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Evaluation on the Soil Flexibility of the Largest HEP Dam Area in East Malaysia using 1-D Equivalent Linear Analysis

Raudhah Ahmadi[a,*], Muhammad Haniz Azahari Muhamad Suhaili[a], Imtiyaz Akbar Najar[a], Muhammad Azmi Ladi[b], Nisa Aqila Bakie[c], Ahmed Faysal Abdullahi[d]

[a] *Department of Civil Engineering, Faculty of Engineering, Universiti Malaysia Sarawak, Kota Samarahan, 94300, Sarawak, Malaysia*
[b] *Kuching Polytechnic, Jalan Matang, Petra Jaya, 93050, Sarawak, Malaysia*
[c] *School of Engineering and Technology, University College of Technology Sarawak, Sibu, 96000, Sarawak, Malaysia*
[d] *School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool, United Kingdom*
Corresponding author: [*]araudhah@unimas.my

Abstract — **This paper presents the evaluation of soil flexibility at the vicinity of the Bakun HEP Dam, the largest in East Malaysia. The dam is located in the Belaga District of Sarawak, approximately 50 km from the active Tubau and Bukit Mersing fault lines. This area experienced earthquakes of magnitudes ranging between 3.5 and 5.4 during the period from 1994 and 2010. This study used global and local earthquake records to evaluate the site-specific seismic hazard using a 1-D equivalent linear analysis. SPT data from 15 boreholes are utilized. Soil flexibility, factor of safety, liquefaction probability and potential index are evaluated to find the ground settlement and soil liquefaction effects. The results show that the ground amplification of Belaga District is between 2.445 and 5.146, while the peak ground accelerations (PGA) at ground surface are at a maximum average of 0.25g PGA. The soil factors for Bakun District range from 2.6 - 3.0, for 2% POE in 50 years. This corresponds to a 2475-year return period. The response spectra are found matching with the target design response spectra for Sarawak as reported in the Malaysia National Annex (MS EN 1998-1:2015). The effects of soil liquefaction are found to be insignificant, as a result the nearby Bakun HEP dam is considered safe from any ground settlement. This study highlights the importance of evaluating the ability of new or existing structures in Belaga District to withstand up to 0.25g PGA in case any seismic event should occur in the future.**

Keywords—**Soil flexibility; Belaga district Sarawak; seismic design response spectra; soil liquefaction hazard assessment.**

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I. INTRODUCTION

Historically, East Malaysia was not considered an area exposed to any significant seismic activity or events. East Malaysia is situated within stable and on the exterior of the seismic zone [1]. The nearest seismic zone is the Philippines Sea Plate, which shifts to the west at a rate of 80 mm/year. This area is exposed to earthquakes of significant magnitudes centered around the Southern Philippines, the Makassar Strait, the Sulu Sea, and the Celebes Sea, as shown in Figure 1 [2].

In the past 20 years, East Malaysia, a combination of the two states of Sabah and Sarawak, seldom experienced any large earthquakes until recently, in June 2015, when an earthquake of magnitude M_w5.9 struck Ranau, Sabah. This is the largest earthquake experienced in Malaysia [3]. Due to this event, more seismic monitoring stations are being built in East Malaysia to monitor any seismic activity. Seismologists have realized that many local faults are in Sabah and Sarawak, which have become active over the years. This is genuinely concerning due to the number of existing and newly constructed dams available in Sabah and Sarawak. Due to the vast potential in Sarawak, many large hydropower electric dams are planned for future construction to supply electricity. These essential and large structures require detailed seismic assessment in the planning, design, construction, and operation stage.

Three large dams, Bakun, Murum, and Baleh, are in a 120 km radius of the Kapit-Belaga region in Sarawak, where the new dextral strike-slip deflected streams and sinistral faults are found along the Rajang-Crocker Belt [4].

The active Tubau fault line extends a 100 km north to south and spans from Belaga in the south to Niah in the north, as shown in Figure 2. Two earthquakes were caused by the Tubau fault, one in May 2004 (M_w5.2) and another in January

2010 (M_b3.5). Another active fault is Bukit Mersing fault line which caused an earthquake (M_b 5.2) in February 1994. [5]. These two active fault lines are found less than 100 km away from the large dams in Sarawak.

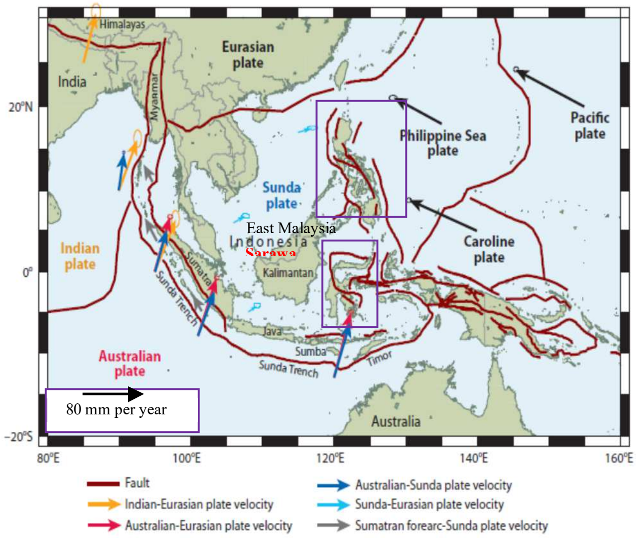

Fig. 1 Plate Tectonic Setting in Southeast Asia with vectors shows relative velocities of plate pairs as labeled [2]

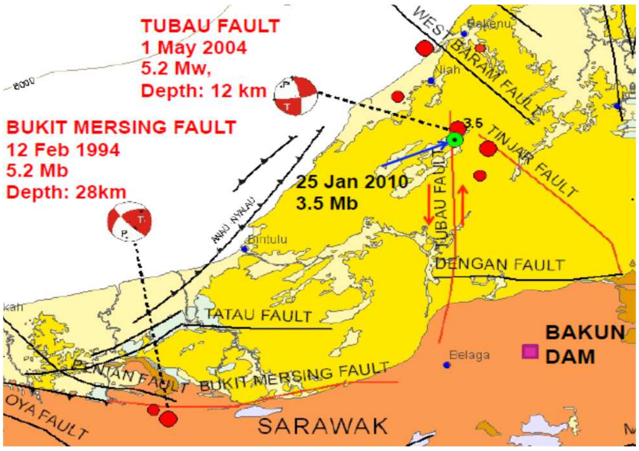

Fig. 2 Active fault lines in Sarawak [5]

Hence, there is a crucial need to assess these existing large dams for seismic hazard conditions. Table 1 shows the record of recent earthquakes in Sarawak. Recently, on 28 September 2018, Palu in Central Sulawesi, Indonesia, was struck by a tsunami of approximately 5 m high following a seismic shock of a magnitude of M_w7.4 that took place about 80 km northwardly of the affected area [6]. The seismic trembling was felt as far as Tawau, Sabah, East Malaysia, approximately 611 km from Palu. The largest hydroelectric dam in Sarawak, the Bakun Dam, is located approximately 770 km from Palu. It is not impossible shortly, because of an earthquake hitting East Malaysia, that soil liquefaction would be experienced below the dam. The most disastrous results will have transpired due to combined damage from both seismic shock and soil liquefaction [7, 8]. Hence, the earthquake and soil liquefaction occurrences in Sarawak shall not be disregarded as there is a potential for earthquakes and soil liquefaction hazard. Such incidence would be detrimental to future planned structures and infrastructure.

TABLE I
RECORD OF FELT EARTHQUAKE AND INTENSITY IN SARAWAK (DATA SOURCE: MALAYSIA METEOROLOGICAL DEPARTMENT)

DATE	LAT (°N)	LONG (°E)	mb	FELT AREA	INTENSITY (MMI)
01/05/2004	3.50	113.9	4.8	Bintulu & Miri	VI
19/04/2005	3.80	113.6	4.8	Batu Niah	V
30/06/2005	4.40	115.4	4.8	Limbang	III
19/03/2008	1.42	110.2	3.3	Semeng-gok	I
24/01/2010	3.65	113.82	3.84	Batu Niah	II
15/07/2011	1.04	110.99	4.26	Sebuyau	III
09/05/2012	2.76	113.75	3.78	Belaga (Bakun)	II
12/05/2012	2.73	113.91	3.53	Belaga (Bakun)	II

The destruction resulting from seismic shock and soil liquefaction is not only based on the magnitude but also on the liability of the structures [9]. Therefore, further seismic performance analysis should be conducted to evaluate the liability under the anticipated magnitude of earthquake phenomena [10]. Besides, to allow forecasting on the dam under a ground movement, the response spectrum analysis could be implemented for handling expected seismic events [8, 11]. It provides valuable insight regarding the necessary design components that must be integrated into the structures.

It is essential to bear in mind that the seismic phenomenon does not require enormous intensity to induce dreadful devastation due to the degree of destruction. The damage is not dependent only on the physical size of a seismic shock but also on other aspects. For example, where and when a seismic event happens, the population density in the affected region, and subsequent events such as tsunami and soil liquefaction [12]. Hence, the engineering projects should be well planned, designed, and erected to withstand the earthquake hazards and soil liquefaction during its lifetime.

In the past, Malaysia had no seismic design requirements in the guideline for every structure due to the insignificant earthquake phenomena in Malaysia [13]. Therefore, embracing the British Standard (BS) and Eurocode (EC) in the design of structures is a typical engineering practice in Malaysia. Nevertheless, the Malaysia National Annex to Eurocode 8 for Structural Design for Seismic Resilience has been established at the end of 2017 (MS EN 1998-1:2015) [14], for the reference of local engineers to comply with the requirement of the Department of Standard Malaysia.

The design plans employing the EC design parameters are common and typically conservative, and it is not representative of a particular location, specifically for lifeline utilities. Furthermore, it is essential to be aware that earthquake risk evaluation techniques employed in some areas may not be applicable to other areas since different locations have site-specific properties [15]. Despite this, several studies have been performed to produce fragility curves for recent structures in Malaysia; most of these have concentrated on public structures [16]. In this research, priority has been given to the region with a hydroelectric dam because of its vitality as the lifeline in providing power to most parts of Sarawak.

Comparably, the impact of soil liquefaction generated by the seismic waves on the structures can be destructive. Soil liquefaction commonly occurs in regions with low density and saturated granular deposits [17]. Thus, the assessment of potential liquefaction assessment is crucial for locations adjacent to the rivers due to the greater probability for soil liquefaction triggered by earthquake events. The evaluation of soil liquefaction liability will give a piece of preparatory information on the resilience of the grounds to liquefaction. Moreover, the response of the subsoil layer subjected to earthquake vibrations plays a vital part in ensuring the stability of substructures and superstructures [18].

The motivation to initiate this study stems from the certainty that some areas of Borneo (East Malaysia, Kalimantan Indonesia and Brunei) are susceptible to earthquake phenomenon and seismic induced soil liquefaction. This investigation proposes an approach to establish design response spectra based on the soil information to acquire the appropriate earthquake parameters. These can be used to perform the soil liquefaction assessment to identify the adverse impacts of liquefaction on the structure [19].

This study aims to evaluate the flexibility of soil using seismic design response spectra and evaluate possible soil liquefaction at the vicinity of Belaga District, Sarawak, which could impact the existing Bakun HEP dam. Data from Malaysia National Annex to Eurocode 8 (MS EN 1998-1:2015) is utilized as a reference [14]. This study carried out the site-specific ground response analysis based on the 1-D equivalent linear shear wave propagation technique, using global and local earthquake records to establish a horizontal elastic design response spectrum for the local soil examination. Further assessments are carried out to check the development of soil liquefaction and settlement by considering the local soil data and local earthquake impact.

II. MATERIAL AND METHODS

A. Site and Boreholes Data Collection

The site-specific response of the ground can be determined using the dynamic attributes of the underground soil layers [20]. Nevertheless, most boreholes input is limited to a depth of less than 30 m, and information can be derived from the soil investigation (SI) report on the ground dynamic attributes. Data such as the types of soil strata, the depth of each layer, and SPT-N blows can be obtained from each borehole. Shear wave velocities for each discerned stratum will be determined afterward [21]. The location of the boreholes is shown in Figure 3. They are located within 1500 km^2 in the vicinity of the Bakun Dam and the active Tubau fault line. Murum Dam is located 40 km to the Southeast of this study area region, while Baleh Dam is 120 km to the Southwest. Due to confidentiality of data, no borehole data at the specific site of Bakun Dam is utilized in this study. Since the distance of Bakun Dam with the available boreholes data is small (less than 5km), a similar soil type is anticipated.

In addition, the summary of ground stratification for fifteen chosen boreholes at the study zone is shown in Figure 4. The soil strata of hard layers in the case study region of the Belaga District are predominantly sandstone overlaid by largely clayey silt, sandy silt, silty clay, sandy clay, silty sand, and clayey sand. The maximal deepness of the specified boreholes is between 9 m and as deep as 30 m.

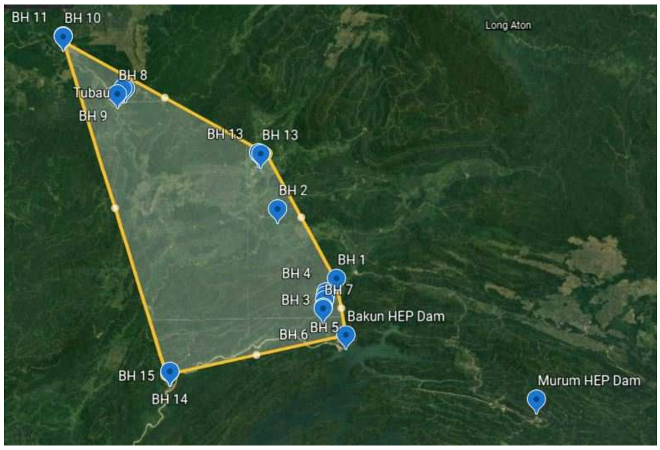

Fig. 3 The 15 Images of Boreholes Locations of the case study from Landsat data captured on 28th April 2020

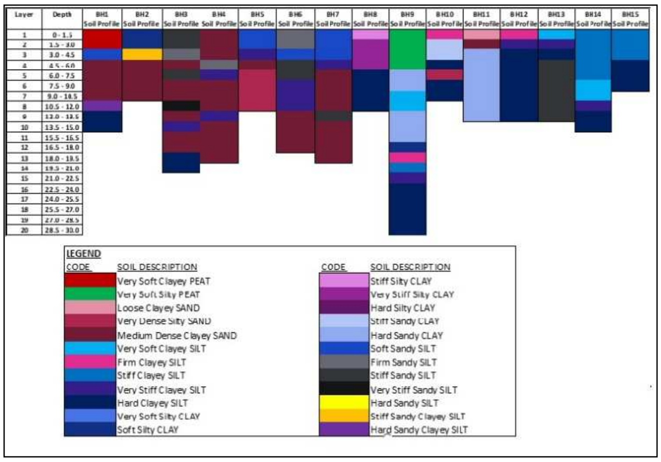

Fig. 4 The Soil Profile for 15 Boreholes

The 15 boreholes data were collected from geotechnical consultants involved with existing construction projects in Belaga District. Nevertheless, the majority of the boreholes input are restrained to a penetration vertical extent of less than 30 m for the reason that these thorough details are not demanded for critical engineering design project.

B. Earthquake Input Ground Motions

Seismic event records play a significant role in developing the PGA on ground surface through site specific ground response analysis [22]. This study has employed seven global and four local seismic earthquake records which were obtained from PEER online database (PEER NGA West-2) [23]. The chosen earthquake records were form earthquakes that took place in seismic active countries, the USA (e.g., Imperial Valley, Mammoth Lakes, Northridge, and Loma Gilroy), Japan (Kobe region), Turkey (Kocaeli region), Taiwan (Chi-Chi region) [24], and East Malaysia (e.g. Kuching, Bintulu, Kota Kinabalu, and Tawau) with the intensity varying from M_w 3.70 to M_w 7.62. These seismic event records are the exemplification of far-field seismic phenomenon with corresponding features to the seismic incidents in Sarawak and are used as input to determine the design response spectrum. The list of the seven global and four local seismic ground movements documented with the PGA values scaled to 0.1g peak ground acceleration (PGA) at bedrock, are shown in Table 2. The latest 10% Probability of

Exceedance (POE) in 475yr return period, seismic hazard map of Sarawak shows the Belaga District is in the region of 0.04g PGA [14]. Hence, this study utilizes 2.5 times the seismic hazard value for seismic hazard assessment for dam facility and other critical lifeline facilities, which is equivalent to a seismic hazard of 2% POE in 2475 years return period or higher.

TABLE II
THE DETAILED 11 INPUT GROUND MOTIONS RECORDS

Input Motion (Source)	Tremor Name	Year	Station Title	(M_w)	PGA (g)	Distance (km)
1 (PEER)	Imperial Valley, California	1979	Westmorland Fire Station	5.62	0.1	16.00
2 (PEER)	Mammoth Lake, California	1980	Mammoth Lake H.S.	6.06	0.1	15.00
3 (PEER)	Northridge, Los Angeles	1994	Featherly Park - Maint	6.69	0.1	31.00
4 (PEER)	Kobe, Japan	1995	Yae	6.90	0.1	17.60
5 (PEER)	Kocaeli, Turkey	1999	Afyon Bay	7.51	0.1	80.00
6 (PEER)	Chi-Chi, Taiwan	1999	CHY023	7.62	0.1	150.00
7 (PEER)	Loma Gilroy, California	2002	Alameda – Oakland Airport	4.90	0.1	11.00
8 (MMD)	Kuching, Sarawak	2004	KSM (Kuching)	3.70	0.1	8.00
9 (MMD)	Bintulu, Sarawak	2004	BTM (Bintulu)	5.20	0.1	13.50
10 (MMD)	Kota Kinabalu	2004	KKM (K.Kinabalu)	5.40	0.1	27.40
11 (MMD)	Tawau, Sabah	2004	TSM (Tawau)	4.78	0.1	16.60

Note: PEER Berkeley Ground Motion Database, MMD (Malaysian Meterological Department)

C. Soil Dynamic Properties

The level of destruction as a result of seismic events is greatly governed by the response of the grounds to cyclic action. This response is principally modulated by the mechanical features of the earth. The deportment of the grounds exposed to dynamic action is modulated by the ground dynamic features [18]. To obtain accurate results from the ground response examination, the profile of the ground dynamics variables e.g., maximal shear modulus, shear wave velocity or (V_s) and damping (β) is essential [25]. Furthermore, these variables are procured by transforming the site dynamic tests using empirical equations. For simplicity, the static variable values, N, from the SPT investigation were transmuted into V_s by utilizing Imai and Tonouchi equation in [26].

The equation by Imai and Tonouchi [26] is the most pertinent for enumerating the shear wave velocity and to ascertain the ground dynamic features of Kapit division for the Belaga District as its standard geology suited the geological attributes.

$$Vs = 97.0\ N0.314 \quad (1)$$

Where, V_s = Shear Wave Velocity
N = Total number of SPT Blow

The V_s at 30 m depth (Vs_{30}) is the total of travel period for the shear waves to progress through every ground stratum to the superficial level beginning from the substratum at a depth of 30 m [27]. As a result of employing the following equation, Vs_{30} for every borehole is acquired as tabulated in Table 3.

$$Vs30 = 30/[sum(d/Vs)] \quad (2)$$

Where, Vs_{30} = V_s at 30 m Deepness
V_s = Shear Wave Velocity
d = Thickness of Ground Stratum

TABLE III
THE ANALYSIS OF SHEAR WAVE VELOCITY AND GROUND CATEGORY FOR 15 BOREHOLES

BOREHOLE	V_{S30} (m/s)	SOIL CATEGORY
1	424.25	B
2	742.88	B
3	397.79	B
4	361.47	B
5	663.02	B
6	436.62	B
7	414.18	B
8	677.77	B
9	220.25	C
10	713.96	B
11	540.78	B
12	575.29	B
13	552.85	B
14	489.61	B
15	836.87	A

D. 1-D equivalent linear method in DEEPSOIL V6 Software

The 1-D equivalent linear approach is a common numerical method used to evaluate the site-specific ground response due to its flexibility, robustness and simplicity. A site response map, Vs_{30}, of Kashmir Valley was produced after the 2008 Kashmir earthquake, using the 1-D equivalent linear approach [19].

In the present research, the DEEPSOIL V6 software, a 1-D site response platform is utilized. The first process is to ascertain the crucial variables correspond to the features of the chosen earthquake motion. All the pre-decided variables and the distance from the fault line to the case study location are decided by empirical interrelationship [28]. Next, the ground characteristics of various stratum are attained from the soil boreholes log report. Subsequently, 5% damping consideration is implemented to every ground class, and dynamic characteristics for all the ground stratum [29]. Afterwards, the shear wave velocity or V_s of the ground strata are enumerated from the detailed SPT-N values utilizing the equation by [26].

Varying output data e.g., displacement, velocity, acceleration, stress, strain, amplification, Fourier and response spectra are obtained from 1-D equivalent linear analysis [30, 31]. The analyses stages in conducting site-specific ground response using DEEPSOIL software is shown in Figure 5.

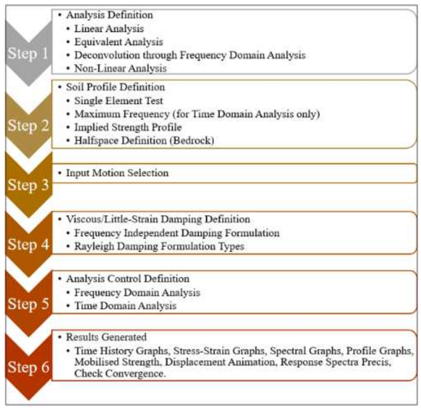

Fig. 5 Analysis Stages in DEEPSOIL Software [36]

E. LiqIT Software

LiqIT software is a software that assesses liquefaction potential and computes the settlement of soil based on dynamic powers. LiqIT software has been used to investigate the liquefaction potential in the district of Belaga. The SPT-N borehole data of the district, shown in Figure 3, has been used for the assessment of the factor of safety, liquefaction probability, and liquefaction potential index. The parameters of liquefaction were determined for each soil layer by adopting the methodology proposed in Idriss and Boulanger [32] using the software LiqIT. This factor of safety is characterized as the proportion of accessible soil resistance from liquefaction, i.e., the ratio of cyclic resistance ratio to the cyclic stress ratio as FS = CRR/CSR. Where CRR is the cyclic resistance ratio based on in–situ test data from SPT or CPT tests, and CSR is the cyclic stress ratio (earthquake load) prompted in the soil by seismic tremors.

TABLE IV
CLASSIFICATION OF THE PROBABILITY OF LIQUEFACTION BY [34]

CLASS	PROBABILITY OF LIQUEFACTION (P_L)	DESCRIPTION
1	$0.00 \le P_L < 0.15$	Practically sure that liquefaction won't happen
2	$0.15 \le P_L < 0.35$	Unlikely
3	$0.35 \le P_L < 0.65$	Liquefaction / non-liquefaction equally likely
4	$0.65 \le P_L < 0.85$	Very likely
5	$0.85 \le P_L < 1.00$	Almost certain liquefaction

The liquefaction potential index (LPI) evaluates the seriousness of phase transition of soil and consequent surface signs of this physical change, harming this phase change or potential failure of a liquefaction-inclined region [33]. The classification based on the probability of liquefaction by [34] is shown in Table 4.

III. RESULT AND DISCUSSION

A. Peak Ground Surface Acceleration

The results of peak surface acceleration for every borehole with respect to seven global and four local chosen input motions are acquired and tabulated in Table 5 and 6, respectively. The PGA values attained are between 0.108g (BH2 with GM11 or Tawau Earthquake) and 0.399g (BH1 with GM7 or Loma Gilroy Earthquake).

TABLE V
PGA FOR BH1 TO BH8 APPLYING 11 GROUND MOTIONS

Ground Motion (GM)	PGA Bed-rock (g)	Peak Surface Acceleration (PGA) in g							
		BH1	BH2	BH3	BH4	BH5	BH6	BH7	BH8
GM1	0.1	0.285	0.189	0.179	0.211	0.177	0.209	0.189	0.201
GM2	0.1	0.223	0.159	0.131	0.133	0.155	0.141	0.128	0.172
GM3	0.1	0.177	0.145	0.164	0.185	0.142	0.142	0.156	0.150
GM4	0.1	0.172	0.118	0.144	0.150	0.114	0.141	0.142	0.120
GM5	0.1	0.314	0.216	0.129	0.172	0.203	0.156	0.141	0.234
GM6	0.1	0.154	0.114	0.160	0.171	0.118	0.145	0.155	0.120
GM7	0.1	0.399	0.227	0.143	0.156	0.225	0.179	0.146	0.249
GM8	0.1	0.202	0.145	0.169	0.191	0.151	0.154	0.166	0.158
GM9	0.1	0.287	0.182	0.142	0.184	0.181	0.179	0.159	0.189
GM10	0.1	0.239	0.185	0.163	0.174	0.176	0.182	0.177	0.170
GM11	0.1	0.131	0.108	0.135	0.143	0.111	0.123	0.126	0.112

TABLE VI
PGA FOR BH9 TO BH15 APPLYING 11 GROUND MOTIONS

Ground Motion (GM)	PGA Bedrock (g)	Peak Surface Acceleration (PGA) in g						
		BH9	BH10	BH11	BH12	BH13	BH14	BH15
GM1	0.1	0.310	0.205	0.220	0.191	0.197	0.213	0.196
GM2	0.1	0.211	0.168	0.169	0.164	0.171	0.171	0.157
GM3	0.1	0.277	0.150	0.164	0.149	0.153	0.159	0.142
GM4	0.1	0.203	0.119	0.128	0.117	0.118	0.129	0.112
GM5	0.1	0.223	0.235	0.200	0.206	0.209	0.191	0.196
GM6	0.1	0.274	0.114	0.126	0.122	0.125	0.126	0.111
GM7	0.1	0.224	0.238	0.257	0.257	0.265	0.245	0.192
GM8	0.1	0.297	0.149	0.165	0.161	0.162	0.162	0.138
GM9	0.1	0.204	0.193	0.204	0.206	0.209	0.195	0.213
GM10	0.1	0.219	0.198	0.203	0.180	0.200	0.239	0.185
GM11	0.1	0.256	0.111	0.126	0.121	0.123	0.124	0.116

The ground response investigation provides finer earthquake amplification factors and prescribed design response spectrum to obtain realistic domestic ground data, in contrast to the simplified design response spectrum defined by EC 8. The average response spectrum utilizing global input motions are greater than the average response spectrum using local input motions for all soil types A, B, and C in Belaga District, Sarawak.

B. Amplification Factor

The soil surface amplification factors values obtained range from 2.45 (BH7 with GM8 Kuching Earthquake) to 5.15 (BH9 with GM10 or Kota Kinabalu Earthquake) as shown in Table 7 and 8, respectively.

TABLE VII
AMPLIFICATION FACTOR FOR BH1 TO BH8 APPLYING 11 GROUND MOTIONS

Ground Motion (GM)	PGA Bed-rock (g)	Amplification Factor							
		BH1	BH2	BH3	BH4	BH5	BH6	BH7	BH8
GM1	0.1	4.195	2.940	2.517	2.751	2.717	2.593	2.461	3.283
GM2	0.1	4.571	3.012	2.696	2.958	2.815	2.921	2.692	3.345
GM3	0.1	4.166	2.931	2.504	2.712	2.705	2.677	2.476	3.279
GM4	0.1	4.331	2.971	2.533	2.723	2.753	2.670	2.492	3.307
GM5	0.1	4.678	2.838	2.753	3.148	2.671	2.893	2.736	3.222
GM6	0.1	4.213	2.963	2.534	2.733	2.719	2.660	2.481	3.298
GM7	0.1	4.426	2.773	2.574	2.805	2.553	2.674	2.528	3.150
GM8	0.1	4.279	2.964	2.482	2.679	2.716	2.658	2.445	3.283
GM9	0.1	4.717	2.991	2.762	3.116	2.828	2.912	2.742	3.351
GM10	0.1	5.047	3.427	3.030	3.525	3.187	3.282	3.084	3.621
GM11	0.1	4.235	3.011	2.540	2.732	2.783	2.714	2.513	3.326

TABLE VIII
AMPLIFICATION FACTOR FOR BH9 TO BH15 APPLYING 11 GROUND MOTIONS

Ground Motion (GM)	PGA Bed-rock (g)	Amplification Factor						
		BH9	BH10	BH11	BH12	BH13	BH14	BH15
GM1	0.1	4.287	3.347	3.413	3.144	3.277	3.152	3.399
GM2	0.1	4.339	3.414	3.750	3.292	3.452	3.405	3.478
GM3	0.1	4.171	3.352	3.524	3.167	3.310	3.233	3.428
GM4	0.1	3.832	3.382	3.675	3.247	3.402	3.342	3.464
GM5	0.1	4.521	3.260	3.634	3.176	3.336	3.321	3.381
GM6	0.1	4.022	3.381	3.618	3.209	3.368	3.292	3.465
GM7	0.1	4.195	3.211	3.366	3.020	3.152	3.119	3.379
GM8	0.1	4.155	3.373	3.551	3.177	3.324	3.251	3.449
GM9	0.1	4.658	3.381	3.767	3.306	3.462	3.416	3.407
GM10	0.1	5.146	3.757	4.042	3.563	3.732	3.696	3.676
GM11	0.1	3.975	3.418	3.642	3.246	3.396	3.316	3.493

C. Response Spectra at Ground Surface

The average response spectrum for both local and global input motions implemented are determined from the plotted response spectra graph (PSA vs. Structural Period) for soil categories A, B, and C based on Figures 6, 7, and 8, respectively.

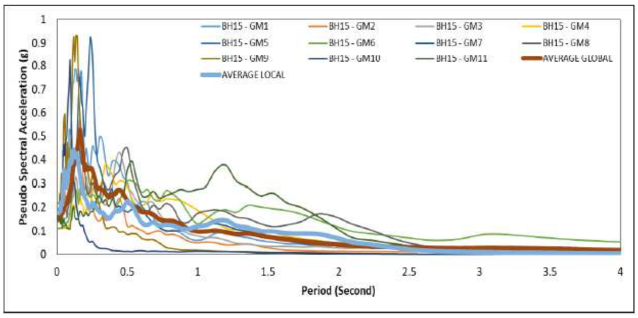

Fig. 6 Response Spectra at Surface for Soil Type A

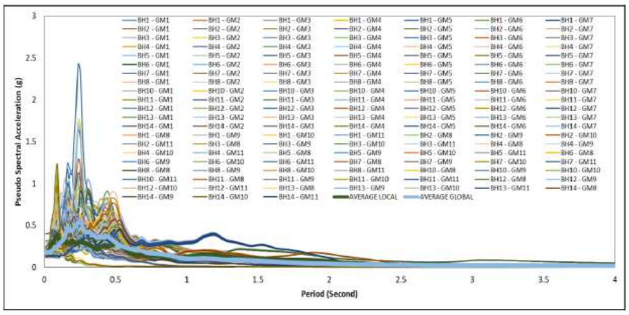

Fig. 7 Response Spectra at Surface for Soil Type B

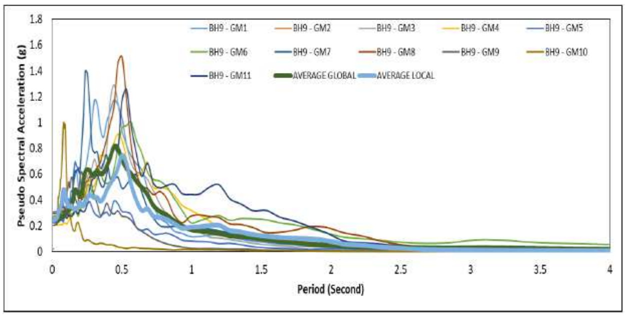

Fig. 8 Response Spectra at Surface for Soil Type C

The results show soil amplification at a lower soil period between 0.1s to 1s, which generally affects medium-rise structures. Dam body structures normally have a higher fundamental period, making them resilient to any seismic hazard expected in the Belaga District region.

D. Recommended Design Response Spectra

The recommended design response spectra, including the mean of both average local and global response spectra at 5% damping, from the ground response analyses for all soil types, are shown in Figures 9 to 11, respectively. The ground factor values for the Belaga District are shown in Table 9 and are compared with the target response spectra for the Sarawak region as per the recommendation of the Malaysia National Annex [14], as shown in Table 10. It can be seen that the soil factors from this study are higher compared to the recommended soil factors [14]. This is because of the different probability of exceedance used (i.e., 2% and 10% POE), which correspond to different return periods (i.e., 475 years and 2475 years). Furthermore, a site-specific study will give a specific soil response, which is normally higher than the code. This is like other studies found in the literature [24,35].

On the other hand, the spectra corner period, T_B, T_C, and T_D for each soil type from this research matched well with the recommended values given in the National Annex [14]. A study by [35] on the response spectra for Bakun HEP dam is also found to match well with the results obtained in this study. This is due to the low-frequency content of long-distance earthquakes, resulting in higher corner period values. The soil period in this region is between 0.05s and 1.3s, following the limit recommended in [14]. Based on the result of the response spectra for soil types A, B, and C, a maximum average of 0.25g peak ground acceleration (PGA) is expected to be the seismic hazard at the Belaga District for 2475 years return period. Hence, Bakun HEP Dam will remain safe if it could sustain a minimum of 0.25g PGA.

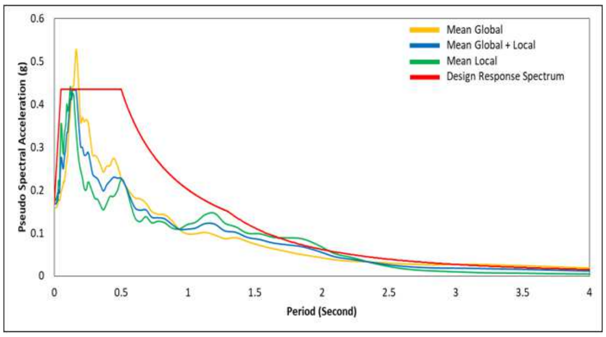

Fig. 9 Recommended Design Response Spectrum for Soil Type A

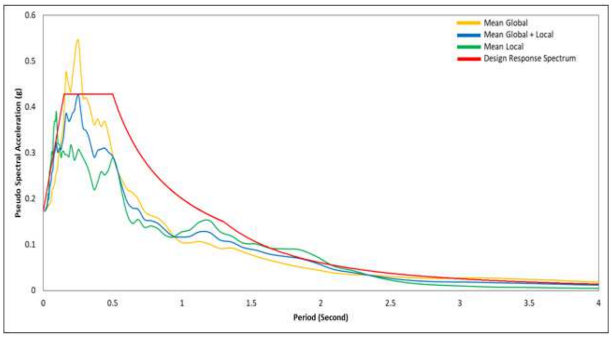

Fig. 10 Recommended Design Response Spectrum for Soil Type B

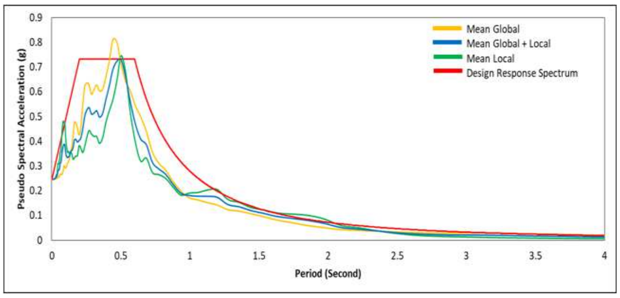

Fig. 11 Recommended Design Response Spectrum for Soil Type C

TABLE IX
GROUND FACTORS AND PERIOD LIMIT OBTAINED FOR BELAGA DISTRICT FOR 2% POE IN 2475 YEARS RETURN PERIOD

Ground Type	S	T_B (s)	T_C(s)	T_D(s)
A	2.6	0.05	0.50	1.30
B	2.5	0.15	0.50	1.30
C	3.0	0.20	0.60	1.20

TABLE X
GROUND FACTORS FOR SARAWAK BASED ON MALAYSIA NATIONAL ANNEX [14]

Ground Type	S	T_B (s)	T_C (s)	T_D (s)
A	1.0	0.05	0.50	1.20
B	1.2	0.15	0.50	1.20
C	1.3	0.20	0.50	1.20
D	1.35	0.20	0.50	1.20
E	1.4	0.15	0.50	1.20

E. Soil Liquefaction Assessment

Seismic soil liquefaction potential LPI is determined at 15 boreholes locations over the Belaga district. The primary parameter is the minimum safety factor (FS) against liquefaction, which the cyclic pressure approach assesses. A FS > 1 is considered as non-liquefiable, and a FS < 1 indicates that alluvium is liquefiable, while FS = 1 indicates the limiting equilibrium [32].

From the results, the majority of areas in the Belaga district are not affected by liquefaction, i.e., there is no potential for liquefaction or a low LPI, as shown in Table 10. The calculated minimum factor of safety for each borehole indicates that the overall probability of liquefaction in the Belaga district is low. Table 11 shows the detailed computation of LPI for BH1 for a peak ground acceleration of 0.10g corresponding to M_w=5.0 and 2% POE in 50 years, 2475 years return period seismic hazard.

TABLE XI
DETAILED COMPUTATION OF LPI OF BH1 IN BELAGA DISTRICT FOR PGA 0.10G CORRESPONDING TO MW = 5.0

Location	Depth	Unit wt.	SPT-N	amax (g)	σ_v	σ'_v	$(N_1)_{60}$	$(N_1)_{60cs}$	CRR	CSR	Fs	LPI
BH 1	1.5	10.5	1	0.1	15.75	10.85	1.22	5.70	0.00	0.06	1.44	0
	3	10.5	3	0.1	31.50	11.88	3.90	8.38	0.11	0.11	0.96	0.52
	4.5	19.5	14	0.1	60.75	26.41	19.95	24.43	0.28	0.09	2.96	0
	6	21	15	0.1	92.25	43.20	17.95	22.43	0.24	0.08	2.86	0
	7.5	21	21	0.1	123.75	59.98	21.60	26.08	0.32	0.08	4.08	0
	9	21	23	0.1	155.25	76.77	22.53	27.01	0.35	0.07	4.74	0
	10.5	21	40	0.1	186.75	93.56	36.18	40.66	2.00	0.07	5.00	0
	12	19.5	45	0.1	216	108.09	39.02	43.50	2.00	0.07	5.00	0
	13.5	19.5	50	0.1	245.25	122.63	41.98	46.46	2.00	0.07	5.00	0
	15	19.5	50	0.1	274.50	137.16	40.61	45.08	2.00	0.07	5.00	0

Where:
A_{max} = Peak ground acceleration
σ_v = Effective Overburden Stress Factor
σ'_v = Effective Overburden Pressure, during earthquake
$(N_1)_{60}$ = Corrected SPT-N
$(N_1)_{60cs}$ = Corrected $(N_1)_{60}$ value for fines
CRR = Cyclic Resistance Ratio
CSR = Cyclic Stress Ratio
Fs = Factor of Safety
LPI = Liquefaction Potential Index

TABLE XII
FACTOR OF SAFETY, LIQUEFACTION PROBABILITY INDEX AND SETTLEMENT FOR 15 BOREHOLES

BH	MinFOS	LPI	Settlement (mm)	Description
BH1	0.96	0.52	5.98	Liquefaction Not Probable
BH2	5	0	0	No Liquefaction
BH3	2.89	0	0	No Liquefaction
BH4	1.91	0	0	No Liquefaction
BH5	3.03	0	0	No Liquefaction
BH6	2.52	0	0	No Liquefaction
BH7	2.84	0	0	No Liquefaction
BH8	3.46	0	0	No Liquefaction
BH9	0.80	4.91	16.82	Liquefaction Not Probable
BH10	4.45	0	0	No Liquefaction
BH11	2.22	0	0	No Liquefaction
BH12	2.83	0	0	No Liquefaction
BH13	2.52	0	0	No Liquefaction
BH14	2.03	0	0	No Liquefaction
BH15	2.83	0	0	No Liquefaction

The results of this study indicate that soil liquefaction is unlikely. However, some repercussions are likely to result from a seismic event, e.g., ground settlement. For instance, from Table 12, the largest ground settlement of 16.82 mm will transpire at BH 9, which is fortunately situated at a safe distance from Bakun Hydroelectric Dam. The soil liquefaction assessment in this research is based on extensive efforts to evaluate the local earthquake threat in the Belaga district, Sarawak. The study results will form the foundation for deciding on the need for any mitigation measures to be enforced in the future.

IV. CONCLUSION

In this study, the evaluation of the flexibility of the soil of the Belaga District, Sarawak, where the largest Bakun HEP Dam in East Malaysia is located, was carried out. This study utilized global and local earthquake records to evaluate the site-specific seismic hazard using a 1-D equivalent linear analysis. Soil liquefaction hazard was also assessed based on SPT data from 15 boreholes using Idriss and Boulanger approach. LiqIT software was used to evaluate parameters, including the factor of safety against liquefaction (FS), liquefaction probability (P_L), and potential liquefaction index (LPI).

The ground amplification for the Belaga District, Sarawak was found to be between 2.45 and 5.15 while, the PGA at ground surface range from 0.11g to 0.39g, this gives an average of 0.25g PGA for 2% POE in 50 years, corresponding to a 2475-year return period. The corner period limit of the design response spectra for the soil categories are category A (S = 2.6, T_B = 0.05s, T_C = 0.5s & T_D = 1.3s), category B (S = 2.5, T_B = 0.15s, T_C = 0.5s & T_D = 1.3 seconds) and category C (S = 3.0, T_B = 0.20s, T_C = 0.6s & T_D = 1.2 s). These results are found to match with the recommended values in the Malaysia National Annex for Sarawak region. Hence, the period corresponding to the maximum amplification coincides with the calculated period of the soil in the Belaga district. This fact shows that medium-rise structures (5 to 10 stories) need to be designed with seismic loads, whereas dam structures are considered safer due to having a higher fundamental period. The potential for soil liquefaction was found to be incredibly low. Hence the existing Bakun HEP

Dam is considered safe from any ground settlement caused by soil liquefaction.

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