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Seismic Resilience in Kota Kinabalu: Ground Response and Liquefaction Risk Assessment for Existing Buildings

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Abstract

Seismic considerations have become increasingly critical in Malaysian structural design due to heightened awareness following notable earthquakes, such as the Ranau earthquake, which recorded a peak ground acceleration (PGA) of 0.15g. This has led to the adoption of the Malaysia National Annex to Eurocode 8 (MS EN 1998-1:2015), providing guidelines for earthquake-resistant design since 2017. This study focuses on: (1) establishing earthquake design response spectra for Kota Kinabalu. (2) Assessing soil liquefaction susceptibility. (3) Investigating potential ground settlement due to liquefaction. The ground response analysis methodology involves: (i) obtaining ground motion data. (ii) Analyzing dynamic soil characteristics from boreholes. (iii) Conducting 1-D shear wave propagation analysis using DEEPSOIL software. (iv) Developing site-specific response spectra. For liquefaction assessment, the process includes acquiring borehole logs, evaluating liquefaction risk, and estimating settlement using LiquefyPro software. The study projects a seismic response spectrum for Sabah with a PGA of 0.16g, reflecting regional seismic hazards. An amplification factor between 3 and 5 is expected based on site-specific conditions. Liquefaction risk is concluded to be minimal, as borehole data and historical evidence indicate low susceptibility in Sabah. These findings provide valuable insights for improving seismic resilience in the region and contribute to the development of safer infrastructure designs aligned with Malaysian standards.

Keywords: *soil flexibility; Kota Kinabalu Sabah; seismic design response spectra; soil liquefaction assessment*

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I. INTRODUCTION

Sabah, Malaysia, is one of the most earthquake-prone regions in the country due to its proximity to major tectonic boundaries, such as the subduction zones near the Sulu Trench and the active Palu-Koro Fault in Sulawesi [1], [2]. These geological features increase the likelihood of seismic events, as evidenced by the 2015 Ranau earthquake (magnitude 6.0, PGA 0.15g), which triggered landslides and rockfalls on Mount Kinabalu, claiming 18 lives and causing extensive damage [3], [4]. This event highlighted Sabah's vulnerability to tectonic activity and its associated hazards, such as soil liquefaction and landslides [5]–[7].

Liquefaction poses a significant risk, particularly in urban areas where critical infrastructure may be compromised. During seismic events, saturated soils can lose strength due to decreased effective stress, behaving like a liquid and causing settlement or lateral spreading that undermines the stability of buildings, roads, and dams [8]–[10]. Studies have shown that dual pressures from seismic forces and liquefaction-induced settlement can lead to catastrophic failures, particularly in poorly designed infrastructure [9]. To mitigate these risks, detailed site response analyses are essential. These analyses involve propagating seismic motions through soil profiles to evaluate ground motion characteristics and their amplification due to underlying geological conditions [10]. For instance, areas like Ranau and Lahad Datu, identified as high-intensity seismic zones, experience amplified ground motions due to bedrock conditions [11]. A map of Sabah's seismic hazard zones (Fig. 1) illustrates five intensity zones, ranging from low (Zone I) to very strong (Zones IV and V) [12]. Given the increasing frequency of seismic events in the region, enhanced engineering practices, including seismic-resilient infrastructure design, are critical. Future research must address data gaps in bedrock amplification effects and liquefaction susceptibility to safeguard Sabah against future earthquakes [8], [12]–[15]. Given the historical frequency of earthquakes in East Malaysia, there is a pressing concern regarding future seismic impacts, particularly in light of the increasing number of tectonic events in neighboring regions. The potential for soil liquefaction poses a substantial risk, particularly in urbanized areas where existing infrastructure may

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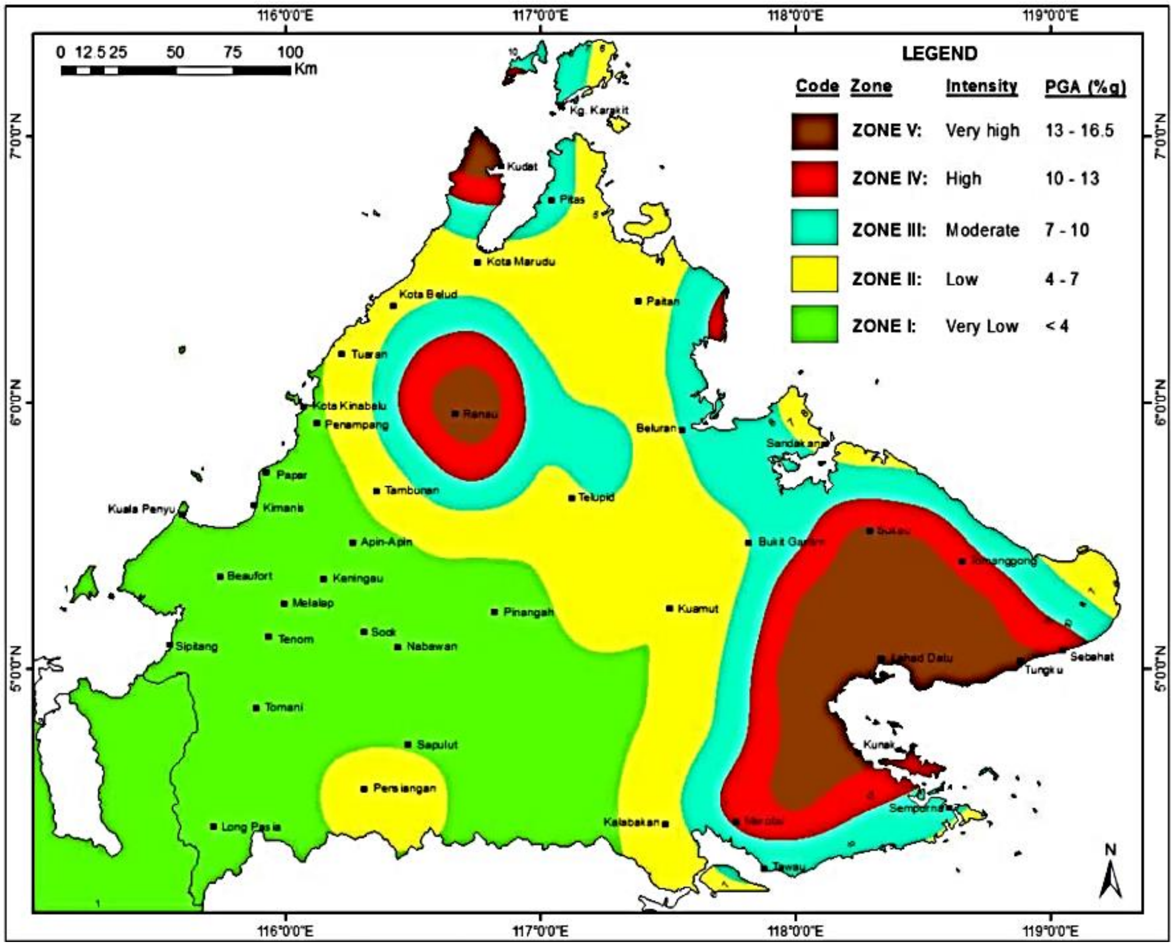

Fig. 1. Isoseismic Intensity Map of Sabah based on Sabah historical earthquake from 1923 to 2015 [24]

compromised. The combination of seismic shock and soil liquefaction can lead to catastrophic damage, particularly to dams and other critical infrastructure [7], [16]–[18].

As noted in previous studies, these structures may fail under the dual pressures of seismic activity and liquefaction-induced ground settlement, resulting in widespread destruction [19]. The June 2015 earthquake in Sabah represented the strongest seismic event since 1976, prompting researchers to reassess the region's earthquake preparedness and response strategies. The mechanisms of soil liquefaction and the resulting impact on structures can be attributed to the loss of soil strength during seismic events [6], [7], [12], [13]. When subjected to strong ground motions, saturated soils may experience a decrease in effective stress, leading to a condition where the soil behaves like a liquid. This phenomenon can result in significant settlement and lateral spreading, ultimately compromising the stability of buildings, roads, and other critical infrastructures [20].

To effectively assess and mitigate the risks associated with seismic activity, it is essential to conduct detailed site response analyses. These analyses involve the propagation of seismic input motions through soil profiles to determine the surface motion characteristics. By employing advanced analytical techniques, engineers can evaluate how specific soil conditions influence ground motion and develop strategies to enhance structural resilience [21]. An examination of the historical seismic activity in Sabah, depicted in Fig. 1, highlights the distribution of earthquake events from 1923 to 2017 [22].

The data illustrates the identification of five seismic hazard zones across the region: Zone I (low intensity), Zone II (moderate intensity), Zone III (strong intensity), and Zones IV and V (very strong intensity) [23]. The varying intensities correlate with the peak ground acceleration (PGA) experienced in these zones. Notably, areas such as Ranau and Lahad Datu are identified as experiencing very strong ground motions compared to other regions of Sabah. This differential in ground motion is significantly influenced by underlying bedrock conditions, which play a crucial role in the amplification of seismic waves [24]. In summary, the tectonic setting of Sabah, coupled with its historical seismic activity, necessitates a comprehensive understanding of earthquake impacts and the corresponding engineering responses. The risks associated with soil liquefaction and the resulting infrastructural vulnerabilities highlight the critical need for ongoing research and enhanced engineering practices to safeguard the region against future seismic events [7].

Part of the energy created by the seismic activity, structural, infrastructural, and natural damage caused by the earthquake that would lead to economic damages and deaths [10], [14], [16]. Many steps have been taken by the respective agencies to help minimize the dangers and threats of seismic activity with a view to disaster reduction and environmental conservation. Hence, the engineering works for seismic should be more focus in designing the structures, well planned due and built due the unpredictable seismic hazard in the future.

II. Objective of this Study

This study is to develop seismic design response spectra and assess soil liquefaction potential in comparison to Malaysia National Annex to Eurocode 8 (MS EN 1998-1:2015). The following objectives are pursued in this study:

i. Perform specific ground analysis based on the 1-D shear wave propagation technique for the local soil examination and establish horizontal elastic design response spectrum.
ii. Examine the soil liquefaction potential and settlement by considering local soil data and seismic local effect.

III. Methodology

The flowchart of the research methodology, shown in Fig. 2, outlines the scope of the study. Key parameters used in the analysis include site-specific geotechnical information, maximum earthquake levels derived from recent seismic events, local geological conditions, and active fault lines. These parameters, which influence seismic activity, were used to perform ground response analyses. The results were used to develop site-specific response spectra that adhere to earthquake design standards, accounting for structural periods at specific intervals.

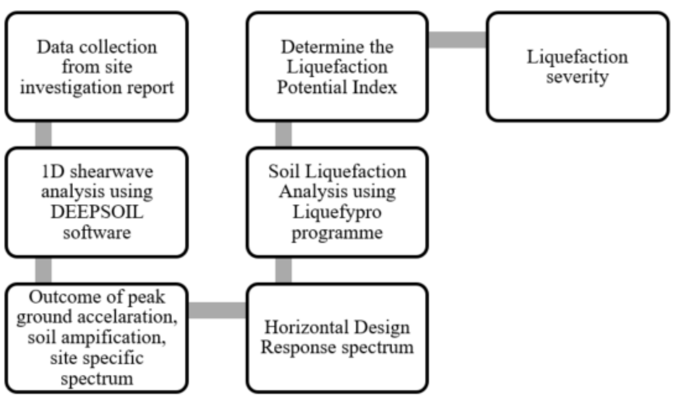

Fig. 2. Flowchart of research

A. Data and Borehole Location

A total of 18 boreholes were identified in the Kota Kinabalu area, with the coordinates of each borehole presented in Fig. 3. These boreholes are distributed within a 22.3 km² area in Kota Kinabalu. Key parameters for each borehole were obtained from the site investigation (SI) report, which utilized the Standard Penetration Test (SPT) method to analyse subsurface conditions. Additionally, a summary of soil classifications for the 18 boreholes is provided in Fig. 4. The soil stratigraphy indicates that the hard layer consists of silt and clay, overlain by layers of clayey silt, sandy silt, silty clay, sandy clay, silty sand, and clayey sand, as detailed in Fig. 4. The boreholes reach depths ranging from 19.5 meters to 26 meters.

B. Earthquake Input Motions

The ground motion records and borehole details used in this study are summarized in Table I. This study employed seven global and four local seismic event records obtained from the PEER online database (PEER NGA West-2). The global earthquakes include active seismic events in the USA, such as Imperial Valley, Mammoth Lakes, Loma Gilroy, and Northridge, as well as earthquakes from Turkey (Aydin, Eregli, and Tokat). Meanwhile, the local earthquakes include events in East Malaysia, specifically in Bintulu (Sarawak) and Sabah (Kota Kinabalu, Tawau, and Sandakan).

TABLE I. RECORD OF IMPLEMENTED GROUND MOTIONS

ID	Ground Motion	Magnitude (Mw)
GM1	Imperial Valley Earthquake	5.62
GM2	Mammoth Lakes Earthquake	6.06
GM3	Loma Gilroy Earthquake	4.90
GM4	Northridge Earthquake	6.69
GM5	Aydin Earthquake	7.00
GM6	Eregli Earthquake	7.00
GM7	Tokat Earthquake	7.00
GM8	Bintulu Earthquake	5.20
GM9	Kota Kinabalu Earthquake	5.40
GM10	Tawau Earthquake	4.78
GM11	Sandakan Earthquake	4.50

The selection of earthquake input motions, comprising both global and local records, was based on their relevance to the seismic characteristics of Kota Kinabalu. Global records from the PEER NGA West-2 database, such as the Imperial Valley and Northridge earthquakes, were selected for their well-documented ground motion profiles and magnitudes, ranging from 4.9 to 7.0. These records provide a comprehensive foundation for simulating strong ground shaking and represent tectonic and seismic conditions comparable to those associated with active fault systems impacting Malaysia. Local records from East Malaysia, including events in Bintulu, Kota Kinabalu, Tawau, and Sandakan, capture the regional seismicity. These records reflect the intensity and frequency of nearby earthquakes, offering valuable insights into their influence on soil response and liquefaction potential specific to Kota Kinabalu. By integrating global seismic characteristics with local seismic impacts, this dataset provides a robust basis for conducting accurate site-specific response analyses, ensuring a comprehensive understanding of the seismic risks in the region.

C. 1-Dimensional Equivalent Linear Analysis

From the data collection consists of standard penetration test (SPT) values and profiles of soils. However, it is very unfamiliar to conduct in-situ tests for shear wave velocity (Vs), hence the Vs values are computed based on the SPT values using formulas developed by researchers [11]. Imai and Tonouchi correlation in 1982 between Vs and N value has been used in Malaysia by several researchers, based on the N-value, soil type and geological age [6]–[8], [10], [15], [18]. The complete regression line where N is SPT-N value as shown in equation 1:

$$Vs = 97.0 * N^{0.314} \tag{1}$$

The damping consideration is 5% implemented to every ground classes and dynamic characteristics of all stratum [26]. In this study, DEEPSOIL software was chosen because the DEEPSOIL program needs information in the theory and techniques for analysis of seismic site response and engineering in geotechnical earthquake [27]. The analysis flows in carrying out site specific ground response assessment study by using DEEPSOIL software as shown in Fig. 5 [28].

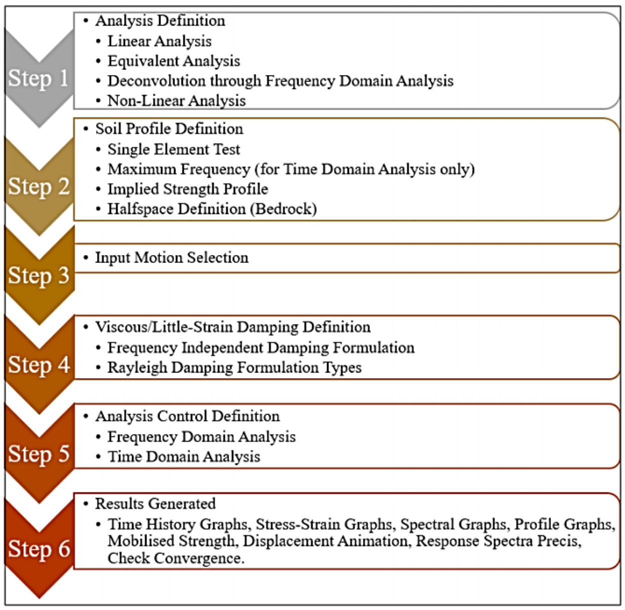

Fig. 3. Flow for analysis of site specific ground response assessment study by using DEEPSOIL software [28]

D. Liquefaction Soil Assessment

Semi-empirical methods are used to identify and determine the liquefaction potential. These methods used to evaluate potential of liquefaction according to historical seismic investigation, effects of liquefaction induced effects and in-situ test. There are three categories can be approaches such as cyclic stress approach, cyclic deformation approach and energy approach. In this study, cyclic stress approach was being used because it usually used to evaluate resistance to soil liquefaction by carried out a Safety Factor (FS). The value of FS can be calculating from the ratio between cyclic resistance (CRR) and cyclic constraint (CSR) (Latifi et al., 2020). LiqIT software also have been used in this study to determine the Factor of Safety.

Cyclic stress ratio (CRR) and cyclic constraint (CSR) can be calculate by using Youd et al. (2001) methods:

Cyclic stress ratio (CRR)

$$CRR(N_1)_{60cs} = exp\left[\left(\frac{(N_1)_{60cs}}{14.1}\right) + \left(\frac{(N_1)_{60cs}}{126}\right)^2 + \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right] \tag{2}$$

Cyclic constraint (CSR)

$$CSR = 0.65\left(\frac{\sigma_v}{\sigma_v'}\right)\left(\frac{\alpha_{max}}{g}\right)(r_d)\left(\frac{1}{MSF}\right)\left(\frac{1}{K_\sigma}\right) \tag{3}$$

Where,
g = gravity acceleration
rd = shear stress reduction factor
α_{max} = peak ground acceleration
σ_v , σ_v' = Total Vertical and Effective Overburden Stress, repectively
MSF = Magnitude Scaling Factor
K_σ = overburden correction factor for cyclic stress ratio
rd = exp [α + βM]
A = -1.012−1:126 sin [5.133 + (z/11.73)]
B = 0.106 + 0.118 sin [5.142 + (z/11.28)]
z = depth of interest (m)
M = moment magnitude
The term K_σ can be calculated as:

$$K_\sigma = 1 - C\sigma\, ln\left(\frac{\sigma_v'}{pa}\right) \leq 1.0 \tag{4}$$

$$C\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60cs}}} \leq 0.3 \tag{5}$$

The MSF can be computed as:

$$MSF = -0.058 + 6.9exp\left(-\frac{M_w}{4}\right) \leq 1.8 \tag{6}$$

Then, the factor of safety in resistance to liquefaction can be determined as:

$$FS = \frac{CRR}{CSR} MSF \tag{7}$$

Also, the liquefaction potential index can be determined by:

$$LPI = \int_0^{20} F(z).w(z)dz \tag{8}$$

Where
F (Z) is a function of Fs
Z = depth in meters
$w(z)$ = weighting factor.
$w(z)$ can be calculated as:

$$w(z) = 10 - 0.5z \quad (z < 20m) \tag{9}$$

The severity of Liquefaction Potential Index can be determine by refer to Table 2 that proposed by [31].

TABLE II LIQUEFACTION SEVERITY BASED ON THE LPI VALUES [31]

LPI	Severity of Liquefaction
LPI = 0	Very low
0 < LPI < 5	Low
5 < LPI < 15	High
15 < LPI	Very High

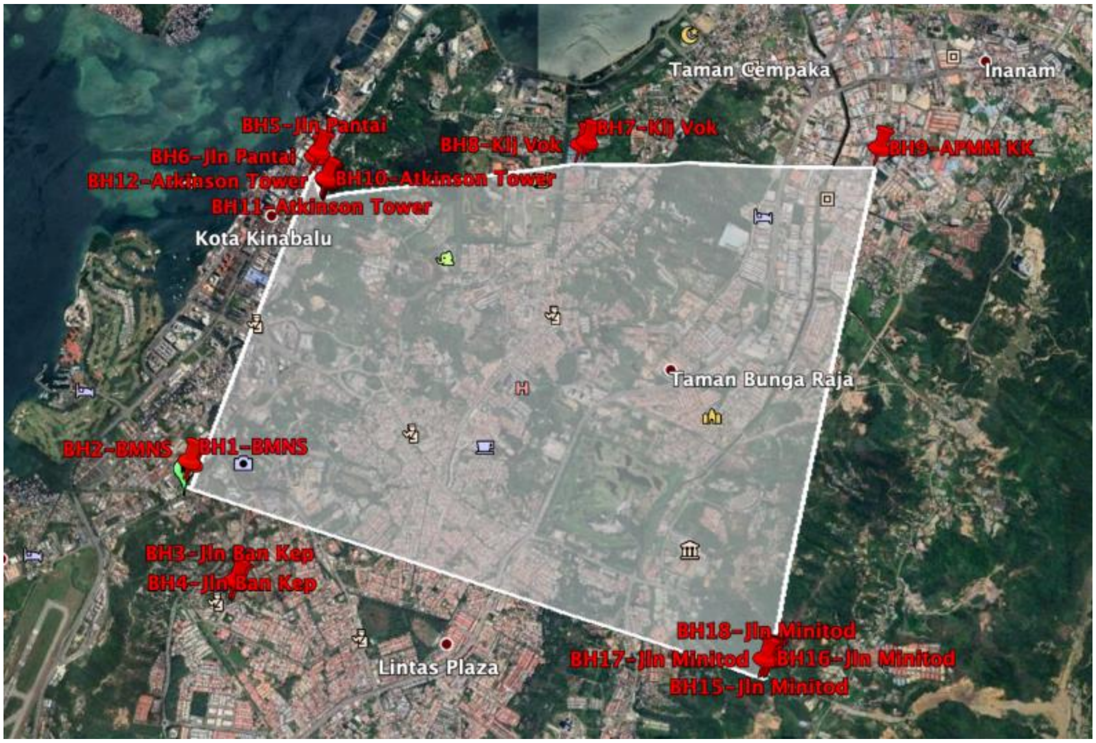

Fig. 4. Location of borehole

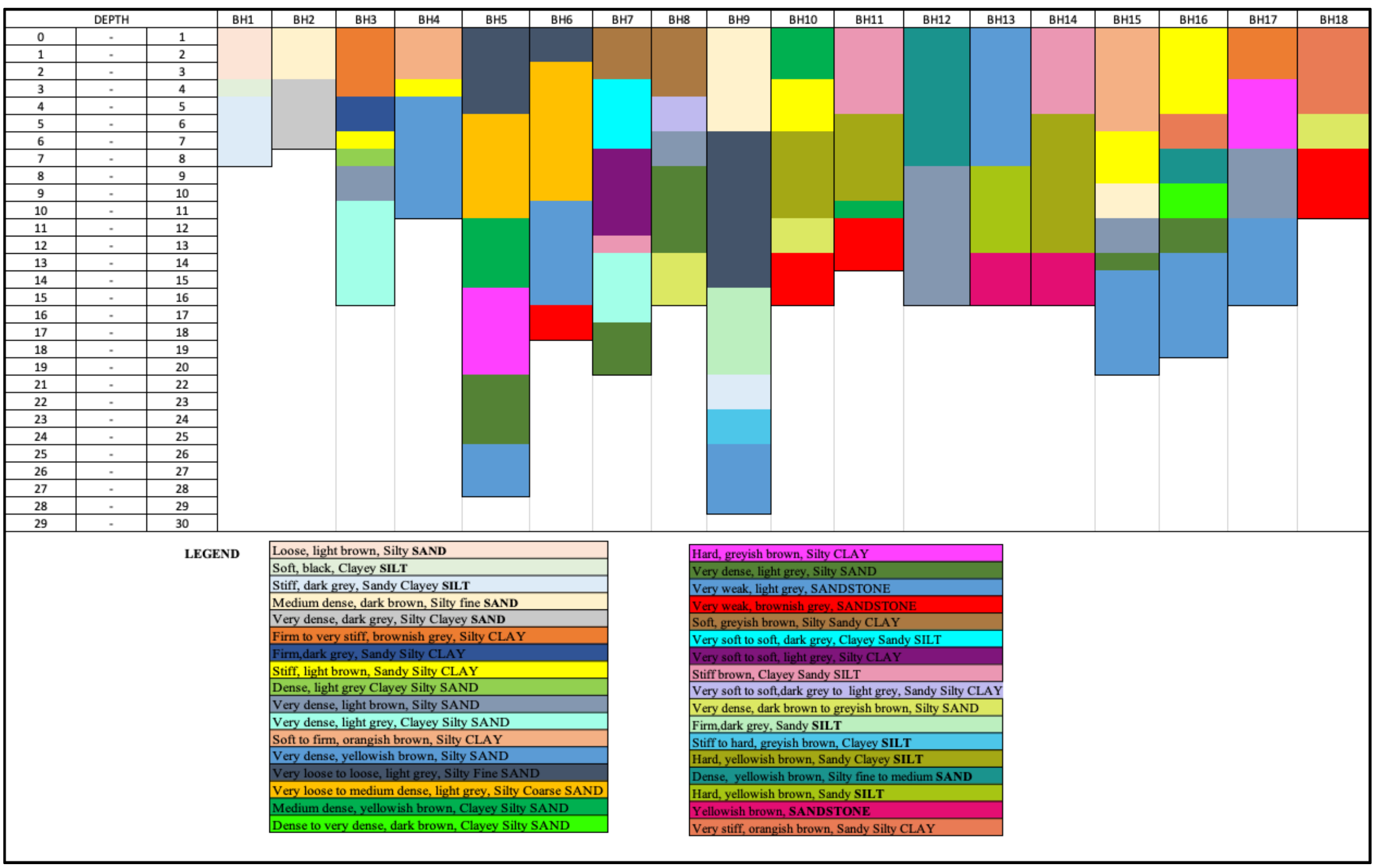

Fig. 5. Soil profile for 18 Boreholes

IV. RESULTS

A. Peak Ground Acceleration

The peak ground acceleration (PGA) results for each borehole, derived from seven global and four local earthquake input motions, are presented in Table III. According to the United States Geological Survey (USGS), the highest PGA recorded in Sabah during the 2015 Ranau earthquake was 0.145g at Tuaran. Consequently, a PGA value of 0.16g was selected for this study to account for a conservative seismic design scenario. The PGA values at the ground surface in Kota Kinabalu range from 0.116g (BH9 with GM6, corresponding to the Eregli Earthquake) to 0.496g (BH2 with GM5, corresponding to the Aydin Earthquake), as detailed in Table III. Among the input motions, the maximum average PGA recorded is 0.306g, which corresponds to GM3 or the Loma Gilroy Earthquake. These results provide crucial insights into the seismic behaviour of the study area and aid in evaluating site-specific seismic risks.

B. Amplification Factor

The ground amplification results for the maximum seismic event in Kota Kinabalu, Sabah, range from 2.790 (BH13 with GM5, corresponding to the Aydin Earthquake) to 4.137 (BH1 with GM4, corresponding to the Northridge Earthquake), as shown in Table IV.

C. Response Spectra at Ground Surface

The average response spectrum for both local and global input motions implemented from the plotted response spectra graph of Peak Surface Acceleration (PSA) (g) versus Period (s) for soil type A, B and C based on Fig. 6, Fig. 7, and Fig. 8, respectively. The highest PSA among the all the soil type is 6.86g (BH2 with Tawau Earthquake) in soil type A.

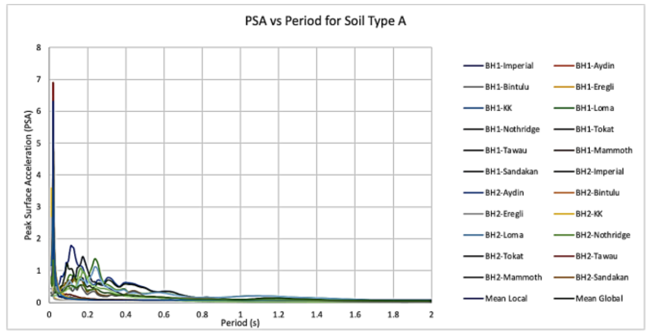

Fig. 6. Response Spectra for Soil Type A

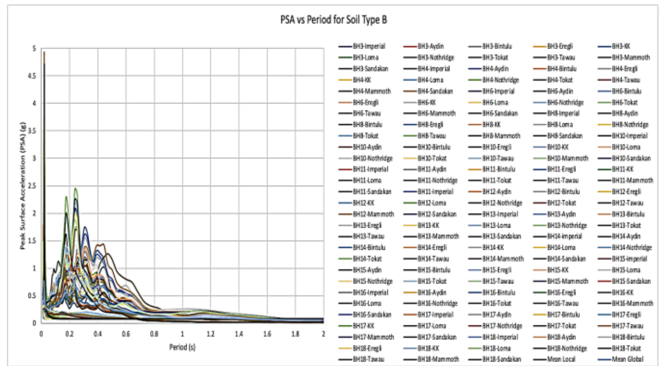

Fig. 7. Response Spectra for Soil Type B

TABLE III PEAK GROUND ACCELERATION (PGA) FOR 18 BOREHOLES

GM	PGA	BH1	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH10	BH11	BH12	BH13	BH14	BH15	BH16	BH17	BH18
GM1	0.16	0.42	0.26	0.35	0.38	0.26	0.38	0.20	0.24	0.23	0.26	0.25	0.28	0.26	0.26	0.32	0.34	0.28	0.31
GM2	0.16	0.29	0.23	0.17	0.29	0.24	0.24	0.17	0.23	0.17	0.22	0.2	0.22	0.22	0.18	0.2	0.2	0.22	0.25
GM3	0.16	0.29	0.2	0.28	0.42	0.27	0.33	0.21	0.22	0.26	0.34	0.33	0.37	0.35	0.31	0.25	0.29	0.34	0.38
GM4	0.16	0.31	0.21	0.3	0.43	0.27	0.32	0.25	0.24	0.21	0.3	0.29	0.31	0.31	0.28	0.29	0.28	0.3	0.37
GM5	0.16	0.4	0.49	0.2	0.31	0.15	0.24	0.16	0.22	0.11	0.13	0.28	0.3	0.29	0.27	0.2	0.18	0.34	0.17
GM6	0.16	0.3	0.2	0.16	0.16	0.11	0.19	0.13	0.17	0.11	0.18	0.14	0.12	0.2	0.19	0.11	0.13	0.14	0.14
GM7	0.16	0.38	0.46	0.2	0.3	0.14	0.23	0.16	0.21	0.14	0.13	0.27	0.28	0.28	0.26	0.19	0.18	0.32	0.16
GM8	0.16	0.36	0.45	0.19	0.28	0.15	0.22	0.16	0.2	0.13	0.13	0.25	0.28	0.27	0.24	0.18	0.17	0.31	0.16
GM9	0.16	0.39	0.48	0.2	0.29	0.12	0.23	0.14	0.23	0.12	0.13	0.25	0.29	0.28	0.24	0.19	0.17	0.31	0.16
GM10	0.16	0.39	0.48	0.2	0.29	0.12	0.23	0.14	0.23	0.12	0.13	0.14	0.29	0.28	0.24	0.19	0.17	0.31	0.16
GM11	0.16	0.37	0.48	0.19	0.29	0.15	0.23	0.16	0.21	0.13	0.13	0.26	0.29	0.28	0.25	0.19	0.17	0.31	0.16

TABLE IV GROUND AMPLIFICATION FOR 18 BOREHOLES

GM	PGA	BH1	BH2	BH3	BH4	BH5	BH6	BH7	BH8	BH9	BH10	BH11	BH12	BH13	BH14	BH15	BH16	BH17	BH18
GM1	0.16	4.62	3.12	3.07	3.69	2.99	3.09	3.05	3.08	3.35	2.57	2.43	2.92	2.56	2.33	3.04	2.77	2.72	3.12
GM2	0.16	4.72	3.18	3.40	3.74	3.17	3.40	3.21	3.40	3.61	2.72	2.53	3.12	2.66	2.44	3.22	3.01	2.93	3.19
GM3	0.16	4.15	3.17	3.19	3.51	3.10	3.20	2.99	3.21	3.31	2.54	2.37	2.86	2.47	2.31	3.14	2.86	2.72	3.02
GM4	0.16	4.14	3.16	3.23	3.54	3.24	3.27	3.68	3.41	3.64	2.63	2.44	2.97	2.55	2.37	3.26	2.92	2.82	3.03
GM5	0.16	4.88	3.28	3.62	3.86	3.33	3.59	3.20	4.25	3.84	3.16	2.93	3.29	2.79	2.54	3.43	3.14	3.19	3.37
GM6	0.16	4.86	3.36	3.59	3.84	3.24	3.54	3.06	4.13	3.77	3.18	2.98	3.28	2.75	2.50	3.34	3.10	3.19	3.33
GM7	0.16	4.88	3.28	3.61	3.86	3.35	3.59	3.29	4.29	3.84	3.16	2.93	3.29	2.79	2.55	3.43	3.14	3.19	3.36
GM8	0.16	4.88	3.28	3.62	3.87	3.32	3.59	3.16	4.23	3.83	3.18	2.93	3.29	2.79	2.54	3.42	3.13	3.20	3.37
GM9	0.16	4.89	3.28	3.57	3.81	3.25	3.55	2.95	4.11	3.79	3.21	2.93	3.26	2.76	2.53	3.35	3.09	3.18	3.36
GM10	0.16	4.89	3.28	3.27	3.81	3.24	3.54	2.94	4.10	3.78	3.21	2.92	3.26	2.76	2.52	3.34	3.09	3.18	3.36
GM11	0.16	4.88	3.28	3.62	3.86	3.31	3.59	3.11	4.21	3.82	3.16	2.92	3.29	2.78	2.54	3.42	3.13	3.19	3.37

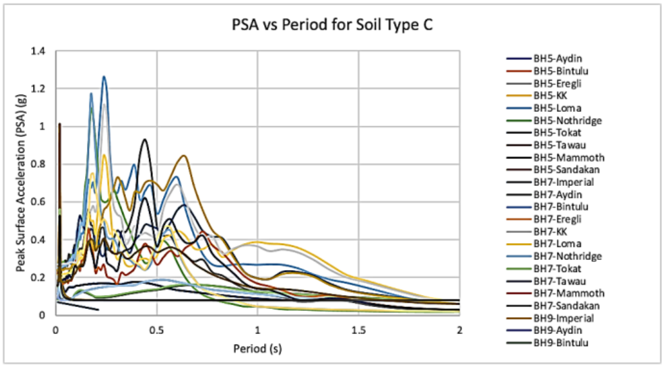

Fig. 8. Response Spectra for Soil Type C

D. *Recommended Design Response Spectra*

The design response recommendation includes the mean of both average local and global response spectra obtained from ground response analysis. This information is depicted in Fig. 9, Fig. 10, and Fig. 11. The values of the design response spectrum were determined by the horizontal elastic spectra for Type 2 according to Eurocode 8, as shown in Table V. These values will eventually be compared with the fixed values specified in the National Annex for Sabah, as shown in Table VI.

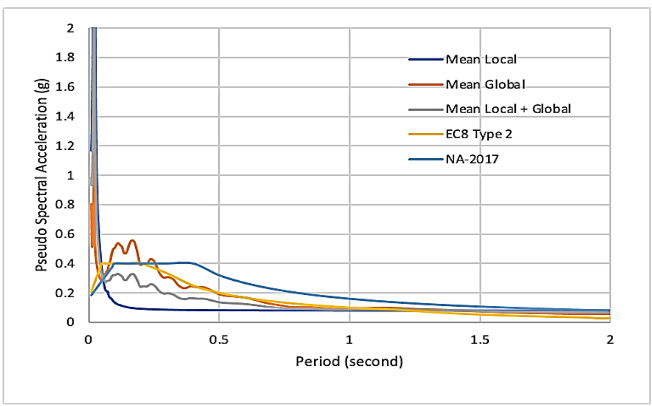

Fig. 9. Recommended Design Response Spectra for Soil Type A

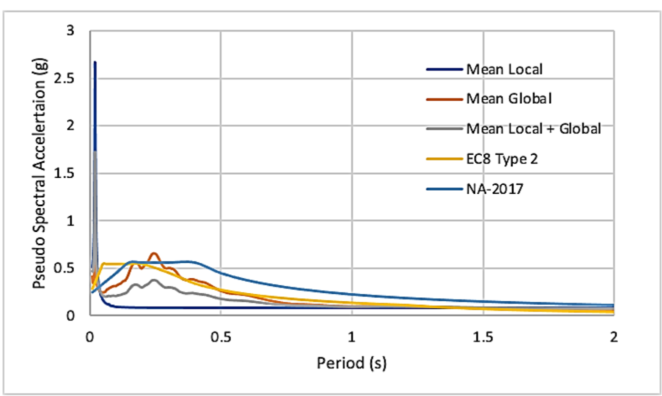

Fig. 10. Recommended Design Response Spectra for Soil Type B

Comparison of Ground Factors and Characteristic Duration

For **soil class A**:

- The ground amplification factor (S) is 1.0 in both Eurocode 8 and NA-2017.
- The characteristic duration parameter (TD) differs, with Eurocode 8 specifying 1.20 seconds compared to 2 seconds in NA-2017.

For **soil class B**:

- In Eurocode 8, S is 1.35 and TD is 1.20 seconds.
- In NA-2017, S is slightly higher at 1.40, and TD is 2 seconds.

For **soil class C**:

- The ground amplification factor (S) in Eurocode 8 is 1.50, which is greater than the NA-2017 value of 1.35.
- However, TD in Eurocode 8 is 1.20 seconds, which is less than the NA-2017 value of 2 seconds.

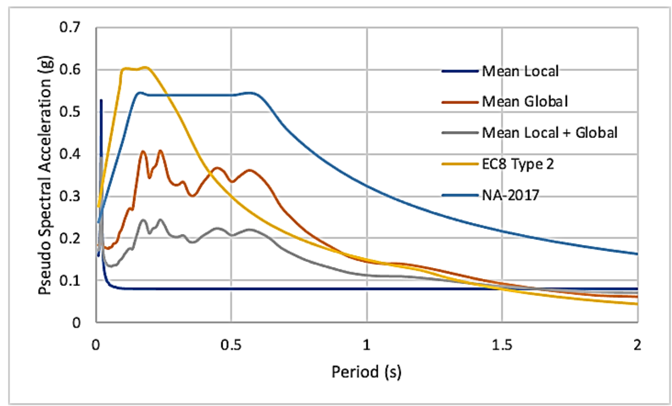

Fig. 11. Recommended Design Response Spectra for Soil Type C

TABLE V DESIGN GROUND RESPONSE TYPE 2 ACCORDING TO EUROCODE 8

Ground Type	S	TB (s)	TC (s)	TD (s)
A	1.0	0.05	0.25	1.20
B	1.35	0.05	0.25	1.20
C	1.5	0.10	0.25	1.20

TABLE VI DESIGN RESPONSE SPECTRA FOR SABAH (NA-2017)

Ground Type	S	TB (s)	TC (s)	TD (s)
A	1.0	0.1	0.4	2
B	1.4	0.15	0.4	2
C	1.35	0.15	0.6	2

E. *Liquefaction Analysis Outcomes*

The liquefaction analysis was conducted using LiqIT software. The input parameters included the depth of each soil layer, the Standard Penetration Test (SPT) blow count (NSPT), the percentage of fines in the soil, the unit weight of each soil layer, and the water table level. These parameters were entered alongside the input ground motion and borehole log data. The peak ground acceleration (PGA) and earthquake magnitude for each borehole were set at 0.16g and 6.00 Mw, respectively.

This research provided a comprehensive analysis of potential ground motion resulting from soil liquefaction. A summary of the liquefaction assessment for all 18 boreholes is presented in Table VII. The findings are as follows:

(a) A factor of safety (FoS) less than 1.0 indicates the potential for soil liquefaction, as determined by LiqIT software. The software limits the FoS to a maximum value of 5. According to Table VII, there are two boreholes (BH7 and BH9) among the 18 assessed with FoS values close to but less than 1.0, specifically 0.99 and 0.93, respectively. Consequently, these boreholes exhibit a susceptibility to liquefaction.

(b) The results for the remaining 16 boreholes indicate no liquefaction potential. However, ground settlement and other repercussions may still occur following a seismic event, should one take place in the future.

This analysis underscores the importance of understanding soil behavior under seismic conditions to mitigate potential risks effectively.

TABLE VII SUMMARY OF SOIL LIQUEFACTION OUTCOME FOR 18 BOREHOLES

Borehole	Factor of Safety	Total Settlement (cm)	Overall Liquefaction Potential	Liquefaction Potential
BH1	1.14	1.79	0	No Liquefaction
BH2	5	0	0	No Liquefaction
BH3	1.29	0.58	0	No Liquefaction
BH4	1.22	1.06	0	No Liquefaction
BH5	1.48	0.61	0	No Liquefaction
BH6	1.14	1.47	0	No Liquefaction
BH7	0.99	23.30	0.13	Liquefaction not preferable
BH8	1.02	10.75	0	No Liquefaction
BH9	0.93	26.64	3.07	Liquefaction not preferable
BH10	3.63	0	0	No Liquefaction
BH11	3.60	0	0	No Liquefaction
BH12	3.06	0	0	No Liquefaction
BH13	5	0	0	No Liquefaction
BH14	5	0	0	No Liquefaction
BH15	1.47	0.67	0	No Liquefaction
BH16	1.99	0.02	0	No Liquefaction
BH17	1.55	0.21	0	No Liquefaction
BH18	2.32	0	0	No Liquefaction

The findings effectively address the research objectives by evaluating seismic response, amplification factors, response spectra, and liquefaction potential specific to Kota Kinabalu. The observed variations in peak ground acceleration (PGA) and amplification across the boreholes reveal significant localized soil effects, directly supporting the objective to model site-specific seismic risks. When compared to previous studies in Sabah, our results indicate higher amplification factors, particularly for soil type A, suggesting greater seismic vulnerability than initially anticipated. This may be attributed to the region's unique soil composition. Similar amplification trends were observed in studies of the 2015 Ranau earthquake, further emphasizing the need for tailored response spectra. By contrasting these findings with regional data, this study underscores the distinct seismic responses in Kota Kinabalu, providing valuable insights for enhancing earthquake resilience in comparable geological environments.

V. CONCLUSION

This study evaluates soil flexibility across 18 borehole locations in and around Kota Kinabalu, Sabah, with a focus on site-specific seismic hazards. Eleven seismic ground input motions were utilized, consisting of seven global and four local earthquake records. The analysis was conducted using a one-dimensional (1-D) equivalent linear approach, implemented through the DEEPSOIL software, to assess the seismic responses of the soil layers. Additionally, soil liquefaction potential was analysed using LiqIT software, which relies on Standard Penetration Test (SPT) data and follows the methodologies of Idriss and Boulanger. While DEEPSOIL and LiquefyPro provide useful preliminary insights, their reliance on idealized soil models and assumptions may not fully capture the complexity of in-situ soil behaviour under seismic loads. As such, these tools have limitations in accurately predicting liquefaction potential and site-specific response spectra. Field validation and further data collection are essential to enhance the accuracy of these models. Real-time monitoring and additional field studies would complement these findings and help verify model assumptions, offering a more comprehensive understanding of seismic risk in Kota Kinabalu.

The analysis produced critical metrics, including the factor of safety (FS) against liquefaction, liquefaction probability (PL), and the liquefaction potential index (LPI). The results indicated that peak ground acceleration (PGA) at the surface in Kota Kinabalu ranged from 0.116g to 0.496g, with an average maximum PGA of 0.306g. The ground amplification factor for the most extreme seismic events in the area varied between 2.790 and 4.137. A comprehensive assessment of liquefaction potential (LPI) at the 18 borehole locations revealed that most areas in Kota Kinabalu exhibited little to no potential for liquefaction. The factors of safety across all boreholes ranged from 0.93 to 5. Notably, the minimum factor of safety, which is critical for assessing liquefaction risk, suggests that the overall probability of liquefaction in Kota Kinabalu remains low. According to established guidelines, a safety factor below 1.0 indicates a heightened risk of liquefaction, indicating that ground improvement methods may be necessary in certain areas to prevent damage from seismic-induced liquefaction. The analysis also found minimal or trivial ground settlement across most borehole sites due to liquefaction, except for boreholes BH7 and BH9. These locations exhibited significant total settlements of 23.30 cm and 26.64 cm, respectively, which suggests the presence of extremely soft and cohesionless soils. The higher total settlements at these sites may be influenced by the lack of vigorous ground acceleration, which would typically stimulate more significant ground movements. The findings from BH7 and BH9 are crucial for informing future foundation design and construction practices in these areas.

A. Recommendations

To enhance the earthquake investigation in the Kota Kinabalu region, several recommendations are proposed for future research endeavors:

1. Detailed Ground Dynamic Studies: Conducting more specific investigations into the ground dynamics is crucial. This includes obtaining detailed information on soil strata, classifications, thicknesses, fines content, groundwater levels, and unit weights from both in situ measurements and laboratory analyses. Such data would contribute significantly to understanding site behavior during seismic events.
2. Increasing Borehole Data Availability: Expanding the number of borehole data points would improve the precision and reliability of the input ground motions used in designing response spectra and conducting liquefaction analyses. A larger dataset in DEEPSOIL and LiqIT software would facilitate more comprehensive evaluations of soil behavior under seismic loading.
3. Exploration of Additional Analytical Software: Future studies should also consider utilizing other earthquake analysis software such as NERA, SHAKE2000, FORTRAN, and EERA. Employing multiple programs can provide a means of corroborating findings from DEEPSOIL and LiqIT, thereby establishing a more robust average of investigation results.

These recommendations aim to refine the assessment methodologies used in seismic hazard evaluations, ultimately contributing to enhanced understanding and mitigation of earthquake risks in Sabah, particularly in areas susceptible to soil liquefaction.

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