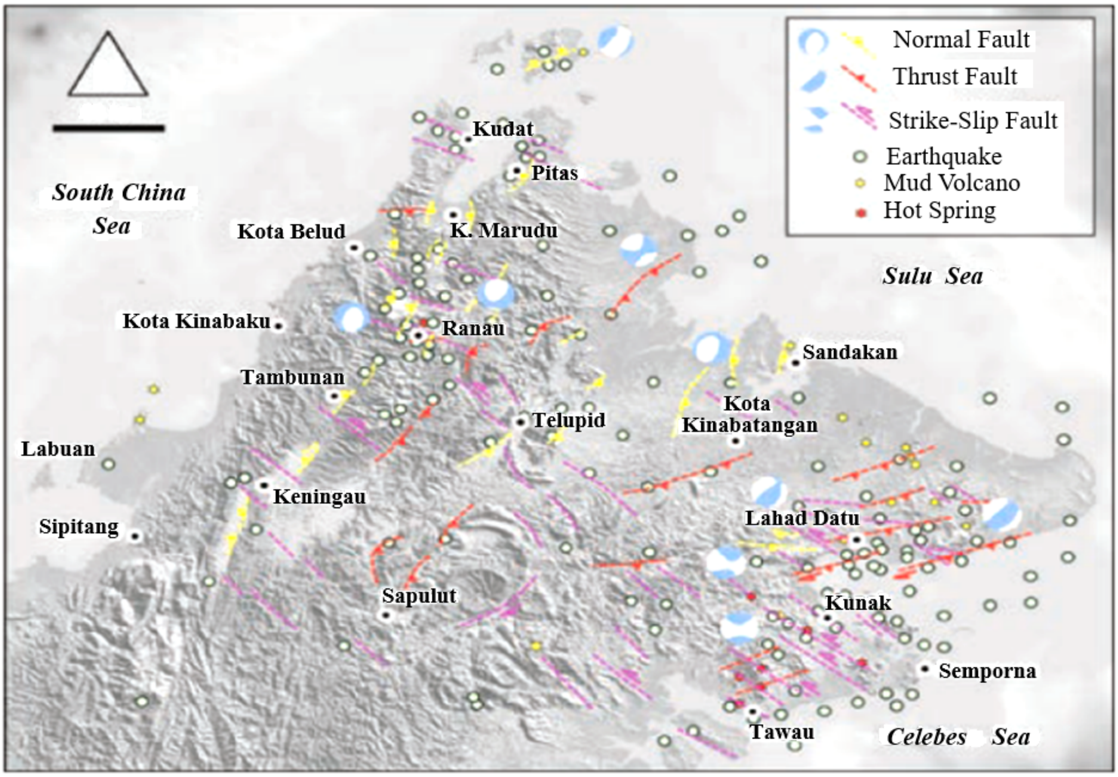

Figure 1. Potential active faults in a few locations in Sabah [4]

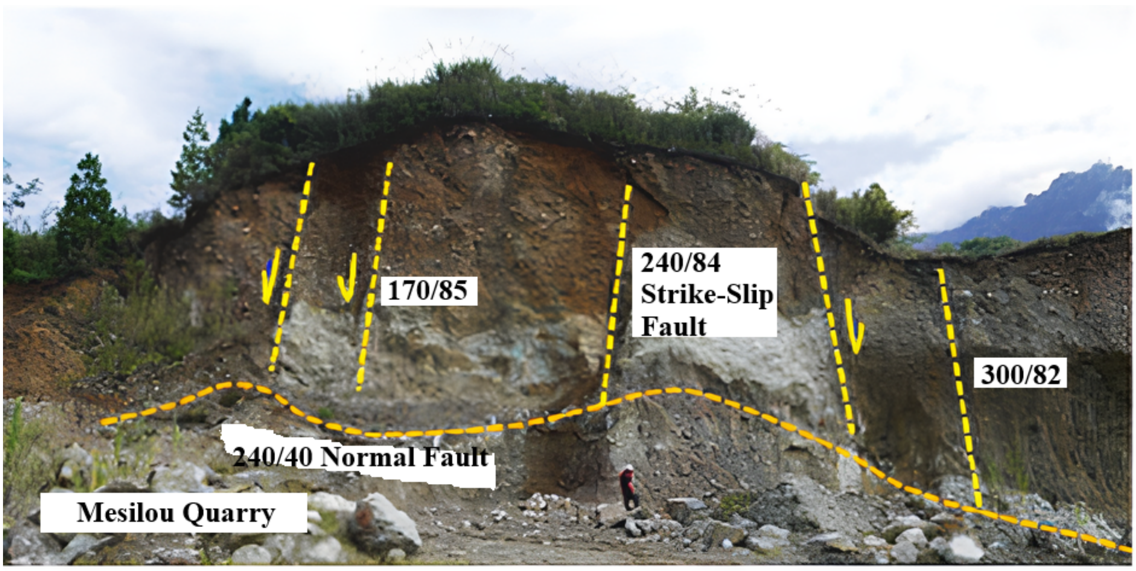

Figure 2. Active faults at Mesilou Quarry [4]

The 2015 Ranau earthquake with 6.0 Mw gives a rare opportunity to enhance the understanding and knowledge of East Malaysia's seismic hazards [7]. Earthquakes are unpredictable and unescapable [8]. The impact of the Ranau earthquake has caused physical damages to infrastructure where the public buildings, drainage pipes, water tanks, water intakes and private buildings suffered mild damage [1, 3, 5]. Besides, Kundasang and Ranau residents experienced a water shortage for several days and fatalities were recorded due to a rock fall on Mount Kinabalu. The liquefaction also occurred in the Poring Hot Spring area due to the shaking [9].

The population in Sabah has been increasing fast. Thus, mostly the major structures were constructed in the earthquake-prone areas, such as new housing, factories, and offices. These buildings might not have considered the effect of earthquake shakings that can cause the movements of the building in the future [10]. Therefore, a seismic hazard analysis must be performed with the purpose of assessing the susceptibility under the predicted intensity of seismic motions [1]. For the seismic hazard analysis, a site-specific ground response assessment must be taken into consideration to consider how the seismic waves would influence the structures. The responsibility as an engineer should be able to quantify the earthquake risk in Malaysia quantitatively to provide optimal solutions to overcome the problems [11]. By now, Sabah should have taken more serious actions by implementing new earthquake-resistant building codes apart from producing detailed seismic hazard maps in high-risk areas [12]. Although the earthquake-proof design buildings are costly, Malaysia should consider in designing the buildings with adequate energy dissipation characteristics, which do not collapse at least [13].

The contribution of this study lies in its site-specific seismic ground response and liquefaction potential analysis for the Ranau District, offering critical data that can be used to inform future structural designs in Sabah [11]. By employing a one-dimensional equivalent linear approach through DEEPSOIL software and using both global and local historical seismic records, this study provides detailed insights into the region's ground amplification, PGA, and soil periods [1, 5]. The study also contributes to the understanding of liquefaction potential in Ranau, revealing it to be a non-liquefaction potential zone. These findings are aligned with the guidelines of the Malaysia National Annex for Sabah (MS EN 1998-1:2015) and can significantly aid in enhancing seismic resilience for future construction projects in the area. Therefore, from the result obtained from this study, the design response spectrum can be used to construct earthquake-resistant buildings and liquefaction analysis for new building structures in the Ranau District in the future.

2 Objective

The objective of this study is to develop seismic design response spectra and evaluate soil liquefaction potential for the case study in Ranau based on the Malaysian National Annex to Eurocode 8 (MS EN 1998-1:2015).

3 Material and Methodology

3.1 Site and Borehole Data Collection

Site characterization can be achieved through various methods, including geological data, geophysical testing, or geotechnical data analysis [14]. In this study, the collected data focuses on areas in the Ranau District of Sabah, which are particularly prone to earthquakes and liquefaction. The site investigation reports were gathered from several parts of Ranau to provide a representative and significant dataset for the study area. Based on these reports, the soil profile was plotted to gain a comprehensive understanding of the subsurface conditions. To ensure a thorough analysis, five locations were selected, with a total of 15 boreholes drilled. The locations for boreholes BH1 to BH5 are in Kg. Sumaang, Ranau; boreholes BH6 to BH9 are situated at SMK Kundasang; and boreholes BH10 and BH11 are located near the Majlis Daerah Ranau. Additionally, BH11 is situated in Ranau town, providing data from a more urban setting. Finally, BH12 to BH15 are located along the Ranau-Tambunan road, offering insights into the soil conditions along a critical infrastructure route. The distribution of these boreholes allows for a detailed investigation of the seismic and liquefaction risks across a broad section of Ranau. The locations of the 15 boreholes are illustrated in Figure 3, providing a visual overview of the geographical spread across the study area. This strategic selection of boreholes ensures that the study captures a diverse range of soil conditions relevant to earthquake and liquefaction analysis.

The site exploration work included rotary wash boring in soil, coring in rock, sampling soil samples, performing the standard penetration test (SPT) in boreholes and groundwater observation. The soil strata of every borehole are shown in Figure 4, which predominantly consists of sandstone, clayey silt, silty clay, and sandy clay. The maximum depth of 15 boreholes ranges from 8.3 m to 25.26 m.

3.2 Earthquake Input Ground Motion

The ground motions implemented in this study are listed in Table 1. There are seven global motions (GM1-GM7) and five local motions (GM8-GM12) used for the analysis of site-specific horizontal elastic design response spectrum.

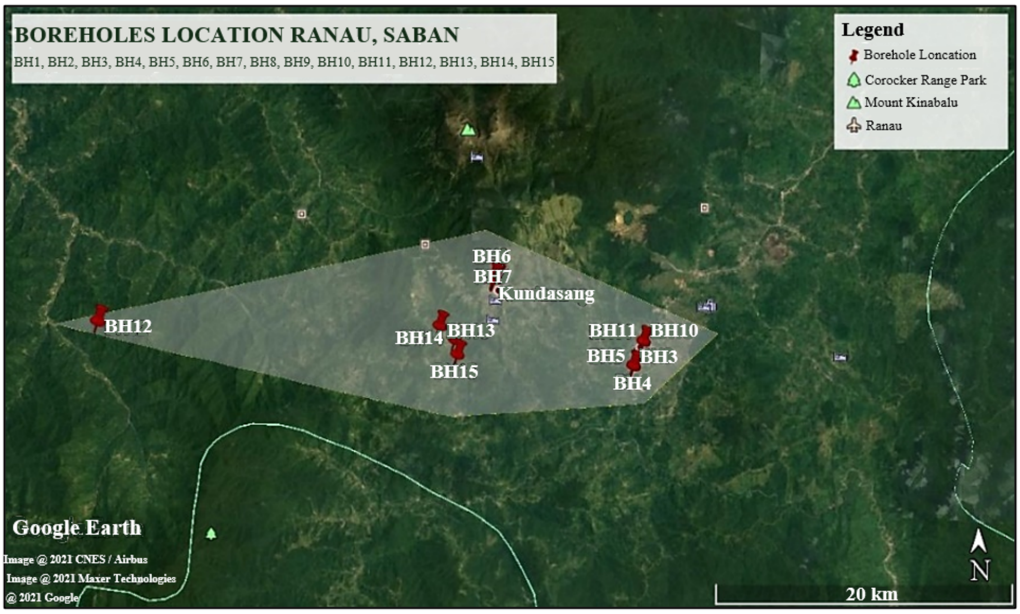

Figure 3. Positions of 15 boreholes in the Ranau District

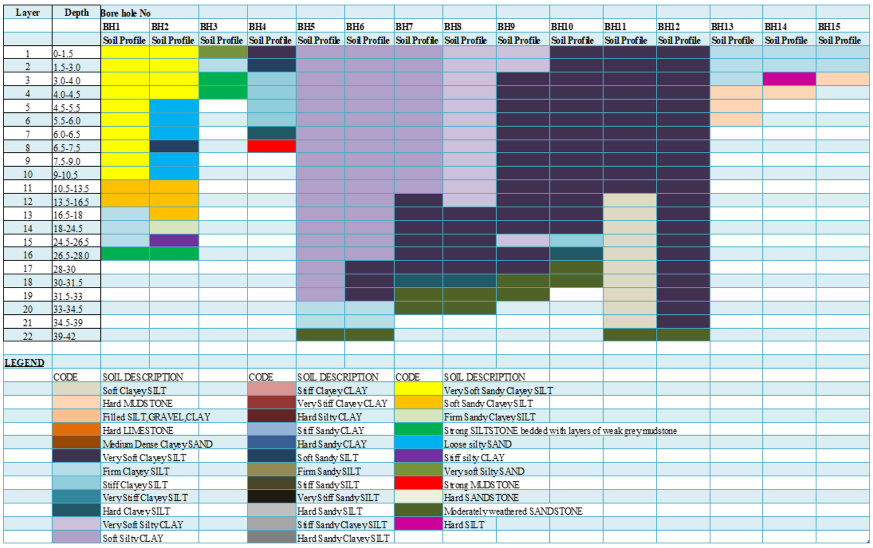

Figure 4. Ground stratification for the 15 boreholes

Table 1. Records of the 12 implemented ground motions

ID	Ground Motion
GM1	RSN209: Imperial Valley earthquake at 5.62 Mw
GM2	RSN232: Mammoth Lakes earthquake at 6.06 Mw
GM3	RSN972: Northridge earthquake at 6.69 Mw
GM4	RSN2011: Loma Gilroy earthquake at 4.90 Mw
GM5	Ayden earthquake
GM6	Eregli earthquake
GM7	Tokat earthquake
GM8	RSN195: Kuching earthquake at 3.70 Mw
GM9	RSN202: Bintulu earthquake at 5.20 Mw
GM10	RSN334: Kota Kinabalu earthquake at 5.40 Mw
GM11	RSN293: Tawau earthquake at 4.78 Mw
GM12	Sandakan earthquake

3.3 Soil Dynamic Properties

In geotechnical earthquake engineering, the characterization of seismic ground response has extensively been investigated in order to generate design response spectra and establish parameters helpful for soil categorization in building rehabilitation and construction standards [15]. The ground response to cyclic action has a big influence on the level of destruction caused by seismic events [16]. The mechanical characteristics of the earth primarily control this response. The ground dynamic properties regulate the deportment of the grounds subjected to dynamic action. The profile of ground dynamics variables such as shear wave velocity, maximal shear modulus and damping (ß) are important in ground response analysis [17]. A widely accepted method for estimating shear wave velocity is based on the empirical relationship proposed in previous study, which utilizes the SPT-N value. This relationship has been found to be the most reliable for determining the shear wave velocity and characterizing the dynamic properties of the soil [16].

$$V_s = 97.0N^{0.31} \tag{1}$$

where, V_s is the shear wave velocity, and N is the total number of SPT blows.

The average shear wave velocity of the top 30 meters of a soil profile, denoted as V_{s30}, is a common metric used to categorize soils into different groups. The purpose of ground response characterization and soil classification is to investigate and quantify the V_{s30} criterion's efficacy in characterizing seismic ground reaction [15]. The result of employing the following equation for every borehole is shown in Table 2:

Table 2. Shear wave velocity and soil category analyses of 15 boreholes

Borehole	$V_{s30}(\mathrm{m/s})$	Soil Category
BH1	369.95	B
BH2	881.10	A
BH3	675.55	B
BH4	595.99	B
BH5	360.67	B
BH6	397.58	B
BH7	397.58	B
BH8	397.58	B
BH9	397.58	B
BH10	607.30	B
BH11	709.97	B
BH12	874.21	A
BH13	815.37	A
BH14	978.94	A
BH15	882.98	A

$$V_{s30} = \frac{30}{\mathrm{sum}\left(\frac{d}{V_s}\right)} \tag{2}$$

where, V_{s30} is the shear wave velocity at 30 m depth, and d is the thickness of ground stratum.

3.4 One-Dimensional Equivalent Linear Method in DEEPSOIL V6 Software

The assumption used in the one-dimensional ground response evaluation is that the soil surface is believed to be horizontal which extends to definiteness, the ground surface is horizontal and the seismic waves spread vertically from the bedrock to the ground surface [18]. Besides, equivalent linear analyses employ approaches through a layered, viscoelastic medium for shear horizontal (SH) body wave propagation [19]. Each layer's soil properties are evaluated iteratively by changing the values of shear modulus (G) and damping ratio (ξ) in each layer until they are consistent with effective shear strains [1].

In this study, the effects of local soil state on earthquake ground motion were evaluated using DEEPSOIL software to perform a detailed one-dimensional equivalent linear wave propagation analysis. Shear wave velocity, density, estimated seismic bedrock depth, shear modulus and damping ratio variation against shear strain, PGA, and input motion time history are the key parameters necessary for site response analysis [20]. In the selected layers, DEEPSOIL generates velocity, displacement, stress time evolution, Fourier amplification ratio spectrum, acceleration, strain, Fourier response spectrum, and response spectrum [21]. The analysis flow is illustrated in Figure 5.

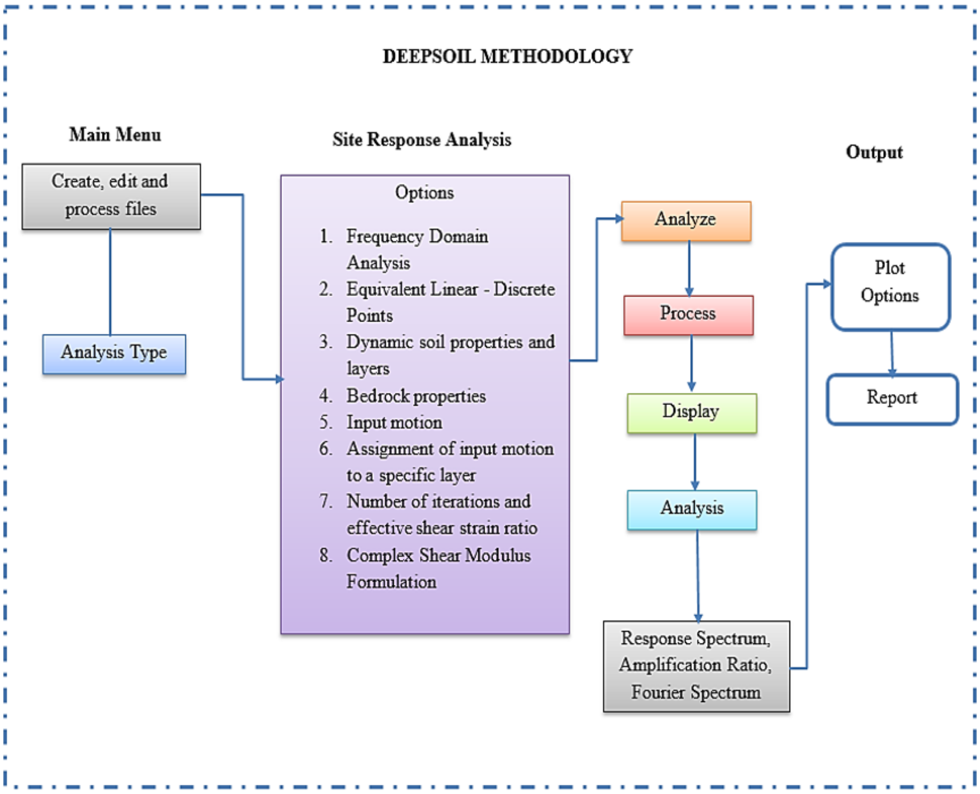

Figure 5. Analysis flow using DEEPSOIL software [1]

3.5 LiqIT Software

The evaluation of the liquefaction potential for the case study of Ranau, Sabah, was conducted using the LiqIT software, which was designed to analyse borehole data and sand strata values. This software enables the calculation of total ground settlement that occurs after an earthquake [2, 5, 12] with results varying based on the earthquake magnitude input. The higher the magnitude, the greater the potential for settlement. This method provides a nuanced understanding of how seismic events impact the ground, producing varying settlement results depending on the intensity of the earthquake and the characteristics of the soil strata. The analysis utilizes the SPT data, following the approach recommended by Boulanger and Idriss, to evaluate the liquefaction susceptibility of each soil layer. The SPT values for each soil layer were input into LiqIT, alongside PGA values generated by the DEEPSOIL software. These parameters allow for the calculation of the cyclic stress ratio (CSR) and cyclic resistance ratio (CRR), which are essential for determining the soil's resistance to liquefaction [2, 22].

LiqIT produces outputs in a one-dimensional format, including plots of CSR, CRR, the factor of safety (FS) against liquefaction, and settlement [23]. The FS is calculated using the following formula:

$$FS = \frac{(CRR)_N}{CSR} \tag{3}$$

where, $(CRR)_N$ is the CRR corresponding to a certain number of loading cycles. A higher FS value indicates greater resistance to liquefaction, while a lower FS (less than 1) suggests that liquefaction is likely to occur.

The SPT blow-count values from each soil layer are crucial in determining the CRR, which reflects the soil's ability to withstand liquefaction. If the FS is less than 1, the soil is considered liquefiable, meaning it is susceptible to failure during an earthquake. Conversely, when the FS exceeds 1, the soil is classified as non-liquefiable [2, 12, 24]. However, even if the FS is greater than 1, there is still a possibility of liquefaction occurring, depending on the magnitude of peak soil acceleration during the seismic event [25]. The classification of the liquefaction potential index (LPI) [26] is shown in Table 3, providing a standardized way to interpret the results of the liquefaction analysis. This classification aids in understanding the extent of liquefaction risk across different locations and helps guide engineers in designing structures that can withstand the seismic hazards specific to the Ranau district. By using these analytical tools, this study provides valuable insights into the seismic resilience of soils in Ranau, Sabah, contributing to safer and more informed engineering practices.

Table 3. Classification of the liquefaction potential [2, 26]

Class	LPI	Description
1	$0.00 \leq \text{LPI} < 0.15$	Practically sure that liquefaction will not happen
2	$0.15 \leq \text{LPI} < 0.35$	Unlikely
3	$0.35 \leq \text{LPI} < 0.65$	Liquefaction/non-liquefaction are equally likely
4	$0.65 \leq \text{LPI} < 0.85$	Very likely
5	$0.85 \leq \text{LPI} < 1.0$	Almost certain liquefaction

4 Results and Discussion

4.1 Peak Ground Surface Acceleration

The soil parameters were analysed using seven global ground motions and five local ground motions to determine the PGA, as summarized in Table 4. The site response analysis, leveraging geotechnical data, reveals that the PGA values range from 0.085g to 0.487g. The minimum PGA values of 0.085g were recorded in borehole BH6 for several ground motions, including GM8 (Kuching earthquake), GM10 (Kota Kinabalu earthquake), GM11 (Tawau earthquake), and GM12 (Sandakan earthquake). Conversely, the maximum PGA value of 0.487 g was obtained from GM5 (Ayden) in BH2, highlighting the variability in ground motion responses across different locations. In the Ranau District of Sabah, the average response spectrum for all soil types A and B derived from global ground motions exceeds that of the average response spectrum calculated from local input motions. This disparity indicates that the local seismic conditions may not fully capture the potential seismic hazards represented by global motions.

Table 4. Peak ground surface acceleration of 15 boreholes

Ground Motion (GM)	PGA Bedrock (g)	PGA BHI	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH10	BH11	BH12	BH13	BH14	BH15
GMI	0.16	0.465	0.276	0.308	0.314	0.268	0.247	0.263	0.263	0.260	0.298	0.254	0.275	0.309	0.304	0.287
GM2	0.16	0.329	0.217	0.270	0.261	0.213	0.203	0.206	0.205	0.203	0.221	0.220	0.225	0.247	0.237	0.229
GM3	0.16	0.329	0.309	0.361	0.359	0.267	0.236	0.229	0.229	0.228	0.318	0.313	0.338	0.370	0.305	0.333
GM4	0.16	0.425	0.306	0.396	0.427	0.221	0.211	0.219	0.219	0.217	0.377	0.354	0.345	0.374	0.291	0.324
GM5	0.16	0.251	0.487	0.419	0.307	0.275	0.120	0.184	0.179	0.168	0.185	0.335	0.411	0.214	0.214	0.418
GM6	0.16	0.340	0.310	0.217	0.176	0.178	0.218	0.262	0.262	0.263	0.156	0.177	0.247	0.274	0.373	0.308
GM7	0.16	0.361	0.317	0.219	0.176	0.178	0.219	0.265	0.265	0.266	0.156	0.177	0.252	0.278	0.381	0.314
GM8	0.16	0.208	0.303	0.284	0.125	0.237	0.085	0.122	0.120	0.117	0.131	0.244	0.257	0.165	0.137	0.261
GM9	0.16	0.271	0.462	0.402	0.218	0.317	0.101	0.168	0.164	0.157	0.188	0.338	0.371	0.194	0.144	0.373
GM10	0.16	0.207	0.301	0.283	0.124	0.237	0.085	0.122	0.119	0.117	0.130	0.243	0.256	0.165	0.137	0.260
GM11	0.16	0.203	0.291	0.276	0.122	0.106	0.085	0.120	0.118	0.115	0.124	0.238	0.250	0.164	0.137	0.253
GM12	0.16	0.211	0.310	0.288	0.135	0.242	0.085	0.123	0.121	0.118	0.131	0.248	0.262	0.163	0.137	0.266

The results of this analysis culminated in the development of a mean site-specific design response spectrum. When compared with the Malaysia National Annex to Eurocode 8 (MS EN 1998-1:2015), the data for all 15 boreholes, considering a 5% damping ratio, were evaluated to create a site-specific horizontal elastic design response spectrum. This spectrum is essential for earthquake engineering design, providing crucial guidelines for both new and existing structures in Ranau, Sabah, thus enhancing the region's preparedness against potential seismic events.

4.2 Amplification Factor

The amplification factor vs. frequency (Hz) was depicted for 15 boreholes and the results are shown in Table 5. The soil surface amplification factor values obtained range from 1.226 to 5.132. GM8 (Kuching), GM10 (Kota Kinabalu), GM11 (Tawau), and GM12 (Sandakan) were recorded as the lowest values at 1.226 in BH5 while GM9 (Bintulu) is the highest value of amplification factor at 5.132.

4.3 Recommended Design Response Spectra

Figure 6 and Figure 7 illustrate the proposed design response spectra for all soil types, which include the mean of both average local and global response spectra at 5% damping for both soil categories A and B. Then it was compared with Eurocode 8 Type 2 and Malaysia National Annex of Sabah as the design ground factors, as shown in Table 6 and Table 7, respectively.

For soil categories A and B, as illustrated in Figure 6 and Figure 7, the mean values for both global and local data in the Ranau District are observed to be higher than the recommended soil factors provided by the Malaysia

National Annex and Eurocode 8. This deviation can be attributed to the differing probabilities of exceedance (POE) used in seismic risk assessments, such as 2% and 10% POE, which correspond to varying return periods of 475 and 2475 years, respectively. As noted by the study of Ahmadi et al. [16], these differences influence the expected seismic hazard and the associated soil response factors. Moreover, site-specific investigations often yield higher soil response factors compared to generalized code provisions, as observed in this study and corroborated by similar findings in the literature. This discrepancy highlights the importance of conducting localized seismic assessments, which can better capture the unique dynamic characteristics of the soil at a specific site, especially in regions with heterogeneous geological formations.

Table 5. Amplification factor of 15 boreholes

Ground Motion (GM)	PGA Bedrock (g)	Amplification Factor														
		BHI	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH10	BH11	BH12	BH13	BH14	BH15
GMI	0.16	3.920	2.679	3.114	3.219	2.620	2.619	2.623	2.622	2.614	2.956	2.571	2.710	3.236	3.201	2.919
GM2	0.16	4.344	2.694	3.142	3.278	2.711	2.679	2.696	2.694	2.684	3.177	2.671	2.767	3.337	3.319	3.005
GM3	0.16	4.344	2.665	3.092	3.217	2.805	2.660	2.667	2.666	2.660	3.020	2.537	2.631	3.107	3.165	2.863
GM4	0.16	3.892	2.666	3.084	3.191	2.651	2.643	2.649	2.648	2.640	2.915	2.476	2.635	3.119	3.184	2.867
GM5	0.16	3.032	2.736	3.178	3.279	1.282	2.798	2.801	2.799	2.793	3.371	1.327	2.899	3.599	3.476	3.136
GM6	0.16	4.629	2.697	3.169	3.309	2.781	2.786	2.784	2.784	2.782	3.323	2.751	2.808	3.405	3.239	2.984
GM7	0.16	4.638	2.695	3.168	3.316	2.772	2.784	2.782	2.782	2.780	3.319	2.746	2.800	3.397	3.229	2.976
GM8	0.16	5.019	2.725	3.169	2.010	1.226	2.780	2.785	2.784	2.777	2.081	1.311	2.865	3.513	3.416	3.097
GM9	0.16	5.132	2.743	3.184	3.285	1.262	2.790	2.793	2.792	2.786	2.133	1.329	2.872	3.162	3.488	3.107
GM10	0.16	5.018	2.724	3.169	2.011	1.226	2.780	2.785	2.784	2.777	2.081	1.311	2.865	3.128	3.416	3.097
GM11	0.16	5.018	2.724	3.169	2.012	1.226	2.780	2.785	2.784	2.777	2.082	1.311	2.866	3.127	3.416	3.098
GM12	0.16	5.021	2.725	3.170	2.010	1.226	2.780	2.785	2.784	2.777	3.300	1.311	2.865	3.128	3.417	3.097

Table 6. Recommended design response spectrum for Ranau, Sabah

GROUND TYPE	S	T_B(S)	T_C(S)	T_D(S)
A	1	0.05	0.25	2
B	1.35	0.05	0.25	2

Table 7. Ground factors for Sabah based on Malaysia National Annex [27]

GROUND TYPE	S	T_B(S)	T_C(S)	T_D(S)
A	1	0.1	0.4	2
B	1.4	0.15	0.4	2
C	1.35	0.15	0.6	2
D	1.35	0.2	0.8	2
E	1.4	0.15	0.5	2

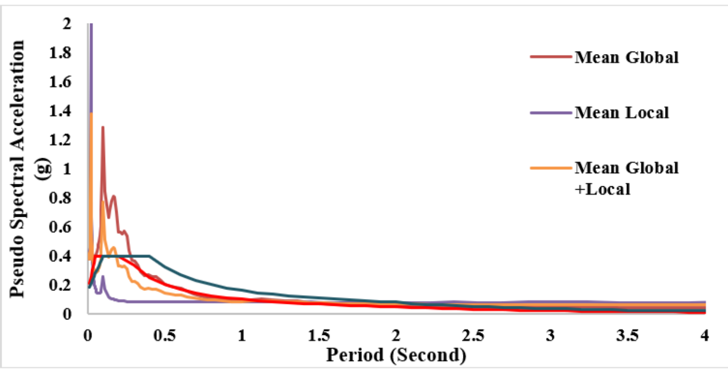

Figure 6. Recommended design response spectrum for ground type A

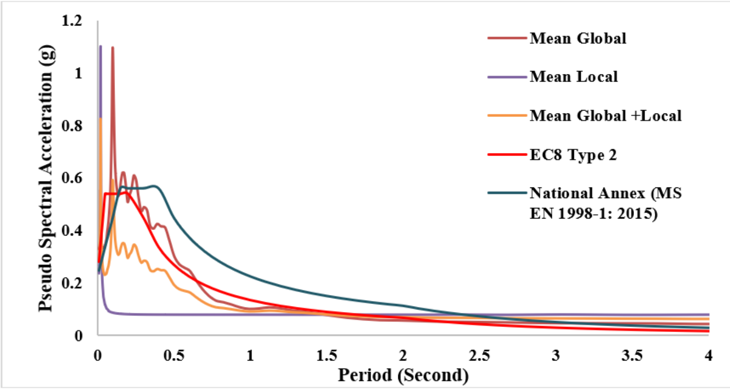

Figure 7. Recommended design response spectrum for ground type B

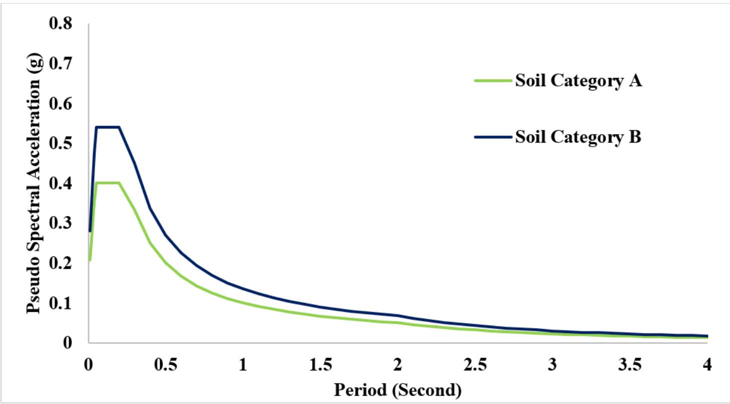

Figure 8. Recommended design response spectrum for soil categories A and B

The uneven distribution of PGA further underscores the non-uniform nature of the alluvial deposits in the Ranau District, indicating significant variability in dynamic soil properties across the area. Despite these variations, the recorded PGA values remain within the expected range for the region. The soil periods, ranging from 0.05s to 1s, also fall within the limits specified by the Malaysia National Annex, ensuring consistency with regional seismic design requirements. Finally, the recommended design response spectra for soil categories A and B are presented in Figure 8, providing a critical reference for the safe and effective design of structures in the Ranau District, taking into account the observed differences in soil behaviour under seismic loading conditions.

Based on the results, a maximum average of 0.314 g PGA was computed based on the response spectra for soil categories A and B. Therefore, in a return period of 2475 years in the Ranau District, the seismic hazard was estimated to be 0.314 g PGA in any existing building to cater to a minimum 0.314 g PGA for the structural safety to be protected.

4.4 Soil Liquefaction Assessment

In this assessment, the Boulanger and Idriss method was employed to calculate the SPT for evaluating the liquefaction susceptibility of soils in the Ranau District. This approach relies on key input parameters, including the PGA of 0.16 g and a moment magnitude of 6.0 Mw. These parameters are essential for assessing the dynamic response of soils under seismic conditions. Table 8 presents the detailed computation of the LPI for borehole 1 (BH1), offering insights into the site-specific liquefaction risk at this location. Liquefaction potential is typically evaluated through the FS, a critical value derived from comparing the CSR and the CRR. Liquefaction is likely to occur when FS is less than 1. A high CSR relative to the CRR serves as an early warning signal that the soil may be vulnerable to liquefaction during an earthquake. This analysis allows for a better understanding of the soil's behaviour under seismic loading, particularly in identifying areas where soil stability could be compromised.

The findings of the analysis indicated that all 15 boreholes in the Ranau District were safe from liquefaction, as the FS values exceeded 1 in each case, signifying adequate resistance against liquefaction. However, BH1 exhibited a FS value close to 1, suggesting that the soil in this specific location is comparatively weaker in terms of liquefaction resistance. This highlights the importance of closely monitoring and reinforcing such boundary areas, especially in the event of future seismic activity. Despite the overall conclusion that the five locations assessed in the Ranau

District are not prone to liquefaction, certain consequences may still arise if a significant seismic event were to occur. One such consequence is ground settlement, particularly in BH1, where the analysis indicated a potential settlement of 2.11 cm. Although this settlement is within the acceptable safety range, it suggests a possible ground movement that could affect infrastructure stability, especially in more vulnerable zones. Table 9 provides a safety factor and settlement of 15 boreholes due to liquefaction.

In conclusion, while the study confirms the absence of liquefaction potential in the assessed locations within the Ranau District, it also underscores the need for continuous monitoring and preparedness. Even though the likelihood of liquefaction is low, the potential for ground settlement warrants further attention, particularly for critical infrastructure in the region. Future studies should consider a more detailed assessment of local seismic conditions to further refine the understanding of liquefaction risks and enhance the resilience of the built environment in Sabah.

Table 8. Detailed LPI computation of BH1 in the Ranau District for PGA 0.16 g corresponding to Mw= 6.0

Location	Depth	Unit wt.	SPT-N	Amax (g)	σ_v	σ'_v	$(N_1)60$	$(N_1)60cs$	CRR	CSR	FS	LPI
BH 1	1.45	18.00	1	0.16	26.10	21.69	1.15	6.65	0.10	0.12	1.15	0.0
	1.95	16.00	1	0.16	34.10	24.78	1.22	6.84	0.10	0.14	1.03	0.0
	2.40	18.00	45	0.16	42.20	28.47	43.24	48.75	2.00	0.15	5.00	0.0
	3.90	19.50	20	0.16	71.45	43.00	20.71	26.27	0.32	0.16	2.94	0.0
	5.40	18.00	15	0.16	98.45	55.29	16.08	21.59	023	0.17	2.00	0.0
	6.74	19.50	50	0.16	124.58	68.27	46.06	51.62	2.00	0.17	5.00	0.0
	8.40	19.50	15	0.16	156.95	84.36	13.43	18.99	0.19	0.16	1.77	0.0
	9.74	19.50	50	0.16	183.08	97.34	44.50	50.05	2.00	0.16	5.00	0.0
	16.00	19.50	50	0.16	305.15	158.00	38.61	44.16	2.00	0.13	5.00	0.0
	20.19	19.50	50	0.16	386.86	198.60	35.63	41.18	2.00	0.12	5.00	0.0

Note: $A_{\max}$ is the PGA, σ_v is the effective overburden stress factor, σ'_v is the effective overburden pressure during an earthquake, (N1)60 is the corrected SPT-N, and (N1)60cs is the corrected (N1)60 value for fines.

Table 9. Test results of classification

Borehole	Min. FS (FOS)	Total Settlement (cm)	LPI	Description
BH1	1.03	2.11	0	No liquefaction
BH2	5	0	0	No liquefaction
BH3	1.94	0.03	0	No liquefaction
BH4	2.16	0	0	No liquefaction
BH5	1.77	0.04	0	No liquefaction
BH6	5	0	0	No liquefaction
BH7	5	0	0	No liquefaction
BH8	5	0	0	No liquefaction
BH9	5	0	0	No liquefaction
BH10	2.26	0	0	No liquefaction
BH11	5	0	0	No liquefaction
BH12	5	0	0	No liquefaction
BH13	2.33	0	0	No liquefaction
BH14	2.06	0	0	No liquefaction
BH15	1.93	0.03	0	No liquefaction

5 Conclusions

The study successfully evaluated the seismic adaptability of soil across 15 boreholes in the Ranau District, Sabah, East Malaysia, employing both global and local earthquake ground motions through a one-dimensional equivalent linear analysis. The results indicate a ground amplification factor ranging from 1.226 to 5.132 and PGA at the surface between 0.085 g and 0.487 g, with local inputs yielding higher average PGA than global inputs. Soil types were classified as A or B based on Vs30 values, in alignment with the Malaysia National Annex to Eurocode 8 (MS EN 1998-1:2015), and the study further determined that the region is a non-liquefaction potential zone.

5.1 Practical Applications

These findings provide a critical framework for designing earthquake-resistant structures in the region. The recommended response spectra, particularly the 0.314 g PGA, offer guidelines for the safe design of essential infrastructure, such as dams and transmission towers.

5.2 Future Research Directions

To enhance the accuracy and applicability of future seismic studies, the following steps are recommended:

a) A wider range of local seismic ground motions could be utilized for more grounded analysis.

b) The borehole data could be increased to refine the results of seismic response and liquefaction potential.

c) Additional in-situ and laboratory tests could be conducted to capture dynamic soil properties more comprehensively.

d) The findings could be validated through alternative earthquake analysis tools like SHAKE2000 or NERA.

e) Research into cost-effective, earthquake-resistant design approaches could be advanced to support updated building codes.

By integrating these suggestions, future studies can improve earthquake resilience in Sabah and other seismically active regions.

Data Availability

Data supporting these conclusions are available in the manuscript or upon request.

Conflicts of Interest

No conflict of interest.

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