INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN SOCIAL SCIENCE (IJRISS)
ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

Site-Specific Surface PGA Assessment Via Site Response Analysis for the SOGIP Area, Sipitang, Sabah

Amy Natasha Norhuda[1]* , Ahmad Safuan A Rashid[2] , Afiqah Ismail[2] , Reguel Mikhail[3]

[1]Khalifa Consult Sdn Bhd, 53300 Kuala Lumpur, Malaysia. Student, Doctor of Professional Practice (DPP), Universiti Teknologi Malaysia, Civil Engineering Faculty, 81310 Skudai, Johor, Malaysia.

[2]Universiti Teknologi Malaysia, Civil Engineering Faculty, 81310 Skudai, Johor, Malaysia.

[3]PhD Student, Nanyang Technological University (NTU), Nanyang Ave, 639798, Singapore.

DOI: https://doi.org/10.47772/IJRISS.2026.100600996

Received : 11 June 2026 ; Accepted : 16 June 2026 ; Published: 10 July 2026

ABSTRACT

This paper presents a site-specific assessment of Surface Peak Ground Acceleration (PGA) for the Sabah Oil and Gas Industrial Park (SOGIP) located in Sipitang, Sabah, Malaysia, motivated by increasing seismic activity in the region and the limitations of regional-scale seismic hazard maps in representing local ground conditions for critical infrastructure. Regional PGA estimates commonly assume uniform subsurface conditions and may therefore underestimate or overestimate seismic demand at specific sites, underscoring the need for localised evaluation that accounts for geological and geotechnical variability. The study uses subsurface data from 23 boreholes distributed across the project area, with borehole logs interpreted to establish stratigraphic profiles and engineering soil properties influencing seismic wave propagation. Site classification was carried out in accordance with MS EN 1998-1:2015 (Malaysia National Annex to Eurocode 8) to determine soil categories and associated amplification characteristics. Equivalent-linear seismic site-response analyses were subsequently performed using DEEPSOIL to model ground-motion amplification from bedrock to the ground surface under varying seismic input motions. Prior to spatial averaging based on borehole cluster locations, the computed results indicate that surface PGA values range from 0.0137g to 0.0552g when adopting a reference bedrock PGA of 0.02g. For higher reference, bedrock PGA values of 0.03g, including rationalised inputs of 0.027g and 0.031g, yield surface PGA values between 0.0153g and 0.0821g. These calculated values exceed the existing regional seismic hazard map for Sipitang, which indicates bedrock PGA values of approximately 0.010g–0.020g for a 475-year return period, demonstrating significant local site amplification effects governed by subsurface conditions. The findings emphasise the importance of conducting site-specific seismic hazard assessments for major industrial developments to improve seismic design parameters, support disaster risk mitigation strategies, and enhance structural resilience in rapidly developing seismic-prone of Sabah.

Keywords: Site response analysis, Surface PGA, Seismic hazard, SOGIP, Sipitang, Sabah, Borehole data, Ground motion amplification.

INTRODUCTION

Malaysia is generally considered a region of low to moderate seismicity; however, the state of Sabah in East Malaysia is recognised as the country's most seismically active region. The seismotectonic framework of Sabah is heavily influenced by the complex active plate boundaries of Southeast Asia, particularly the interactions among the Eurasian, Philippine Sea, and Indo-Australian plates (Hutchings & Mooney, 2021). Furthermore, regional seismicity is driven by nearby subduction zones, such as the Sulu and Celebes Sea trenches, as well as an intricate network of local active faults. Tongkul (2021) highlighted that active fault lines in Sabah significantly elevate the local earthquake risk, emphasising that historical seismic events in the region are primarily of tectonic origin rather than mere tremors radiating from distant neighbouring countries.

Historically, structural design in Malaysia largely omitted seismic provisions due to a perceived lack of significant threat. Early global and regional Probabilistic Seismic Hazard Analyses (PSHA) classified Malaysia as a low-hazard zone (Giardini et al., 2003; Petersen et al., 2007; 2008). However, subsequent localised studies by Adnan et al. (2008) demonstrated that local active faults in East Malaysia could generate substantial ground motions, prompting a paradigm shift in the nation's engineering practices. This evolution culminated in the publication of the Malaysia National Annex to Eurocode 8 (MS EN 1998-1:2015), which formalised baseline bedrock Peak Ground Acceleration (PGA) values for seismic design. Recent literature has continued to refine these baseline hazard estimates. For instance, Adnan (2022) and Harith et al. (2025) incorporated local active fault systems, such as the Kuala Penyu fault, into their seismic hazard models, updating bedrock PGA estimates for the Sipitang region to between 0.027g and 0.031g.

While these updated regional models represent a major advancement in characterising baseline bedrock hazards, they fundamentally assume uniform reference rock outcrops. Peak Ground Acceleration (PGA), a critical parameter in geotechnical engineering used to evaluate foundation loading, assess site response, and estimate liquefaction risk, can be profoundly altered by overlying soil deposits. It is a well-established geotechnical principle that soft, cohesive soils, such as marine clays and loose silts, can severely amplify low-frequency ground motions due to impedance contrasts between the soil and the underlying bedrock (Idriss, 1990; Dobry et al., 2000). As seismic waves transition from stiff bedrock into softer surface layers, they decelerate and increase in amplitude to conserve energy, leading to significantly higher surface PGAs than those recorded at the bedrock level. Consequently, relying solely on regional-scale bedrock maps can severely underestimate the actual surface seismic demand.

Despite improvements in Malaysia's regional hazard mapping, there remains a critical shortage of site-specific micro-zonation studies that utilise rigorous 1D equivalent-linear site response analyses in East Malaysia. This gap is particularly concerning for critical infrastructures situated on highly variable coastal and reclaimed marine deposits.

One such critical facility is the Sabah Oil and Gas Industrial Park (SOGIP), located in the Sipitang district, approximately 150 km south of Kota Kinabalu (SOGDC-SOGIP, 2022). As the first integrated industrial park specifically designated for oil, gas, and heavy industries in Sabah, SOGIP spans 5,539 acres in a sheltered area of Brunei Bay (Figure 1). Given its extensive development investments, critical assets, and proximity to major global shipping lanes like the Asian Supply Base in Labuan, effective structural design is paramount.

Currently, the SOGIP industrial complex lacks the detailed, site-specific seismic data necessary to capture local soil and geological variations, posing risks of over- or under-designing critical infrastructure. To address this urgent research gap, this study focuses on conducting a site-specific soil response seismic hazard assessment for the SOGIP area. By integrating comprehensive borehole data with the established bedrock PGA from MS EN 1998-1:2015 (2017), this study employs an overarching data analytics approach to evaluate the attenuation and amplification of seismic wave propagation from bedrock to the surface.

The primary objective is to develop localised, borehole-derived surface PGA spectra, soil amplification factors, and site periods. Ultimately, this micro-zonation assessment will provide engineers and urban planners with the critical, high-resolution inputs required to design safe and resilient infrastructure against earthquake hazards in the Sipitang region.

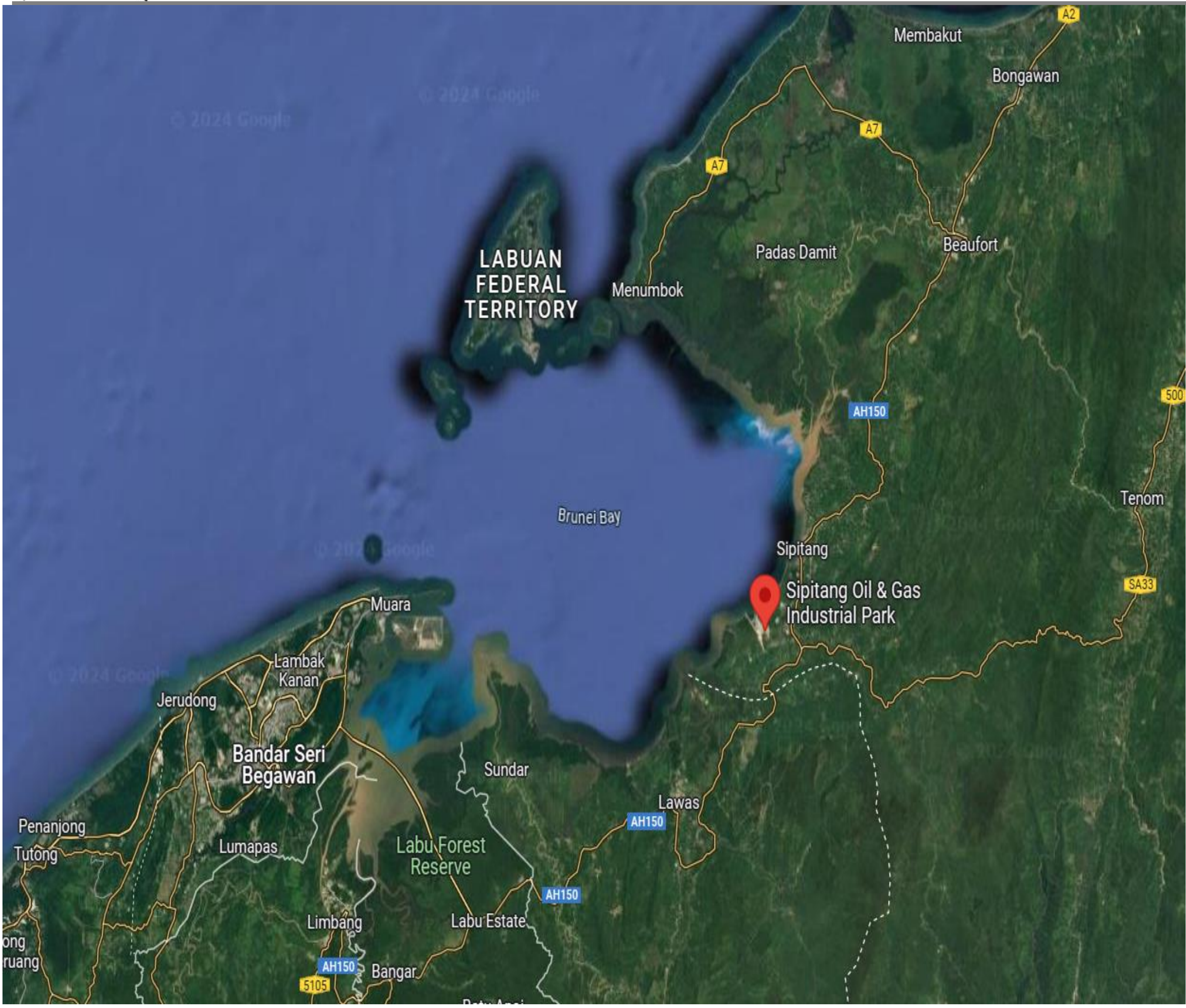

Figure 1. Location of SOGIP on Google Map

Problem Identification

Problem Statement

The Sabah Oil and Gas Industrial Park (SOGIP) serves as a critical catalyst for Malaysia's industrial and economic expansion. Given its proximity to active seismotectonic sources, ensuring the seismic resilience of its infrastructure is of paramount importance. Currently, however, seismic hazard assessments for the region rely heavily on generalised regional bedrock models. These macro-level models fundamentally fail to account for the unique, highly variable marine and alluvial soil deposits present at the SOGIP site.

By overlooking critical site-specific factors such as local soil amplification, stratigraphic resonance, and impedance contrasts, regional predictions introduce significant uncertainty into the structural design process. The absence of localised surface Peak Ground Acceleration (PGA) data risks both the under-design (compromising safety) and over-design (compromising economic feasibility) of critical industrial facilities. Ultimately, this lack of high-resolution seismic data limits engineers' ability to apply cost-effective, performance-based design measures. Therefore, a rigorous, site-specific surface PGA assessment utilising localised geotechnical, seismological, and geological data is essential to guarantee the long-term sustainability and structural integrity of the SOGIP development.

To bridge this critical research gap, a robust analytical framework is required to systematically integrate extensive geotechnical borehole records, geological profiles, and regional seismological data. By employing computational ground motion modelling and systematic data processing, this study transforms raw subsurface data into actionable engineering insights. This integrated approach enables the creation of highly localised micro-zonation maps and accurate predictions of localised seismic responses, providing a quantitative baseline for reliable infrastructure planning in complex geological settings.

Objectives Of The Research

To address identified gaps in localised seismic hazard data, this research aims to conduct a comprehensive, site-specific seismic ground response assessment for the SOGIP development area. Specifically, this study sets out to achieve the following objectives:

i. To characterise and classify the localised subsurface stratigraphy and dynamic soil properties (Vs) of the SOGIP site using extensive borehole data.

ii. To derive site-specific surface Peak Ground Acceleration (PGA) spectra and localised soil amplification factors by executing 1D equivalent-linear ground response analyses.

iii. To evaluate the adequacy of the regional Malaysian Seismic Hazard Map (2017) against localised site effects and formulate data-driven recommendations for resilient structural design.

LITERATURE REVIEW

Seismic Hazard in Sabah

Sabah is considered the most seismically active region in Malaysia due to its proximity to regional tectonic activities surrounding the Philippine Plate, Eurasian Plate, and Sunda Plate. Historical earthquake records indicate that Sabah has experienced several moderate earthquakes over the years. The 2015 Ranau earthquake with a magnitude of 6.0 caused structural damage, landslides, and casualties, demonstrating the vulnerability of infrastructure in the region. Previous studies have shown that local geological and soil conditions play an important role in modifying seismic ground motions. Areas with soft alluvial deposits may experience greater amplification effects compared to areas with shallow bedrock conditions.

Peak Ground Acceleration (PGA)

Peak Ground Acceleration (PGA) represents the maximum acceleration experienced by the ground during an earthquake event. PGA is commonly used in seismic hazard assessment and earthquake-resistant structural design.

The relationship between acceleration and seismic force can be simplified as:

$$F = ma$$

where:

F = seismic force

m = structural mass

a = ground acceleration

Higher PGA values generally result in larger seismic forces acting on structures.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

Site Response Analysis

Site response analysis is a method used to evaluate the effect of local soil conditions on earthquake ground motion propagation from bedrock to the ground surface. The analysis is commonly performed using one-dimensional equivalent linear or nonlinear approaches.

The equivalent linear method is widely applied in geotechnical earthquake engineering because it provides a practical balance between computational efficiency and acceptable engineering accuracy. The analysis considers soil dynamic properties such as shear modulus reduction and damping ratio under cyclic loading conditions.

The basic concept of site response analysis can be represented by:

$$\text{Surface PGA} = S \times a_g$$

where:

Surface PGA	= Surface peak ground acceleration
S	= Site amplification factor
a_g	= Bedrock peak ground acceleration

The soil amplification factor depends on soil stiffness, layering, and seismic input motion characteristics.

Previous Studies on Sabah Seismic Assessment

Several researchers have conducted seismic hazard studies in Sabah using probabilistic seismic hazard assessment (PSHA), microzonation studies, and site response analysis. Most studies indicate that local soil amplification significantly affects surface ground motion parameters.

However, limited published studies are available specifically for the SOGIP area in Sipitang. Therefore, this study provides additional contribution by focusing on site-specific surface PGA assessment using actual borehole data from the industrial development area.

METHODOLOGY

Borehole Data Collection

To construct a robust and representative geotechnical model of the SOGIP site, comprehensive subsurface investigation records were compiled and analysed. The primary dataset comprises 23 strategically distributed geotechnical boreholes, carefully selected to capture the site's local geology's spatial variability and complex stratigraphy. To ensure holistic coverage of the industrial park's diverse topography and planned infrastructure, the boreholes are categorised into three distinct operational zones: 8 along the proposed onshore pipeline route, 8 within the primary onshore facility footprint, and 7 in the nearshore marine environment. This wide spatial distribution is particularly critical for capturing the geotechnical transition from terrestrial alluvial deposits to deep, soft marine clays. The depth of exploration for these boreholes varied across the site, primarily dictated by the localised depth required to reach a competent stratum or engineering bedrock. Identifying this competent layer is a fundamental prerequisite for establishing the seismic boundary conditions and input motion depths for the subsequent 1D equivalent-linear ground response analysis.

From the detailed borehole logs, essential geotechnical and geological parameters were systematically extracted for each soil stratum. The in-situ field data incorporated into the model included continuous soil classification and stratigraphy, Standard Penetration Test (SPT-N) blow counts recorded at regular depth intervals, and the stabilised elevation of the groundwater table. Furthermore, to accurately characterize the physical and index properties of the soil which directly influence strain-dependent dynamic soil behavior, such as modulus degradation and damping, extensive laboratory test results were integrated. These laboratory parameters included natural moisture content, bulk unit weight, and Atterberg limits (Liquid Limit and Plastic Limit) to properly classify cohesive layers. The spatial distribution and zoning of all 23 boreholes utilized in this assessment are illustrated in Figure 2.

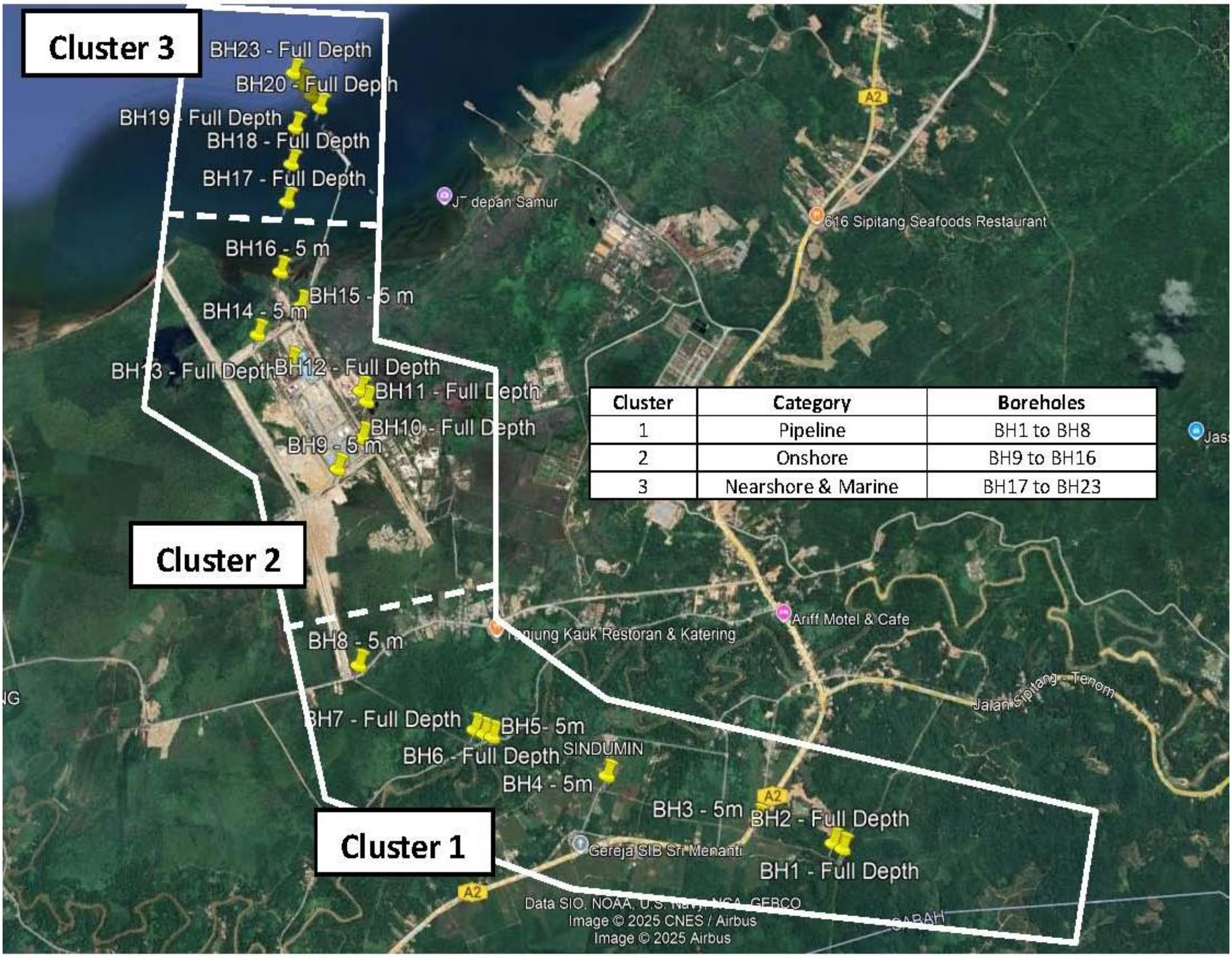

Figure 2. Borehole locations in the SOGIP area in Sipitang, Sabah (BH1 – BH23)

Site Classification

In accordance with the Malaysian National Annex to Eurocode 8 (MS EN 1998-1:2015), the local site conditions were classified based on the geotechnical properties of the uppermost 30 meters of the subsurface profile. In the absence of direct geophysical measurements for the time-averaged shear wave velocity (V_s), the standard permits the use of the equivalent Standard Penetration Test blow count $N_{SPT,30}$ as a reliable empirical proxy for determining the seismic Ground Type.

To determine this parameter, the average SPT-N value over the upper 30 meters $N_{SPT,30}$ was calculated using a depth-weighted harmonic mean. This methodology strictly adopts the same mathematical formulation utilised to calculate $V_{s.}$ Specifically, the total depth of 30 meters is divided by the sum of the ratios of each individual soil layer's thickness (h_i) to its corresponding field SPT-N value (N_i). This rigorous classification framework was systematically applied to the extensive dataset of all 23 boreholes across the SOGIP site. By evaluating the stratigraphic profile, the presence of soft cohesive layers, and the computed $N_{SPT,30}$ values, each borehole location was assigned a specific seismic Ground Type to establish the appropriate site amplification baseline. The detailed stratigraphic parameters, calculated $N_{SPT,30}$ values, and the resulting Eurocode 8 site classifications for the

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

onshore pipeline, onshore facility, and marine zones are comprehensively summarised in Tables 1, 2, and 3, respectively.

Table 1. Soil classification based on MS ES 1998-1:2015 for Cluster 1

Depth 1 (m)	Depth 2 (m)	BH1 (SPT-N)	BH2 (SPT-N)	BH3 (SPT-N)	BH4 (SPT-N)	BH5 (SPT-N)	BH6 (SPT-N)	BH7 (SPT-N)	BH8 (SPT-N)
0.0	1.5	13	4	8	9	20	2	30	0.1
1.5	3.0	13	4	8	9	20	3	50	0.1
3.0	4.5	19	8	2	4	25	4	50	2
4.5	6.0	22	10	0.1	3	30	7	50	2
6.0	7.5	50	50	0.1	2	50	9	50	2
7.5	9.0	50	50	2	4	50	12	50	4
9.0	10.5	50	50	3	5	50	15	50	6
10.5	12.0	50	50	4	6	50	19	50	8
12.0	13.5	50	50	5	7	50	20	2	10
13.5	15.0	50	50	6	8	50	22	8	12
15.0	16.5	50	50	7	9	50	10	14	14
16.5	18.0	50	50	8	10	50	13	17	16
18.0	19.5	50	50	9	11	50	27	22	18
19.5	21.0	50	50	15	19	50	34	24	20
21.0	22.5	50	50	20	20	50	14	29	25
22.5	24.0	50	50	25	21	50	18	30	30
24.0	25.5	50	50	30	22	50	16	34	35
25.5	27.0	50	50	35	23	50	20	38	40
27.0	28.5	50	50	40	24	50	21	44	45
28.5	30.0	50	50	50	25	50	17	50	50
Remarks		Deep BH	Deep BH	Shallow BH	Shallow BH	Shallow BH	Deep BH	Deep BH	Shallow BH
Average SPT-N for 30m depth of Soil		34.97	19.14	0.88	7.11	40.54	8.99	16.92	0.88
Ground Type EC8		C	C	D	D	C	D	C	D
Soil Profile Type UBC97		SD	SD	SE	SE	SE	SE	SD	SE
(Note:		Denotes no SPT-N data from borelogs, thus used assumed values)							

Table 2. Soil classification based on MS ES 1998-1:2015 for Cluster 2

Depth 1 (m)	Depth 2 (m)	BH9 (SPT-N)	BH10 (SPT-N)	BH11 (SPT-N)	BH12 (SPT-N)	BH13 (SPT-N)	BH14 (SPT-N)	BH15 (SPT-N)	BH16 (SPT-N)
0.0	1.5	22	1	10	10	3	8	8	40
1.5	3.0	22	1	46	21	4	50	10	45
3.0	4.5	13	2	50	50	5	50	50	45
4.5	6.0	2	3	50	50	6	11	29	50
6.0	7.5	3	4	50	50	6	34	44	55
7.5	9.0	4	6	5	8	6	34	44	60
9.0	10.5	6	13	8	2	6	34	44	60
10.5	12.0	8	18	13	13	6	34	44	60
12.0	13.5	10	20	14	12	8	34	44	60
13.5	15.0	12	17	16	13	9	34	44	60
15.0	16.5	14	24	17	13	11	34	44	60
16.5	18.0	16	31	22	8	17	34	44	60
18.0	19.5	18	38	24	14	21	34	44	60
19.5	21.0	20	42	23	13	23	40	45	60
21.0	22.5	25	36	26	16	26	40	45	60
22.5	24.0	30	43	29	19	30	40	45	60
24.0	25.5	35	50	33	22	35	45	45	60
25.5	27.0	40	50	32	50	42	45	50	60
27.0	28.5	45	50	37	50	46	50	50	60
28.5	30.0	50	50	39	50	50	50	50	60
Remarks		Shallow BH	Deep BH	Deep BH	Deep BH	Deep BH	Shallow BH	Shallow BH	Shallow BH
Average SPT-N for 30m depth of Soil		9.37	5.34	18.28	12.19	8.85	29.41	31.60	55.92
Ground Type EC8		D	D	C	D	D	C	C	B
Soil Profile Type UBC97		SE	SE	SD	SE	SE	SD	SD	SD
(Note:		Denotes no SPT-N data from borelogs, thus used assumed values)							

Table 3. Soil classification based on MS ES 1998-1:2015 for Cluster 3

Depth 1 (m)	Depth 2 (m)	BH17 (SPT-N)	BH18 (SPT-N)	BH19 (SPT-N)	BH20 (SPT-N)	BH21 (SPT-N)	BH22 (SPT-N)	BH23 (SPT-N)
0.0	1.5	1	0.1	0.1	0.1	0.1	0.1	0.1
1.5	3.0	2	0.1	0.1	0.1	0.1	0.1	0.1
3.0	4.5	3	0.1	0.1	0.1	0.1	0.1	0.1
4.5	6.0	3	0.1	0.1	0.1	0.1	0.1	0.1
6.0	7.5	4	0.1	0.1	1	0.1	0.1	1
7.5	9.0	5	0.1	0.1	1	0.1	0.1	1
9.0	10.5	4	0.1	0.1	2	0.1	0.1	2
10.5	12.0	6	0.1	0.1	1	0.1	0.1	1
12.0	13.5	7	0.1	0.1	1	0.1	0.1	1
13.5	15.0	6	0.1	1	2	1	0.1	2
15.0	16.5	8	2	2	1	1	1	1
16.5	18.0	6	3	3	2	4	1	2
18.0	19.5	7	3	3	2	5	3	2
19.5	21.0	7	4	4	3	9	2	3
21.0	22.5	6	5	5	3	11	9	3
22.5	24.0	9	7	3	2	14	11	2
24.0	25.5	10	8	6	3	15	14	3
25.5	27.0	9	6	5	4	17	18	4
27.0	28.5	11	7	7	2	19	17	2
28.5	30.0	9	12	10	5	21	20	5
Remarks		Deep BH	Deep BH	Deep BH	Deep BH	Deep BH	Deep BH	Deep BH
Average SPT-N for 30m depth of Soil		**4.34**	**0.20**	**0.21**	**0.40**	**0.22**	**0.19**	**0.40**
Ground Type EC8		**D**	**D**	**D**	**D**	**D**	**D**	**D**
Soil Profile Type UBC97		**SE**	**SE**	**SE**	**SE**	**SE**	**SE**	**SE**

(Note: [yellow] Denotes no SPT-N data from borelogs, thus used assumed values)

Soil Parameters Input

Soil parameters used in the site response analysis were derived from 23 borehole logs and laboratory test data across the SOGIP area in Sipitang, Sabah. Key parameters include unit weight, shear-wave velocity (Vs), damping ratio, and modulus-reduction curves. These parameters were essential for modelling the dynamic behaviour of subsoil layers under earthquake loading.

Standard Penetration Test (SPT) values were used to estimate shear wave velocity when direct measurements were unavailable, using well-established empirical correlations appropriate for local soil conditions. Laboratory tests such as Atterberg limits, grain size distribution (sieve and hydrometer), and oedometer tests provided information on soil classification, compressibility, and consistency. Strain-dependent damping ratios and shear modulus degradation curves were assigned based on soil classification, utilising the classical models of Seed and Idriss (1970) for granular soils and Vucetic and Dobry (1991) for cohesive soils. Although more recent pressure-dependent models exist in the literature, the Vucetic and Dobry (1991) curves were explicitly adopted because they remain a highly robust and industry-standard method for capturing the plasticity-dependent nonlinear behaviour of the distinct cohesive marine clays present at the SOGIP site. These established curves provide a conservative and widely validated baseline for the equivalent-linear site response modelling utilised in this study.

The soil profile was simplified into representative layers for each borehole, and dynamic properties were assigned accordingly. These inputs formed the basis for a one-dimensional equivalent-linear analysis using software such as DEEPSOIL. **Tables 4, 5**, and **6** are examples of summarising the soil input parameters prepared for this research project.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

Table 4. Example of soil parameters input for soil response analysis

DEEPSOIL Software Data Input - 1D Equivalent Linear and Nonlinear Site Response Analyses Platform							
Project Loc:	**SOGIP, Sipitang, Sabah**						
BH:	**13 (Onshore)**						
RL:	**14.309m LSD**						
Water Level:	**4.2m below GL**						
Generalized Soil Layer Number	**Soil Layers**	**Depth 1 (m)**	**Depth 2 (m)**	**Thickness (m)**	**SPT-N Results**	**Unit Weight, (kN/m^3)**	**Location of Water Table**
1	Coarse grained SAND with gravels	0.00	0.80	0.80	6.0	16.00	-
2	Moderately weathered SANDSTONE	0.80	11.00	10.20	10.0	20.00	W
3	Firm CLAY	11.00	13.00	2.00	6.0	17.00	W
4	Firm to stiff SILT CLAY	13.00	15.00	2.00	8.0	20.10	W
5	Stiff CLAY	15.00	17.80	2.80	11.0	18.00	W
6	Very stiff CLAY	17.80	24.30	6.50	26.0	19.00	W
7	Hard CLAY	24.30	39.45	15.15	50.0	20.00	W
8	Assumed Soil to Bedrock depth (CLAY)	-	-	10.00	60.0	21.00	W
				49.45			
9	Assumed Bedrock			**0.00**		24.00	
(Note:		Denotes no SPT-N and other data from SI Report, thus used assumed or calculated values)					

Table 5. Example of soil parameters input for soil response analysis (continued)

DEEPSOIL Software Data Input - 1D Equivalent Linear and Nonlinear Site Response Analyses Platform					
Project Loc:	**SOGIP, Sipitang, Sabah**				
BH:	**13 (Onshore)**				
RL:	**14.309m LSD**				
Water Level:	**4.2m below GL**				
Generalized Soil Layer Number	**Soil Layers**	**Shear Wave Velocity (Imai & Tonouchi 1982) (m/s)**	**Shear Wave Velocity (Hasancebi & Ulusay, 2006) (m/s)**	**Shear Wave Velocity (Maheshwari, 2009) (m/s)**	**Average Shear Wave Velocity, V_s (m/s)**
1	Coarse grained SAND with gravels	170.08	156.56	164.01	163.55
2	Moderately weathered SANDSTONE	199.68	183.33	191.27	191.43
3	Firm CLAY	170.08	156.56	164.01	163.55
4	Firm to stiff SILT CLAY	186.16	171.12	178.84	178.71
5	Stiff CLAY	205.74	188.81	196.83	197.13
6	Very stiff CLAY	269.54	246.30	255.00	256.95
7	Hard CLAY	330.98	301.46	310.48	314.30
8	Assumed Soil to Bedrock depth (CLAY)	-	-	-	560.00
9	Assumed Bedrock				1130.00
(Note:		Denotes no SPT-N and other data from SI Report, thus used assumed or calculated values)			

Table 6. Example of soil parameters input for soil response analysis (continued)

DEEPSOIL Software Data Input - 1D Equivalent Linear and Nonlinear Site Response Analyses Platform							
Project Loc:	**SOGIP, Sipitang, Sabah**						
BH:	**13 (Onshore)**						
RL:	**14.309m LSD**						
Water Level:	**4.2m below GL**						
Generalized Soil Layer Number	**Soil Layers**	**Max Shear Modulus, G_s (kN/m^2)**	**Effective Stress at Bottom (kN/m^2)**	**Shear Strength (5 x N or σ' x Tan Φ) (kN/m^2)**	**PI (%)**	**Assumed or Calculated OCR (Pc'/σ')**	**Calculated K_0**
1	Coarse grained SAND with gravels	43627.55	12.80	8.96	-	1.00	0.53
2	Moderately weathered SANDSTONE	74706.64	150.09	86.66	-	1.00	0.50
3	Firm CLAY	46354.27	164.47	30.00	31	2.30	0.62
4	Firm to stiff SILT CLAY	65435.74	185.05	40.00	31	2.59	0.62
5	Stiff CLAY	71302.68	207.98	55.00	49	2.97	0.64
6	Very stiff CLAY	127873.17	267.72	130.00	35.0	4.52	0.65
7	Hard CLAY	201400.72	421.61	250.00	32.0	5.18	0.62
8	Assumed Soil to Bedrock depth (CLAY)	671314.98	534.00	431.71	15	4.99	0.51
9	Assumed Bedrock	3123914.37					
(Note:		Denotes no SPT-N and other data from SI Report, thus used assumed or calculated values)					

Input Ground Motions

A minimum of three (3) input ground motions were selected to generate the site-specific soil response from the bedrock. These include records from the 1995 Kobe, 1999 Chi-Chi, and 1999 Kocaeli earthquakes. These specific ground motion records were strategically selected because their seismological parameters, including magnitude (7.4 to 7.6), shallow crustal fault mechanisms, and rich frequency content, serve as highly appropriate proxies for the seismic hazard scenarios threatening Sabah. Furthermore, these records feature long, significant durations capable of mobilising the nonlinear behaviour and strain-dependent damping of the soft clay and marine deposits found at the SOGIP site. The selected motions were scaled to match the target bedrock peak ground acceleration (PGA) values based on two references: (i) MS EN 1998-1:2015/2017, with a target PGA of 0.02g, and (ii) combined findings from recent studies by Adnan (2022), who reported a PGA of 0.031g for a FEED project in Sipitang, and Harith *et al.* (2025), who presented a PGA of 0.027g in her latest journal publication.

Therefore, for this study, two target PGA values at the bedrock of **0.02g** and **0.03g** were adopted to conduct the soil response analysis. Refer to **Fig. 3** for the scaled input acceleration time history for types of earthquake input motions.

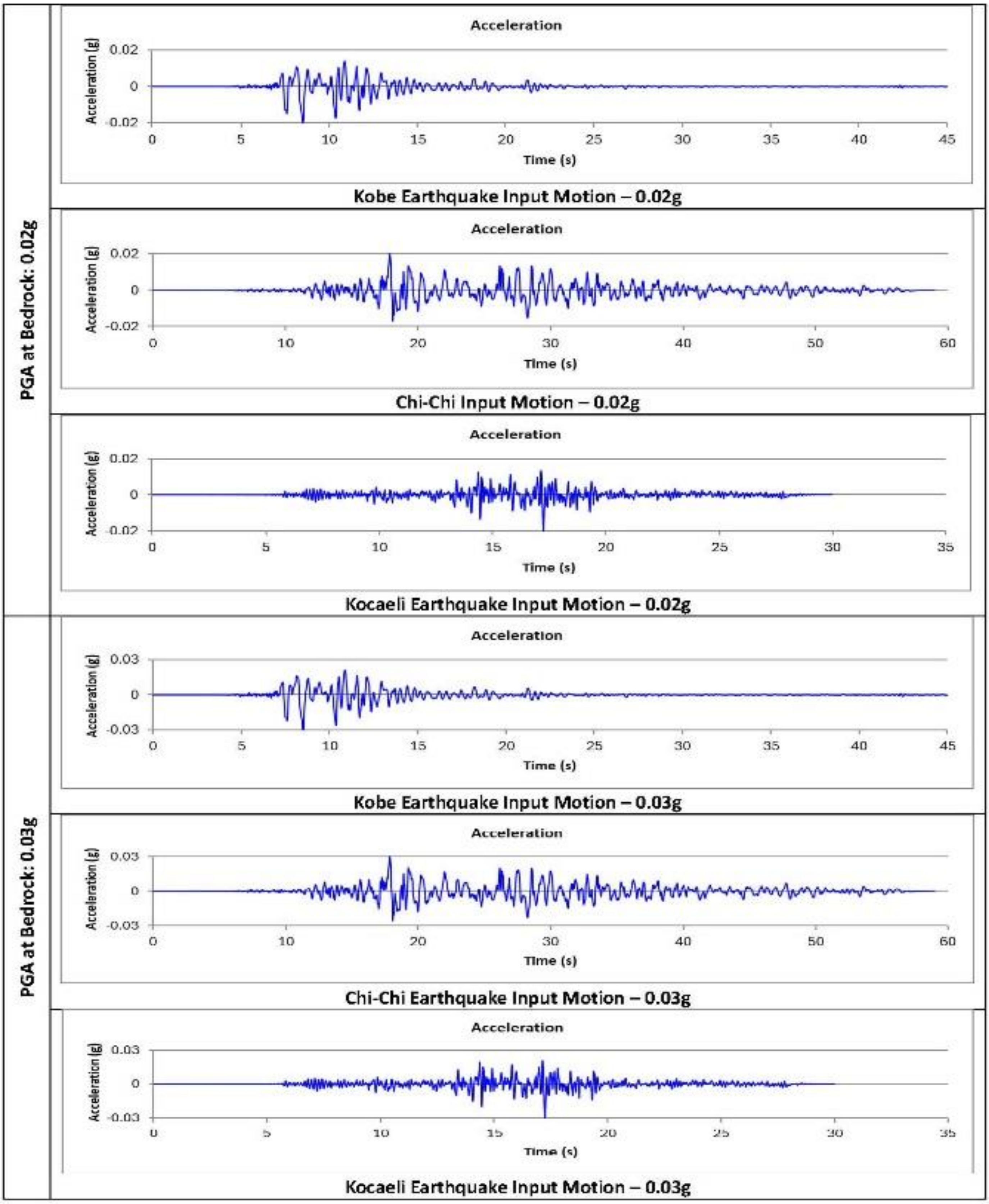

Fig. 3. Example of scaled input acceleration time history

Site Response Analysis

DEEPSOIL v7.0 was used for equivalent-linear 1D site response analysis. Input motions were applied at the base rock interface, and surface acceleration time histories were recorded. The surface PGA was extracted as the peak output acceleration.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue VI June 2026

RESULTS AND DISCUSSION

Subsurface Conditions

The SOGIP onshore and marine sites exhibited a range of soil types, including soft clay, firm clay, stiff clay, silt, and dense sand, underlain by weathered sandstone, siltstone, or hard clay. The observed heterogeneity in subsurface conditions plays a critical role in seismic wave propagation and amplification behaviour. Soft clay and loose silty layers, particularly in the upper soil strata, tend to exhibit lower shear stiffness and higher compressibility, which significantly increase ground motion amplification due to impedance contrast with underlying stiffer materials. In contrast, dense sand and weathered rock layers contribute to reduced amplification due to higher stiffness and energy dissipation capacity.

The variability across clusters indicates that local stratigraphic differences govern site response behaviour, underscoring the need for microzoning rather than relying on uniform site classification. This spatial variability is particularly important in coastal and reclaimed zones, where marine deposits may amplify seismic waves more significantly than inland deposits. Groundwater depth ranged from the surface or the seabed to 4.2 m. For marine boreholes, the SPT-N could not be found until the termination depth of 70.95m. The lateral soil stratigraphy variations of the site are shown in **Figures 5, 6, 7, 8,** and **9.**

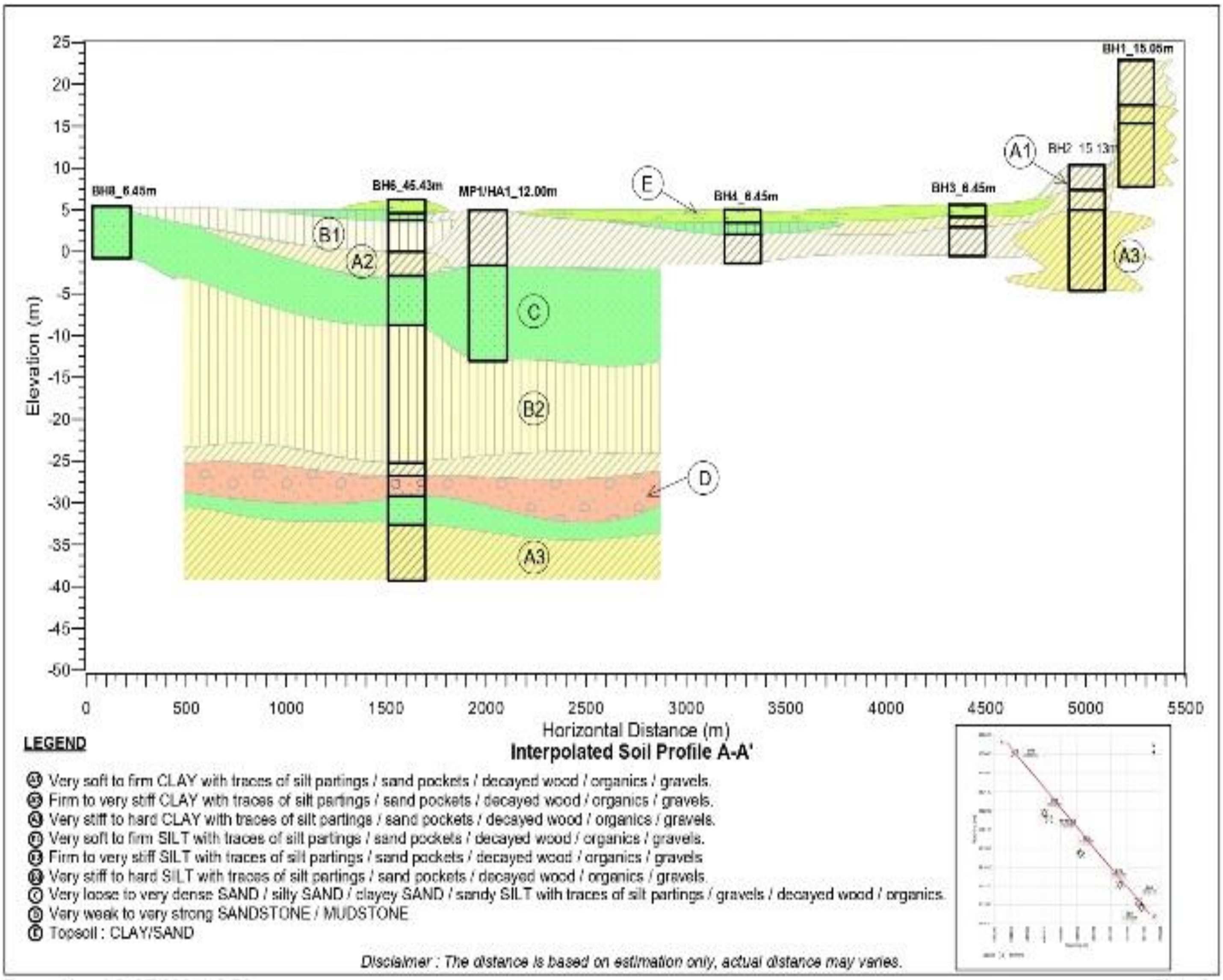

Figure 5. Lateral variation subsurface profile for BH1, 2, 3, 4, 6, & 8

INTERNATIONAL JOURNAL OF RESEARCH AND INNOVATION IN SOCIAL SCIENCE (IJRISS)
ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

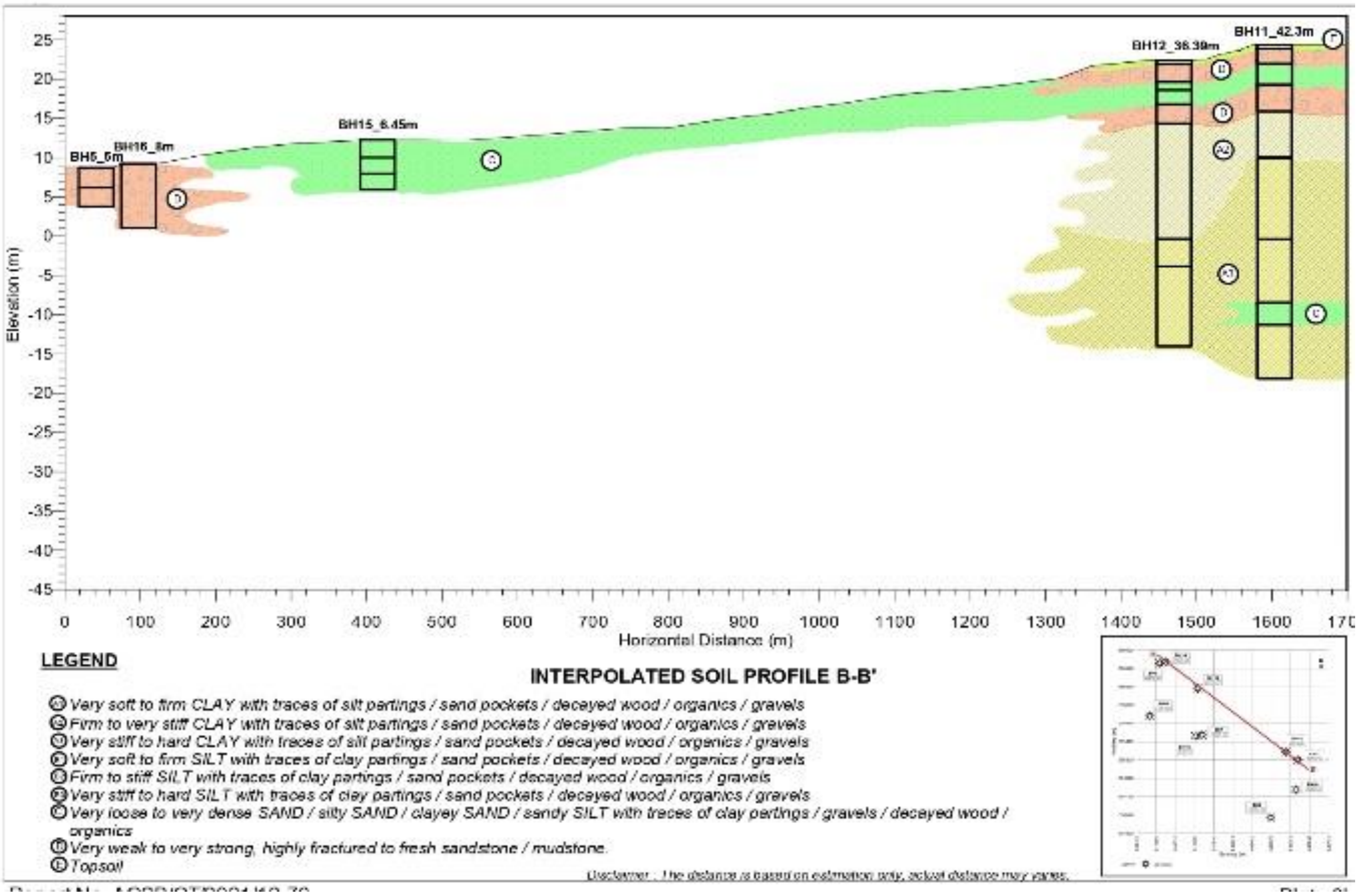

Figure 6.. Lateral variation subsurface profile for BH5, 11, 12, 15, & 16

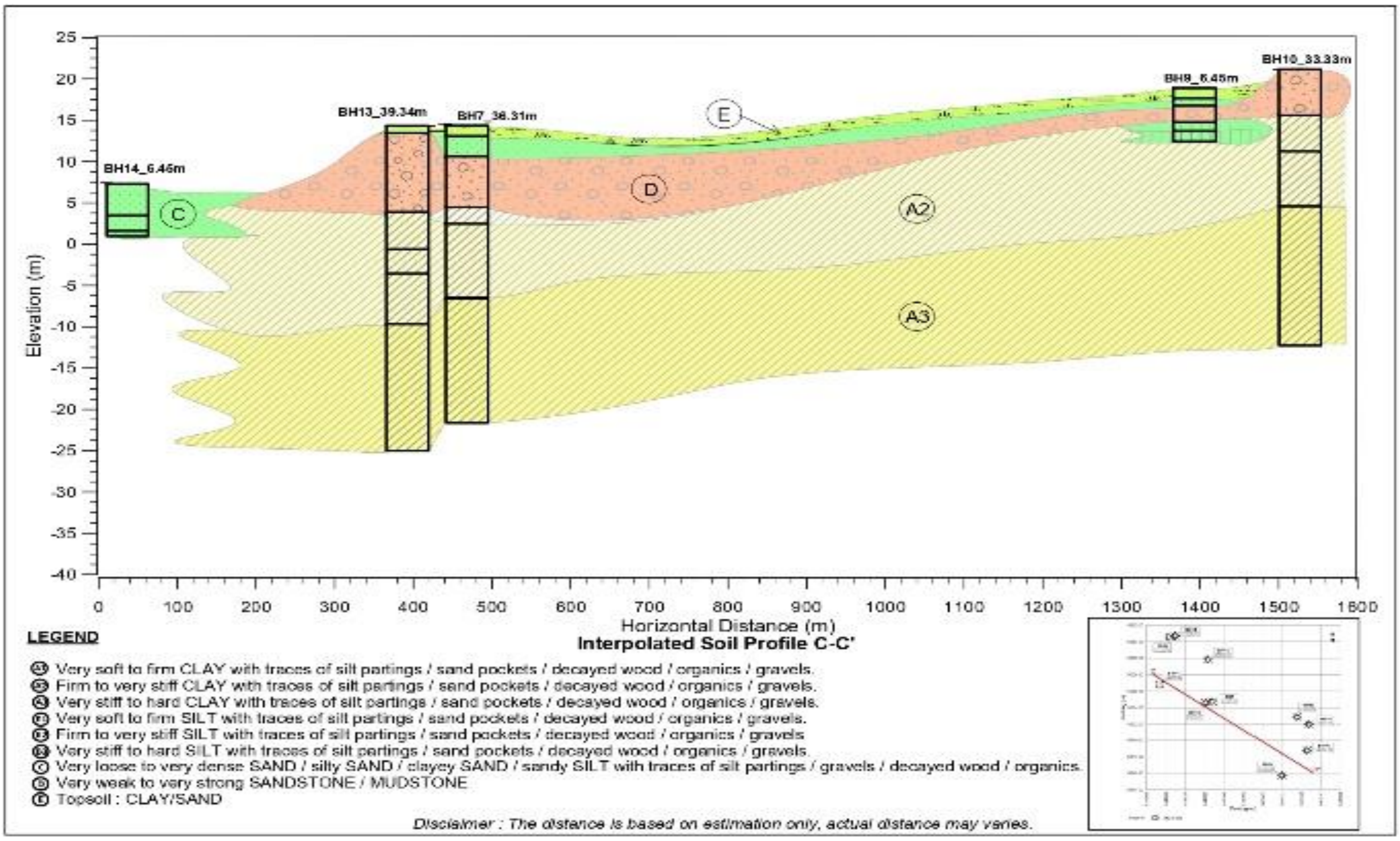

Figure 7. Lateral variation subsurface profile for BH7, 9, 10, 13, & 14

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

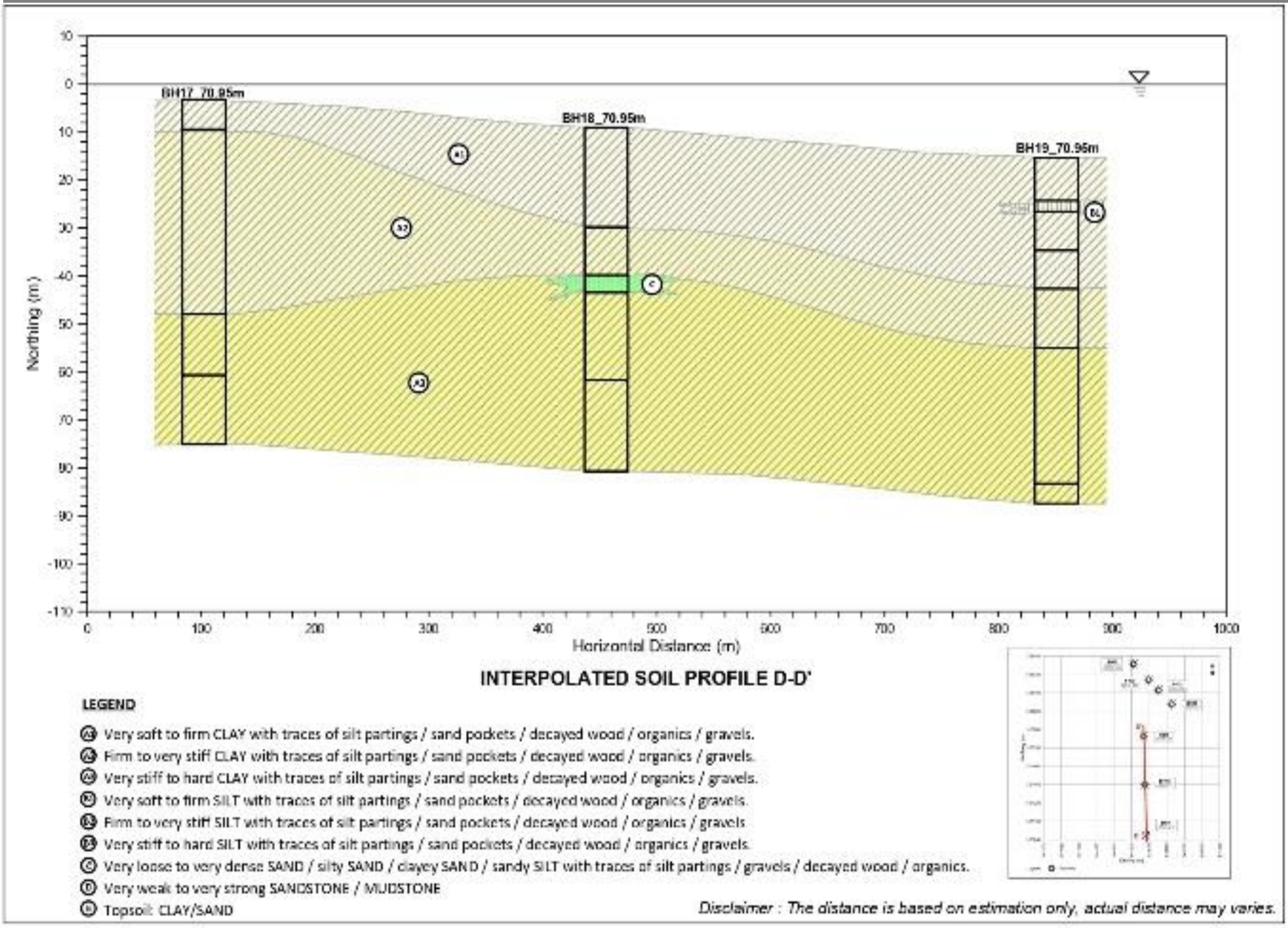

Figure 8. Lateral variation subsurface profile for BH17, 18, & 19

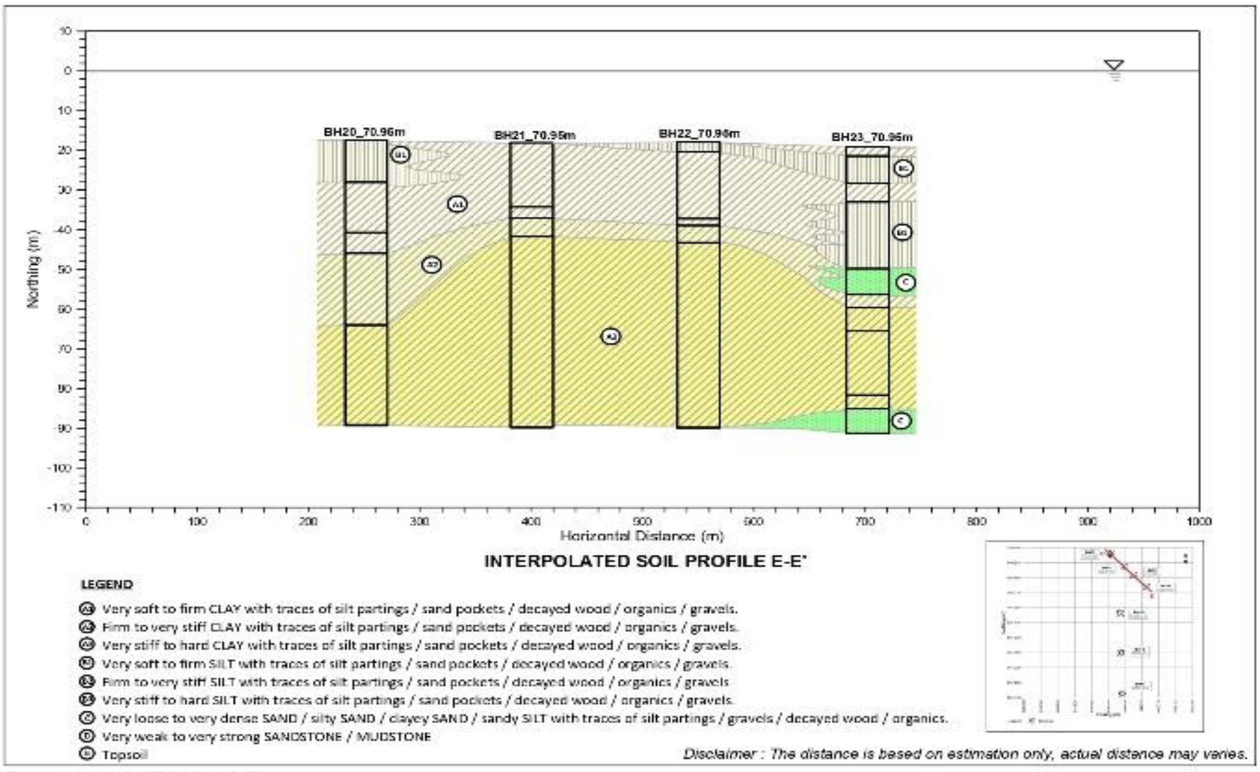

Figure 9. Lateral variation subsurface profile for BH20, 21, 22, & 23

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

Soil response analysis requires approximate engineering bedrock depth data. According to Roslee *et al.* (2020), the engineering bedrock depth in Luyang, Kota Kinabalu, Sabah, was estimated to be between 4 m and 32.5 m below the original ground level. It should be noted that estimating the engineering bedrock depth introduces uncertainty into the site response analysis. The adopted assumptions are based on regional geological studies, given the absence of direct geophysical measurements, such as downhole or MASW testing. Variations in actual bedrock depth may influence the fundamental site period and amplification characteristics.

However, the adopted approach represents a practical engineering approximation commonly used in preliminary seismic assessments. Future studies incorporating direct shear-wave velocity profiling are recommended to refine bedrock depth estimates and improve the reliability of site response predictions. As such, several assumptions have been made regarding the extended depth of boreholes for soil response analysis, as listed in **Table 7.** Because depth to engineering bedrock governs the fundamental site period, overestimating the depth could shift the resonance to longer periods, while underestimating it could artificially concentrate amplification at higher frequencies. Future structural designs utilising these site-specific spectra should account for a margin of error in the long-period range (T_D) to accommodate this uncertainty.

Table 7. Assumption on the extended depth of the borehole to the engineering bedrock

No.	Description of Conditions	Extended Depth from Existing Terminated BH
1	Weathered rock or hard clay encountered	10 m more depth to bedrock
2	Terminated BH SPT-N= 40-50	15 m more depth to bedrock
3	Terminated BH SPT-N= 25-40	20 m more depth to bedrock
4	Shallow depth BH, no SPT-N=50	30 m more depth to bedrock
5	All Marine BHs	30 m more depth to bedrock

Shear Wave Velocities, V_s

To estimate the shear wave velocity of the soil profile, empirical correlations relating Standard Penetration Test (SPT-N) values to Vs were utilised. Several established formulas were selected based on their proven suitability for Malaysian and tropical soil conditions. For each soil stratum, the Vs values derived from these selected methods were calculated and subsequently averaged. This averaging technique mitigates the inherent statistical scattering of individual empirical models, thereby reducing uncertainty and yielding a more robust and reliable estimate of the soil's dynamic stiffness. While these empirical correlations are widely adopted, they inherently introduce variability due to differences in soil type, stress history, and local geological conditions. It is acknowledged that direct site-specific geophysical measurements, such as Multichannel Analysis of Surface Waves (MASW) or downhole testing, would yield more accurate velocity profiles. Nevertheless, in the absence of direct geophysical data, this averaged empirical approach is considered a highly practical and acceptable methodology for regional-scale seismic assessments.

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

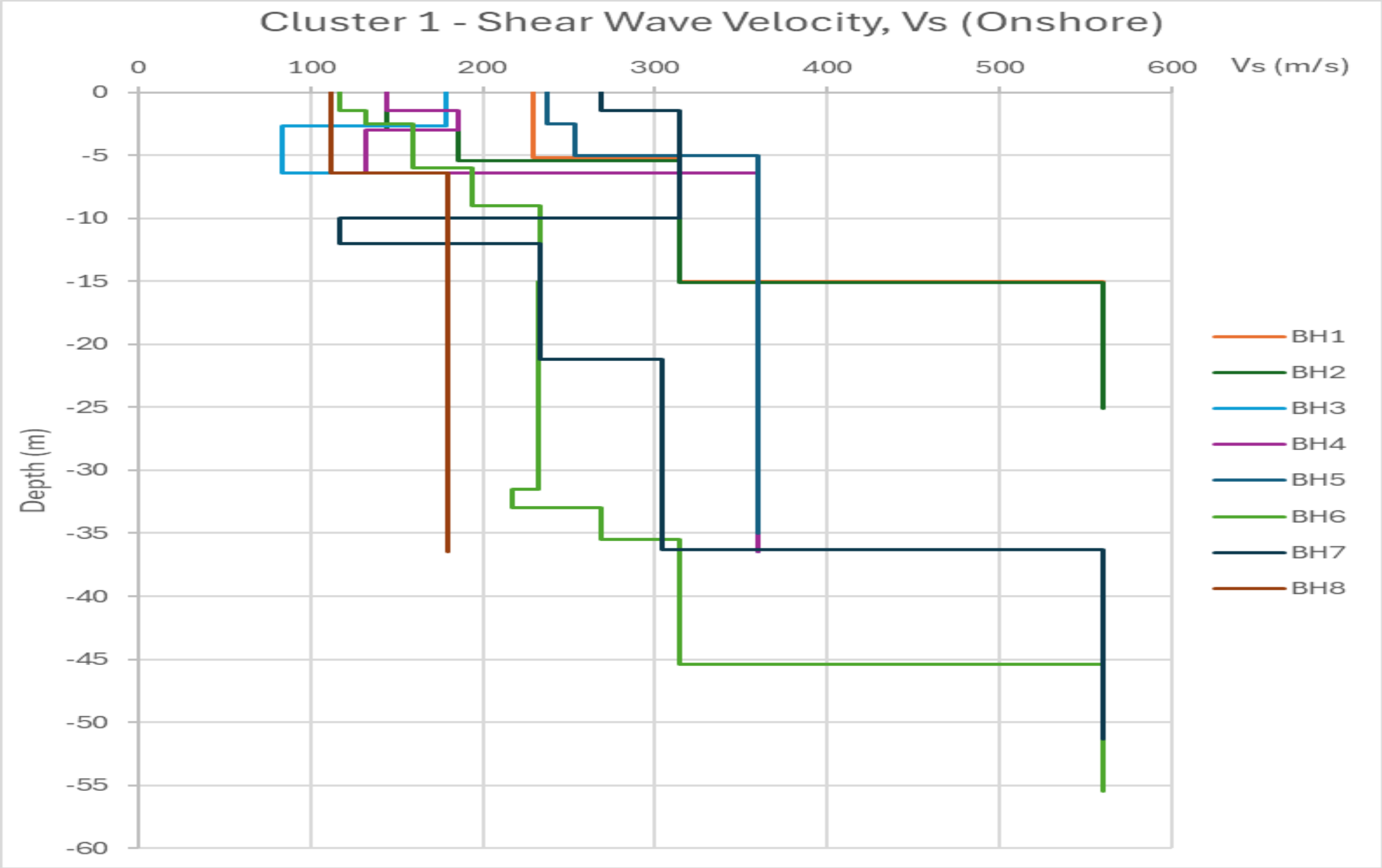

Figure 10. Shear wave velocity for Cluster 1

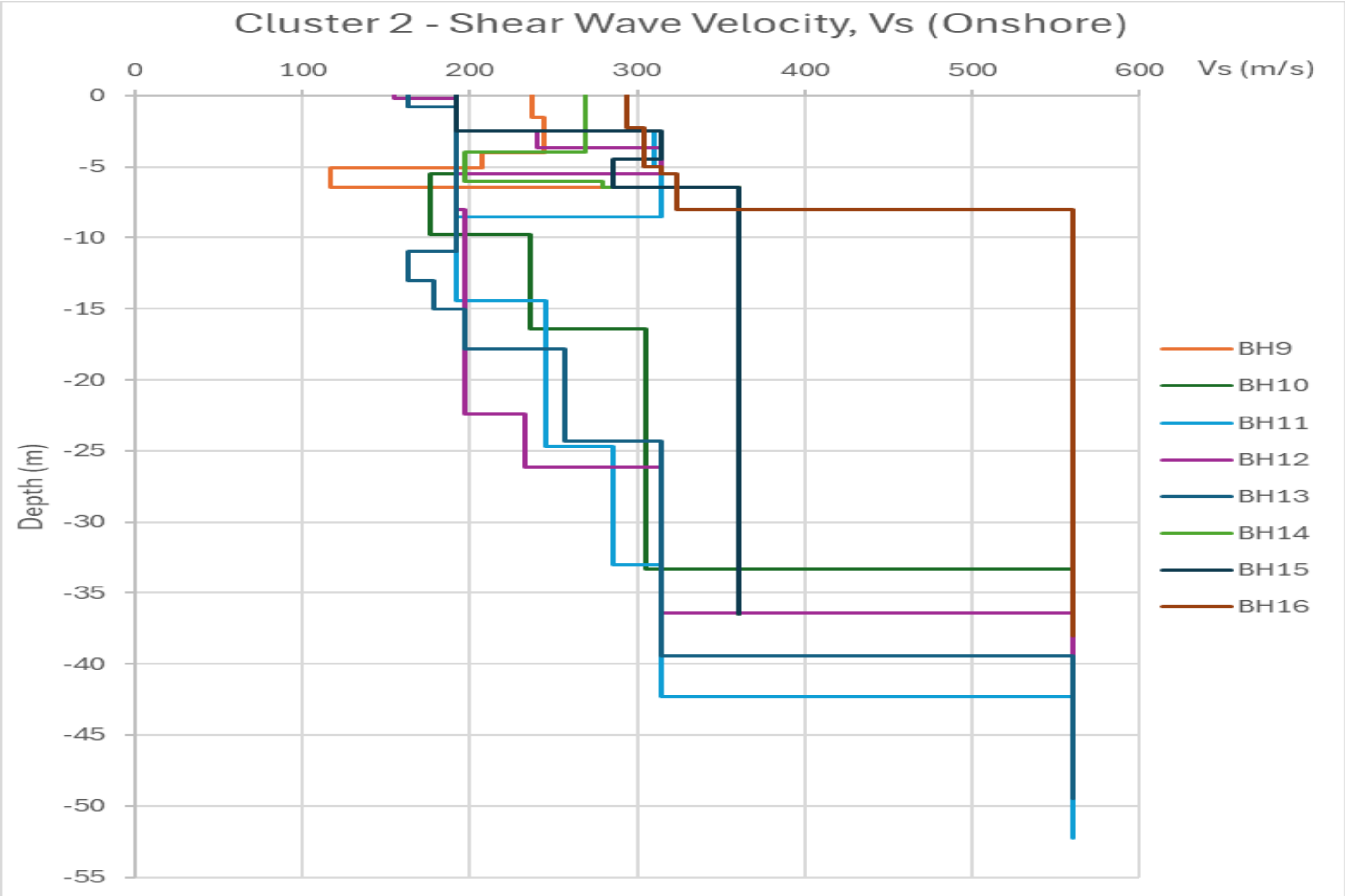

Figure 11. Shear wave velocity for Cluster 2

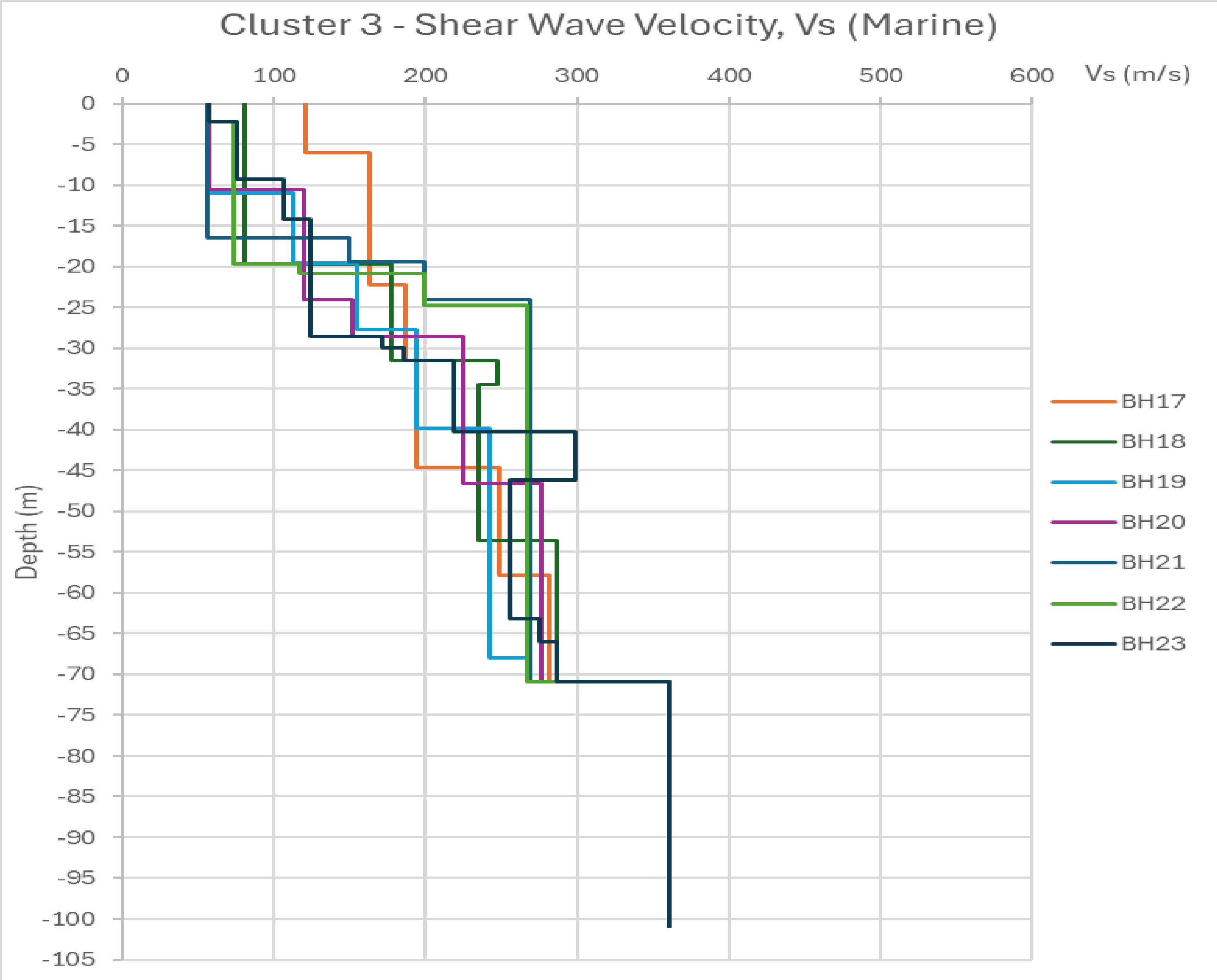

Figure 12. Shear wave velocity for Cluster 3

These average Vs values are then used in the DEEPSOIL software to carry out soil response analysis. This method is a practical solution when field measurements are unavailable, yet it still allows for a meaningful site-specific assessment of surface PGA. All 23-borehole shear wave velocity plots are divided into 3 clusters as per **Figures 10, 11,** and **12.**

Soil Response Analysis

In this study, three representative ground motion records from past earthquake events (Kobe 1995, Chi-Chi 1999, and Kocaeli 1999) were selected and used as input motions in the DEEPSOIL software. These records were appropriately scaled to match the target bedrock Peak Ground Acceleration (PGA) values of 0.02g and 0.03g for the SOGIP area in Sipitang, Sabah. In accordance with Eurocode 8 (EC8), scaled input motions were used to derive key seismic design parameters via equivalent-linear site response analysis. Figures 13–18 present the computed surface acceleration time histories and corresponding response behaviour for the different input motions and borehole clusters. The results consistently demonstrate amplification of ground motion from bedrock to the surface across all clusters, with the degree of amplification varying with both input motion characteristics and local subsurface conditions. A clear trend observed in the figures is that softer soil profiles exhibit more pronounced amplification, particularly within the low- to mid-frequency range. This behaviour is attributed to the lower stiffness and higher deformability of soft clay and silty layers, which tend to resonate with incoming seismic waves. In contrast, soil profiles dominated by denser or stiffer materials exhibit lower amplification, reflecting higher shear stiffness, more effective energy dissipation, and reduced impedance contrast between layers.

Variations in response among the three earthquake records are also evident. Each input motion possesses distinct frequency content, duration, and energy distribution, which influence the resulting surface response. Ground motions with dominant frequencies closer to the soil profile's natural period tend to produce greater amplification due to resonance. This explains the observed differences in surface PGA across clusters under identical bedrock input levels.

Furthermore, increasing the bedrock PGA from 0.02g to 0.03g results in an overall increase in surface acceleration; however, the amplification response does not scale linearly. This behaviour reflects the strain-dependent characteristics of soil captured in the equivalent-linear analysis, where stiffness degradation and increased material damping occur at higher strain levels, thereby moderating the amplification response. The variability in amplification observed across the different clusters highlights the influence of spatial heterogeneity in subsurface conditions within the SOGIP area. Marine and near-coastal deposits, which are typically characterised by thicker, soft soil layers, exhibit higher amplification compared to inland locations with relatively stiffer stratigraphy. These findings underscore the limitations of generalised seismic design assumptions and reinforce the necessity of site-specific analysis to accurately capture local ground response characteristics.

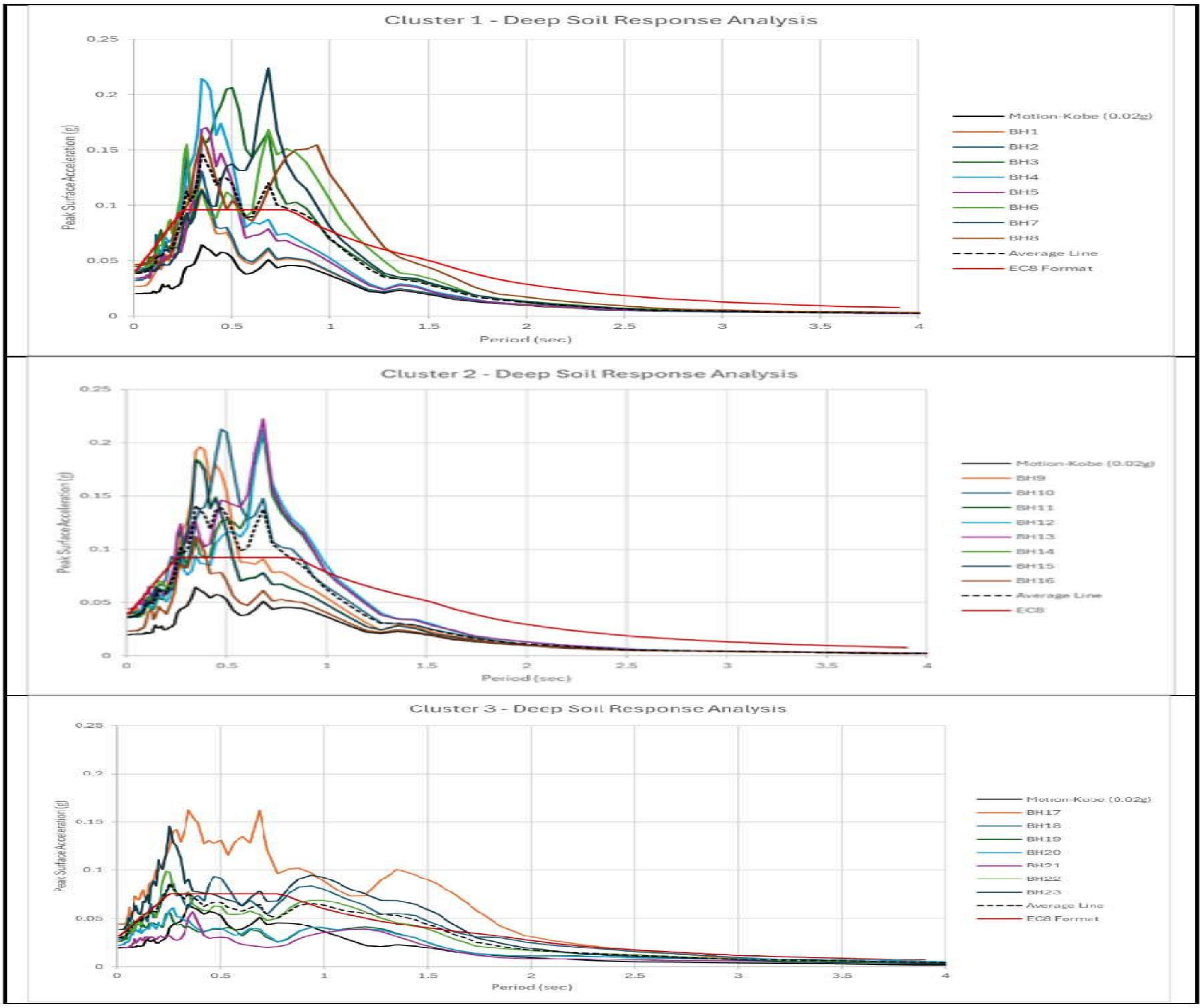

Figure 13. Soil response analysis graph for Kobe EQ-**0.02g**

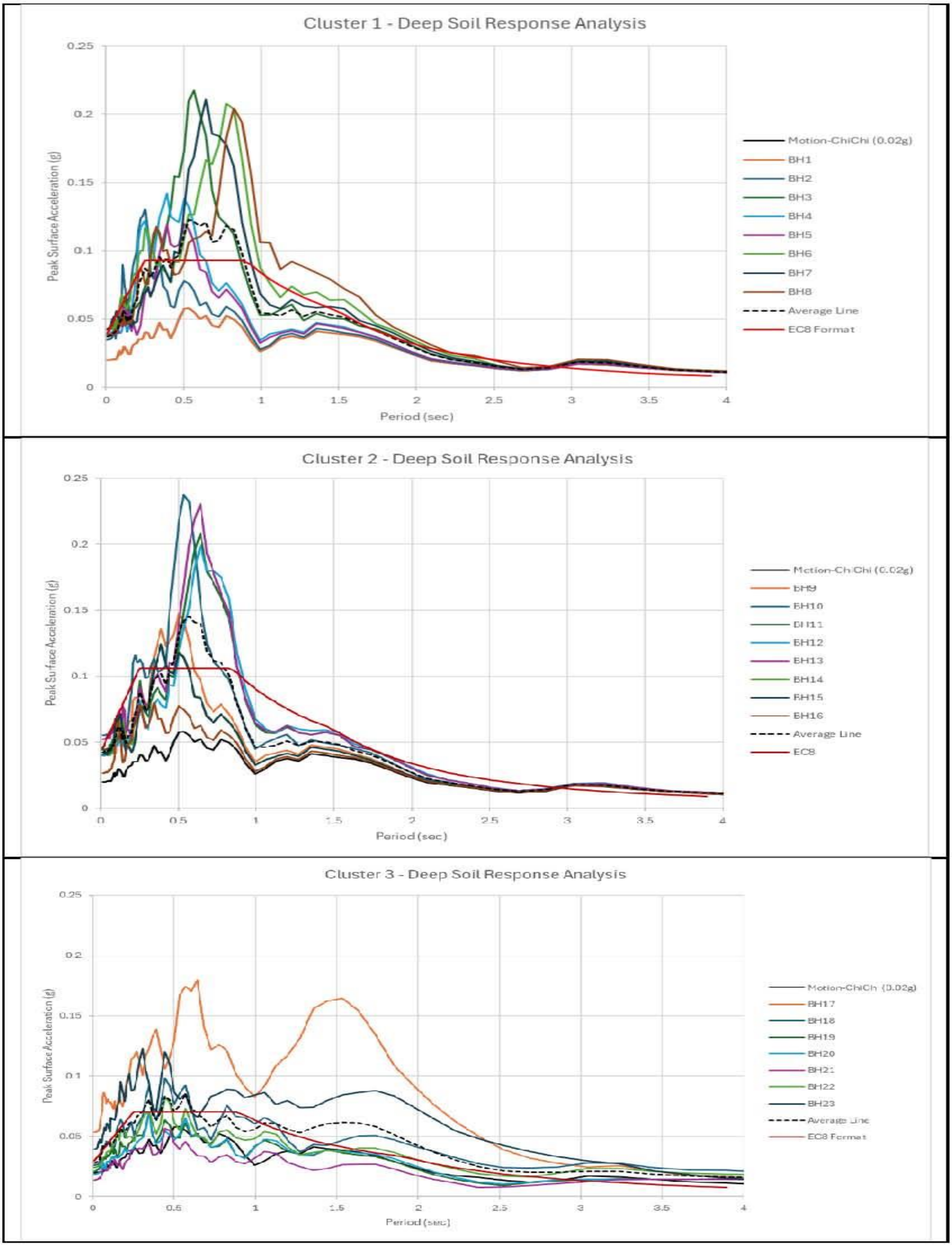

Figure 14. Soil response analysis graph for Chi-Chi EQ-**0.02g**

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

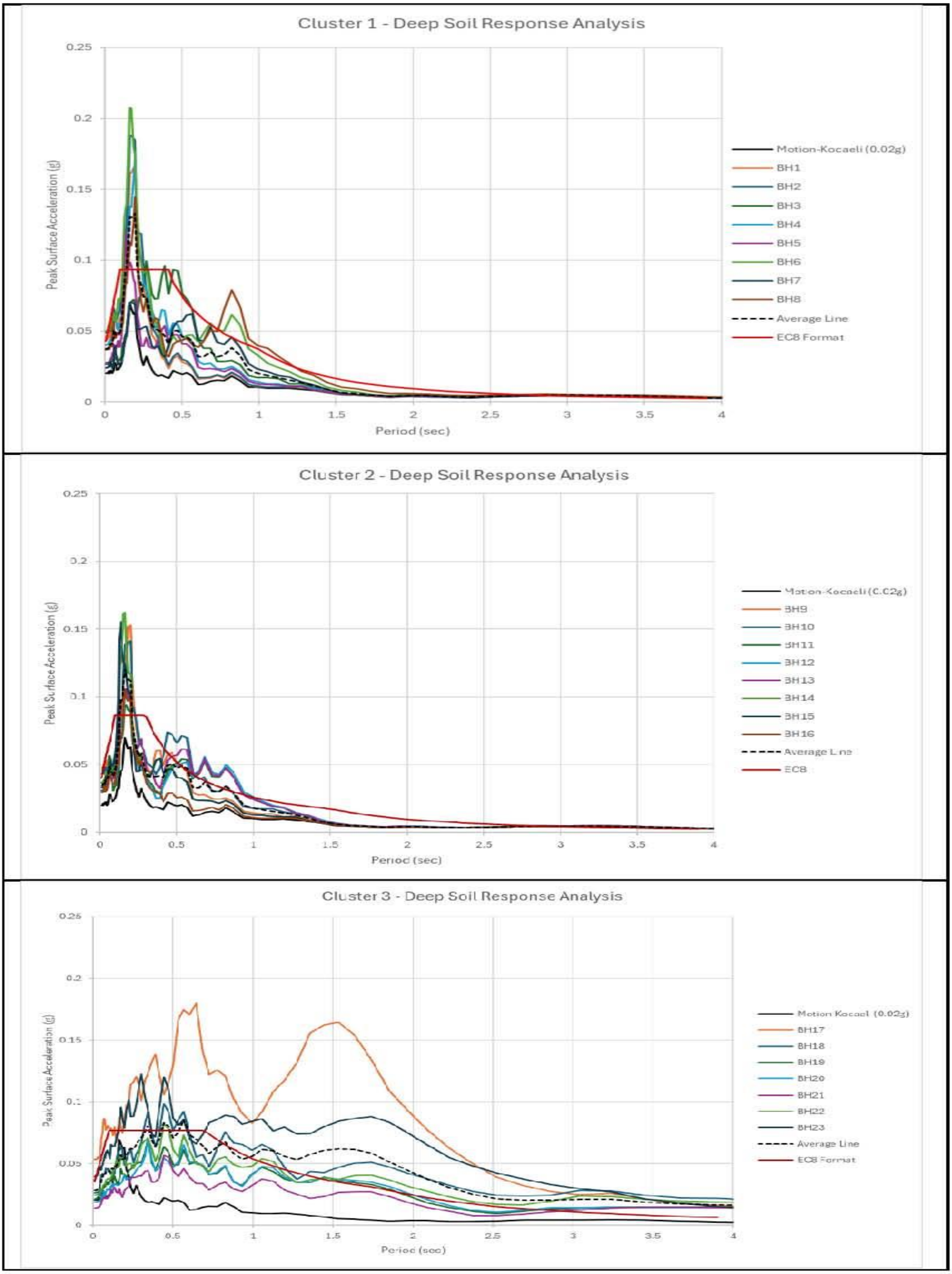

Figure 15. Soil response analysis graph for Kocaeli EQ-**0.02g**

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

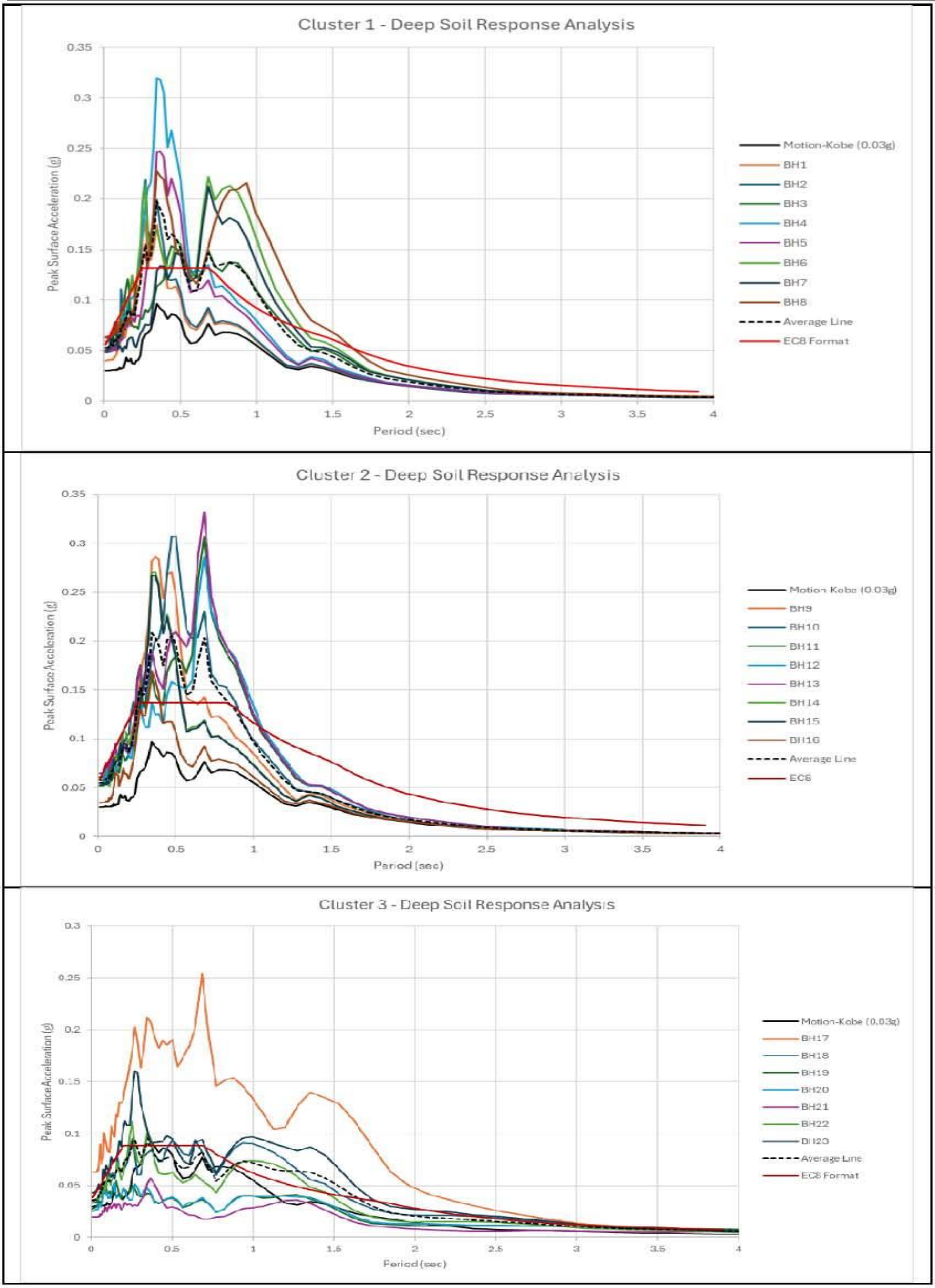

Figure 16. Soil response analysis graph for Kobe EQ-**0.03g**

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

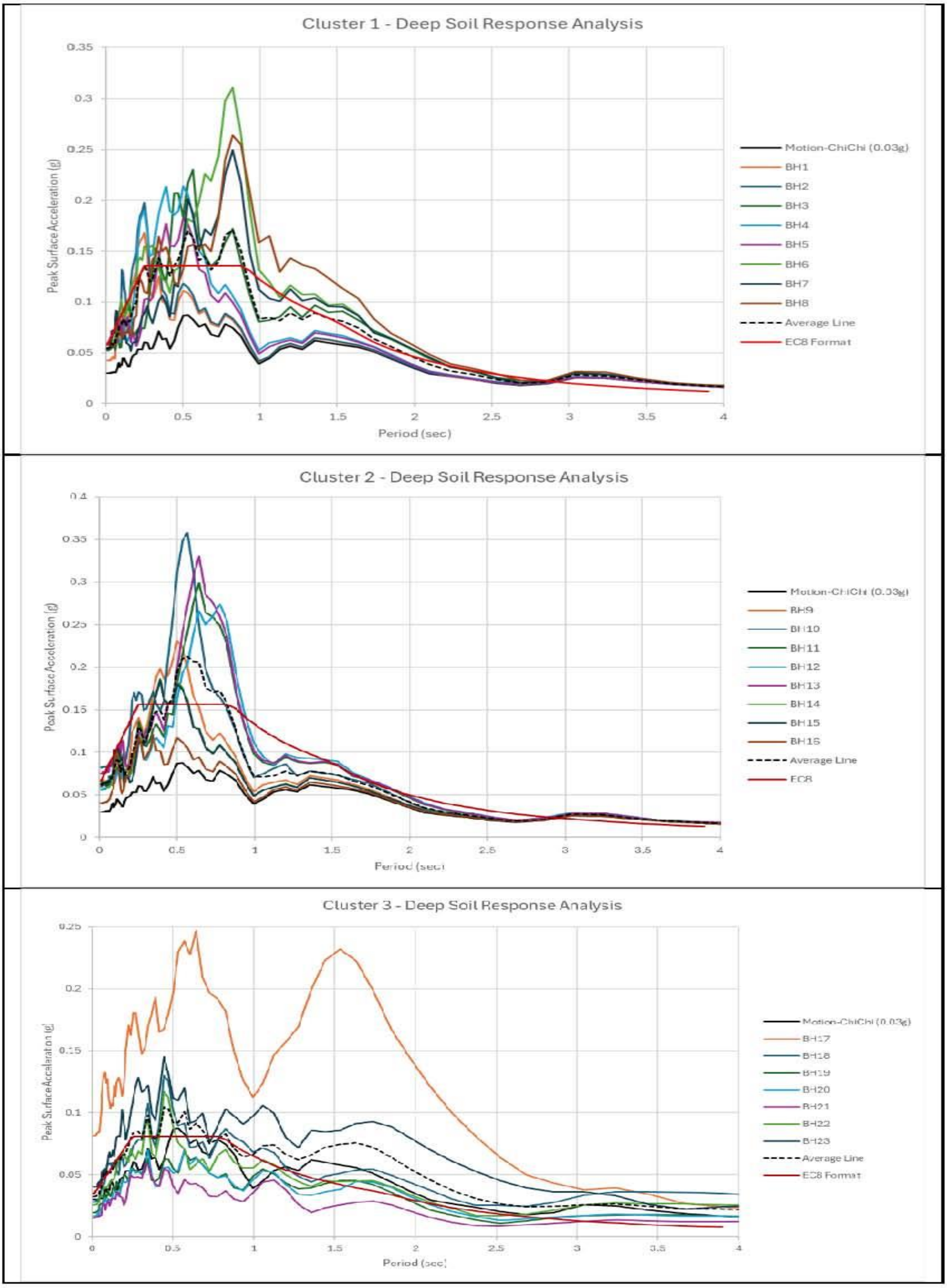

Figure 17. Soil response analysis graph for Chi-Chi EQ-**0.03g**

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

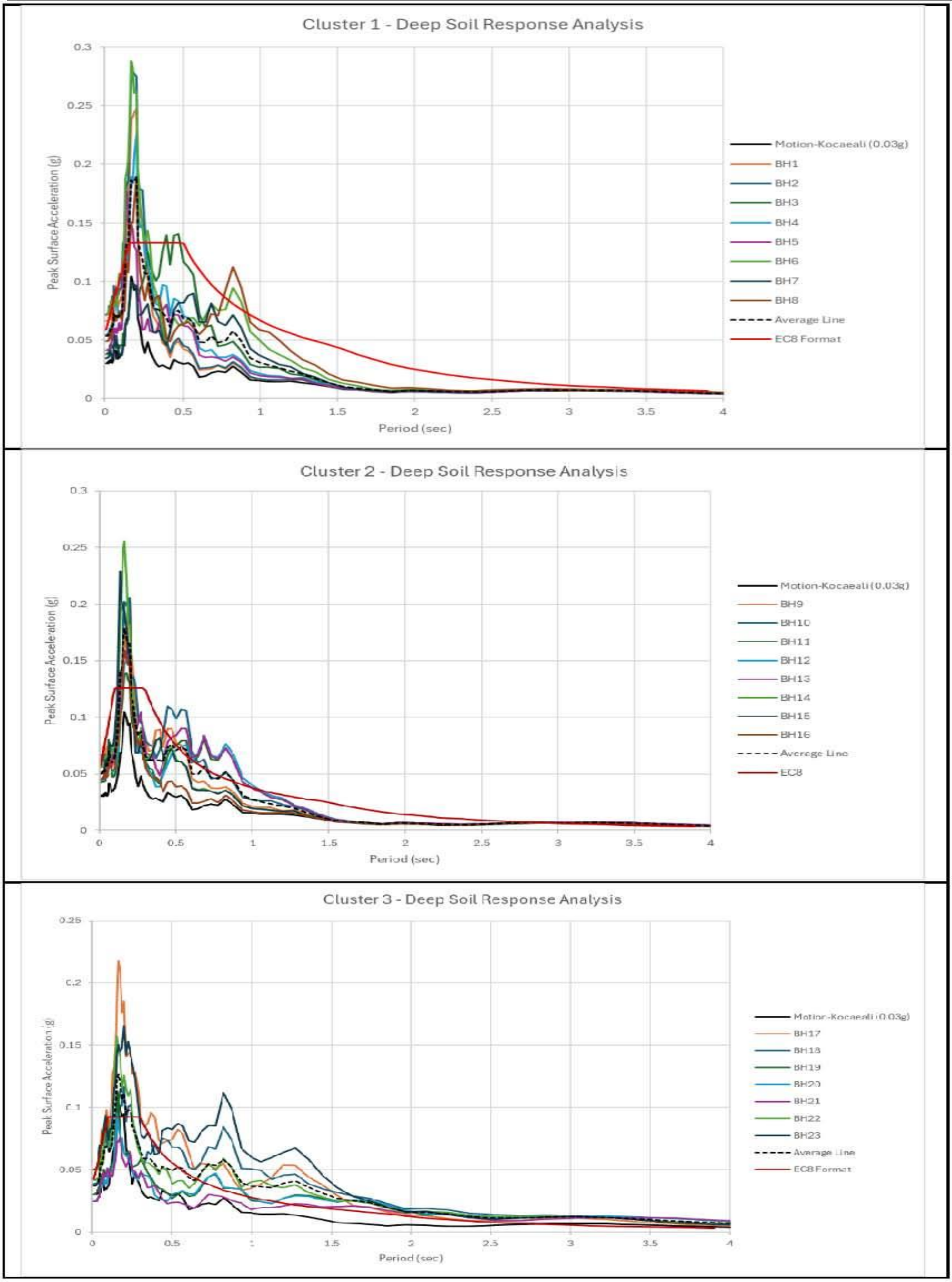

Figure 18. Soil response analysis graph for Kocaeli EQ-**0.03g**

Soil Amplification Factor Evaluation

Based on various soil response analyses, the data sets and results have been carefully studied to ensure the outcomes are practical and eliminate possible errors. The studies on amplification effects for both cases of PGA at bedrock (0.02g and 0.03g) have been tabulated in **Tables 8** and **9**. The results, before averaging the datasets concerning cluster locations, indicate that surface PGA values range from 0.0137g to 0.0552g based on a bedrock PGA of 0.02g (MS EN 1998-1:2015/2017), and from 0.0153g to 0.0821g for higher reference bedrock PGAs 0.03g (rationalized PGA value of 0.027g (Harith *et al.*, 2025) and 0.031g (Adnan, 2022)).

Table 8. Summary of soil amplification effects based on PGA of **0.02g** at Bedrock

Item / Cluster	Return Period	475 Years			Average Soil Amplification Factor Based on EQ Events (Unitless)
Input Motions	Based on Earthquake Event and Scaled Down to Local Site Bedrock	**Kobe - 0.02g**	**ChiChi - 0.02g**	**Kocaeli - 0.02g**	
Bedrock in Sipitang	PGA Based on MSEN1998-1:2015(2017) (0.02g) at 0.01s	**0.02004**	**0.02001**	**0.02007**	
Soil Surface		**Peak Surface Acceleration (PSA) (g)**			
Cluster 1 (Onshore Pipeline)	BH 1 (Soil Type C)	0.0266	0.0200	0.0449	
	BH 2 (Soil Type C)	0.0321	0.0350	0.0489	
	BH 3 (Soil Type D)	0.0446	0.0431	0.0267	
	BH 4 (Soil Type D)	0.0418	0.0391	0.0402	
	BH 5 (Soil Type C)	0.0341	0.0381	0.0275	
	BH 6 (Soil Type D)	0.0410	0.0421	0.0501	
	BH 7 (Soil Type C)	0.0397	0.0424	0.0241	
	BH 8 (Soil Type D)	0.0465	0.0383	0.0368	
	Average PSA	0.0383	0.0373	0.0374	
	Soil Amplification (Average PSA/PGA)	**1.9110**	**1.8614**	**1.8631**	**1.8785**
Cluster 2 (Onshore)	BH 9 (Soil Type D)	0.0407	0.0403	0.0417	
	BH 10 (Soil Type D)	0.0406	0.0552	0.0433	
	BH 11 (Soil Type C)	0.0393	0.0441	0.0295	
	BH 12 (Soil Type D)	0.0364	0.0398	0.0310	
	BH 13 (Soil Type D)	0.0441	0.0522	0.0307	
	BH 14 (Soil Type C)	0.0356	0.0404	0.0366	
	BH 15 (Soil Type C)	0.0358	0.0408	0.0331	
	BH 16 (Soil Type B)	0.0232	0.0267	0.0305	
	Average PSA	0.0370	0.0424	0.0346	
	Soil Amplification (Average PSA/PGA)	**1.8438**	**2.1201**	**1.7222**	**1.8954**
Cluster 3 (Marine)	BH 17 (Soil Type D)	0.0444	0.0533	0.0388	
	BH 18 (Soil Type D)	0.0286	0.0262	0.0314	
	BH 19 (Soil Type D)	0.0263	0.0210	0.0238	
	BH 20 (Soil Type D)	0.0222	0.0187	0.0230	
	BH 21 (Soil Type D)	0.0192	0.0137	0.0202	
	BH 22 (Soil Type D)	0.0317	0.0243	0.0354	
	BH 23 (Soil Type D)	0.0382	0.0394	0.0424	
	Average PSA	0.0301	0.0281	0.0307	
	Soil Amplification (Average PSA/PGA)	**1.5008**	**1.4031**	**1.5309**	**1.4783**

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

Table 9. Summary of soil amplification effects based on PGA of **0.03g** at Bedrock

Item / Cluster	Return Period	475 Years			Average Soil Amplification Factor Based on EQ Events (Unitless)
Input Motions	Based on Earthquake Event and Scaled Down to Local Site Bedrock	Kobe - 0.03g	ChiChi - 0.03g	Kocaeli - 0.03g	
Bedrock in Sipitang	PGA Based on MSEN1998-1:2015(2017) (0.03g) at 0.01s	0.03006	0.03002	0.03010	
Soil Surface		Peak Surface Acceleration (PSA) (g)			
Cluster 1 (Onshore Pipeline)	BH 1 (Soil Type C)	0.0401	0.0424	0.0662	
	BH 2 (Soil Type C)	0.0483	0.0522	0.0720	
	BH 3 (Soil Type D)	0.0488	0.0533	0.0382	
	BH 4 (Soil Type D)	0.0623	0.0590	0.0546	
	BH 5 (Soil Type C)	0.0496	0.0575	0.0413	
	BH 6 (Soil Type D)	0.0591	0.0597	0.0712	
	BH 7 (Soil Type C)	0.0503	0.0540	0.0345	
	BH 8 (Soil Type D)	0.0638	0.0551	0.0489	
	Average PSA	0.0528	0.0542	0.0533	
	Soil Amplification (Average PSA/PGA)	**1.7551**	**1.8041**	**1.7722**	**1.7771**
Cluster 2 (Onshore)	BH 9 (Soil Type D)	0.0611	0.0612	0.0565	
	BH 10 (Soil Type D)	0.0608	0.0821	0.0613	
	BH 11 (Soil Type C)	0.0574	0.0637	0.0427	
	BH 12 (Soil Type D)	0.0549	0.0561	0.0443	
	BH 13 (Soil Type D)	0.0645	0.0754	0.0448	
	BH 14 (Soil Type C)	0.0511	0.0594	0.0559	
	BH 15 (Soil Type C)	0.0526	0.0608	0.0504	
	BH 16 (Soil Type B)	0.0346	0.0403	0.0454	
	Average PSA	0.0546	0.0624	0.0502	
	Soil Amplification (Average PSA/PGA)	**1.8173**	**2.0785**	**1.6665**	**1.8541**
Cluster 3 (Marine)	BH 17 (Soil Type D)	0.0627	0.0811	0.0500	
	BH 18 (Soil Type D)	0.0333	0.0280	0.0387	
	BH 19 (Soil Type D)	0.0278	0.0193	0.0301	
	BH 20 (Soil Type D)	0.0254	0.0166	0.0246	
	BH 21 (Soil Type D)	0.0194	0.0153	0.0243	
	BH 22 (Soil Type D)	0.0366	0.0257	0.0417	
	BH 23 (Soil Type D)	0.0430	0.0402	0.0501	
	Average PSA	0.0355	0.0323	0.0371	
	Soil Amplification (Average PSA/PGA)	**1.1798**	**1.0765**	**1.2311**	**1.1625**

Horizontal Elastic Response Spectra

These results are derived from the average response spectra curves generated through the soil amplification factors, site periods characteristics, acceleration response spectra curves for 5% damping ratios, EC8 spectra shape parameters, and surface motion characteristics used for structural design inputs. Please refer to **Figures 19** and **20** for further information about the response spectra curves based on various input motions, clusters, and PGA values. Tabulation of results and recommendations for clusters is available in **Tables 10, 11,** and **12.**

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

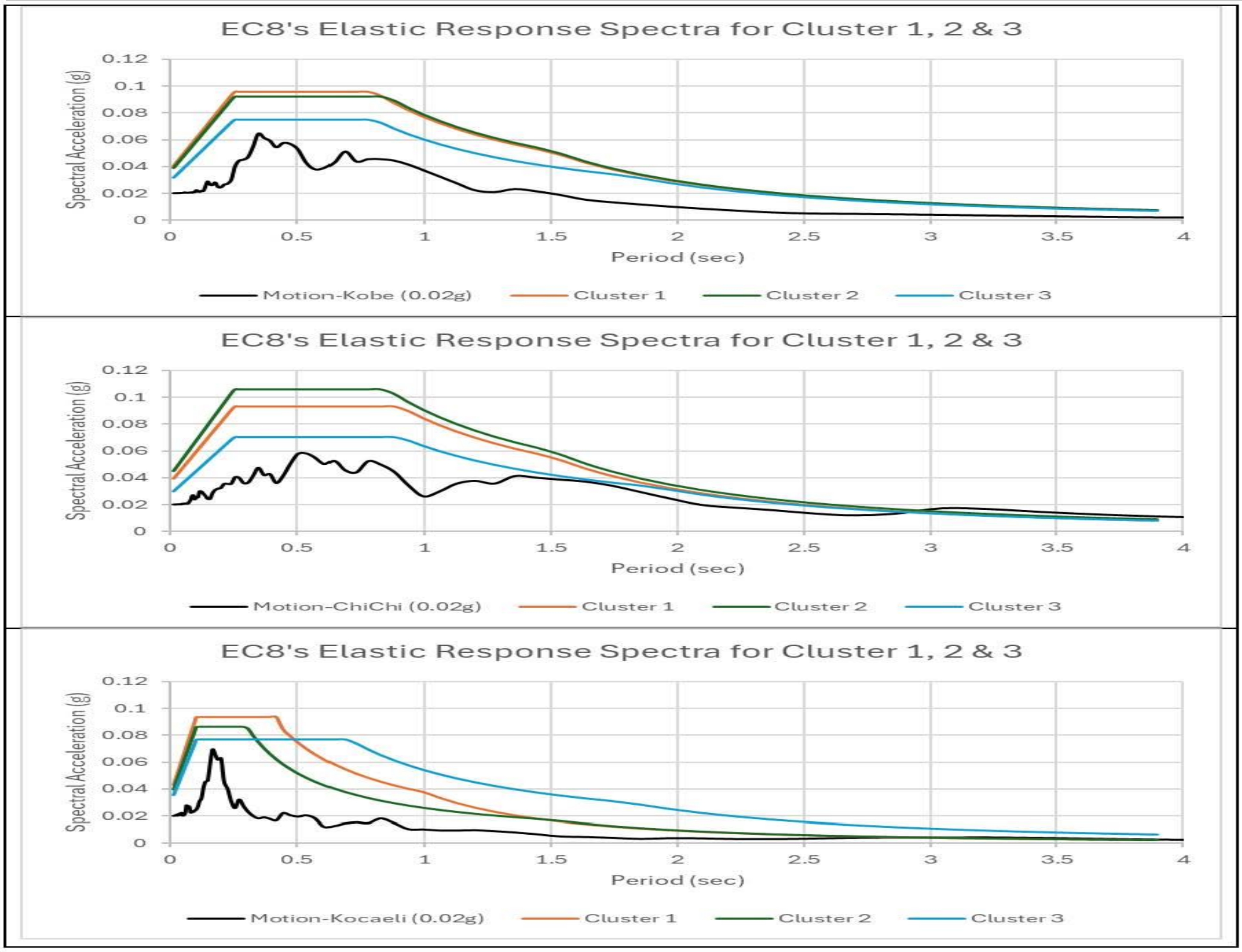

Figure 19. EC8 Response Spectra for **0.02g** input motions

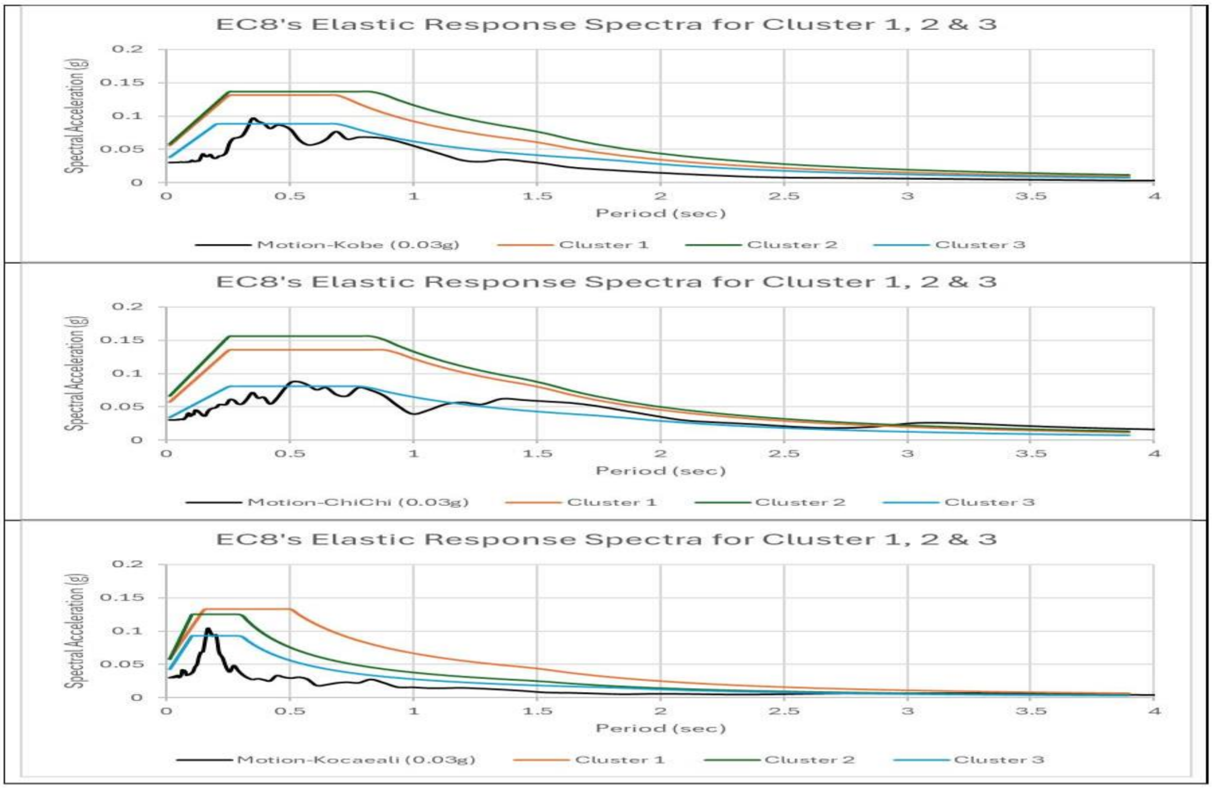

Figure 20. EC8 Response Spectra for **0.03g** input motions

Table 10. Summary of response spectra shape parameters for Cluster 1

Bedrock PGA (g)	Input Motions	Soil Amplification Factor, S	T_B (s)	T_C (s)	T_D (s)
0.02g	Kobe EQ 1995	1.9110	0.25	0.80	1.50
	Chi-Chi EQ 1999	1.8614	0.25	0.90	1.50
	Kocaeli EQ 1999	1.8631	0.10	0.40	1.00
0.03g	Kobe EQ 1995	1.7551	0.25	0.70	1.50
	Chi-Chi EQ 1999	1.8041	0.25	0.90	1.50
	Kocaeli EQ 1999	1.7722	0.15	0.50	1.50

Table 11. Summary of response spectra shape parameters for Cluster 2

Bedrock PGA (g)	Ground Input Motions	Soil Amplification Factor, S	T_B (s)	T_C (s)	T_D (s)
0.02g	Kobe EQ 1995	1.8438	0.25	0.85	1.50
	Chi-Chi EQ 1999	2.1201	0.25	0.85	1.50
	Kocaeli EQ 1999	1.7222	0.10	0.30	1.50
0.03g	Kobe EQ 1995	1.8173	0.25	0.85	1.50
	Chi-Chi EQ 1999	2.0785	0.25	0.85	1.50
	Kocaeli EQ 1999	1.6665	0.10	0.30	1.50

Table 12. Summary of response spectra shape parameters for Cluster 3

Bedrock PGA (g)	Ground Input Motions	Soil Amplification Factor, S	T_B (s)	T_C (s)	T_D (s)
0.02g	Kobe EQ 1995	1.5008	0.25	0.80	1.80
	Chi-Chi EQ 1999	1.4031	0.25	0.90	1.90
	Kocaeli EQ 1999	1.5309	0.10	0.70	1.80
0.03g	Kobe EQ 1995	1.1798	0.20	0.70	1.80
	Chi-Chi EQ 1999	1.0765	0.25	0.80	1.80
	Kocaeli EQ 1999	1.2311	0.10	0.30	1.80

Surface PGA Results

Previous relevant studies indicate PGA values at bedrock for the Sipitang area in Sabah, as shown in **Table 13. While the** computed surface PGA from this study is summarised in **Table 14**. The computed surface PGA values are consistently higher than those shown in the Malaysian Seismic Hazard Map (2017), suggesting bedrock PGA values of approximately 0.01g to 0.02g. This indicates that reliance solely on regional hazard maps may lead to underestimation of seismic demand at the site. The increase in PGA due to local site effects underscores the importance of accounting for soil amplification in seismic design. For critical infrastructure such as oil and gas facilities, even moderate increases in PGA can significantly impact structural performance and safety margins.

Table 13. The range of PGA at bedrock values for Sipitang, Sabah

Reference	10% PE (g) / 475 Yrs
(Giardini, 2003)	0.04g – 0.08g
(Petersen M. D., 2007; Petersen M. D., 2008)	0.02g – 0.04g
(Leyu C. H., 2009)	0.04g

ISSN No. 2454-6186 | DOI: 10.47772/IJRISS | Volume X Issue IV April 2026

(Adnan, 2008)	0.06g – 0.08g
(MSEN1998-1:2015, 2017)	**0.01g – 0.02g**
(M. Pagani et al., 2018)	0.01g – 0.02g
(Adnan, 2022), The Kuala Penyu fault is included	**0.031g**
(Harith *et al.*, 2025), The Kuala Penyu fault is included	**0.027g**

Table 14. The peak surface acceleration (surface PGA) computed from this study

Bedrock PGA (g)	Locations	Soil Amplification Factor, S	Surface PGA (g)
0.02g	Cluster 1 (Pipeline)	1.9110	**0.0382**
	Cluster 2 (Onshore)	1.8614	**0.0372**
	Cluster 3 (Marine)	1.8631	**0.0373**
0.03g	Cluster 1 (Pipeline)	1.7551	**0.0527**
	Cluster 2 (Onshore)	1.8041	**0.0541**
	Cluster 3 (Marine)	1.7722	**0.0532**

Implications for Engineering Design

The results indicate that local amplification factors ranging from 1.0765 to 2.1201 (Tables 10–12 and 14) are primarily attributed to the presence of soft surface soil layers across multiple locations within the SOGIP area. In several instances, these amplification factors exceed the values recommended in MS EN 1998-1:2015 (Table N.A.1, Annex C, and Annex D), suggesting that standard code provisions may not fully capture the influence of local subsurface conditions. Consequently, reliance solely on national-scale PGA values may lead to underestimation of seismic demand, particularly for critical infrastructure.

The observed increase in surface PGA has significant implications for the design of industrial facilities in SOGIP. Elevated seismic demand directly influences the design requirements of shallow and deep foundations, storage tanks, pipelines, and retaining structures. Flexible systems, such as pipelines and offshore facilities, are particularly vulnerable to ground deformation and amplification, making them more sensitive to site-specific seismic response.

These findings highlight the importance of adopting site-specific response spectra in place of standard code-based spectra to better reflect actual ground behaviour. Such an approach not only enhances structural safety but also enables more economical and performance-based design solutions.

Furthermore, the presence of soft, potentially saturated soil layers indicates increased susceptibility to seismic-induced ground failures, including liquefaction and slope instability. These hazards should be explicitly considered in the design and risk assessment of infrastructure within the study area.

Comparison with Previous Studies

The results obtained in this study generally agree with previous seismic studies conducted in Sabah, where soft soil deposits produced higher amplification effects compared to stiffer ground conditions. However, this study provides more localized assessment specifically for the SOGIP industrial area using actual borehole information. Therefore, the results offer more representative seismic response estimates for the site-specific conditions.

Limitations of the Study

Several limitations were identified during the study:

i. The analysis was performed using one-dimensional site response assumptions, which may not fully represent complex three-dimensional ground conditions.

ii. The soil dynamic properties were estimated using empirical correlations instead of direct geophysical measurements.

iii. Limited earthquake input motions were considered during the analysis.

iv. Groundwater fluctuation effects and nonlinear soil behaviour may influence actual seismic response during strong earthquakes.

Despite these limitations, the study provides useful preliminary information for seismic assessment and engineering planning in the SOGIP area.

CONCLUSIONS

This study demonstrates the critical importance of conducting site-specific seismic hazard assessments in seismically influenced regions such as Sipitang, Sabah. By integrating borehole-derived subsurface data with one-dimensional site response analysis, the study provides a more realistic representation of ground-motion characteristics than generalised regional approaches. The results confirm that local soil conditions play a dominant role in modifying seismic wave propagation, with amplification factors reaching up to 2.1 times the regional baseline, thereby significantly increasing surface PGA.

The computed surface PGA values for the SOGIP area, ranging from 0.0372g to 0.0541g, consistently exceed those inferred from national seismic hazard maps. This highlights the limitation of relying solely on regional PGA values for engineering design, as such approaches may underestimate seismic demand and compromise the safety and performance of critical infrastructure. The findings strongly support the adoption of site-specific response spectra to better capture local ground behaviour and improve the reliability of seismic design practices.

Nevertheless, this study is subject to several limitations, including the use of empirical correlations for shear wave velocity estimation, assumptions regarding engineering bedrock depth, and the application of equivalent-linear analysis. These simplifications may introduce uncertainties in the predicted ground response. Future work incorporating direct geophysical measurements and advanced nonlinear analysis is recommended to further enhance the accuracy of seismic hazard evaluations.

Overall, this study provides valuable insights into the influence of subsurface conditions on seismic response and establishes a practical framework for incorporating geotechnical data into site-specific PGA assessment. The outcomes are particularly relevant for the design and risk assessment of industrial developments in SOGIP and similar coastal and geologically variable environments.

RECOMMENDATIONS

Based on the findings of this study, several recommendations are proposed to enhance the reliability of seismic hazard assessment and support safer infrastructure development in the SOGIP area, Sipitang, Sabah. Firstly, it is strongly recommended that site-specific Peak Ground Acceleration (PGA) values be incorporated into seismic design practices, particularly for lifeline systems and high-importance structures such as industrial facilities, pipelines, storage tanks, and critical infrastructure. The use of generalised regional seismic parameters may lead to underestimation of seismic demand, whereas site-specific inputs provide a more accurate representation of local ground conditions and associated risks.

Secondly, future studies should extend the current analysis by incorporating nonlinear site response modelling to better capture soil behaviour under strong ground motion. In addition, direct shear wave velocity profiling techniques, such as Multichannel Analysis of Surface Waves (MASW) and Seismic Cone Penetration Testing (SCPT), are recommended to improve the accuracy of subsurface dynamic properties and reduce uncertainties associated with empirical correlations.

Furthermore, the development of a localised seismic design spectrum tailored specifically for the SOGIP area is highly encouraged. Such a spectrum would provide engineers with more reliable design parameters that reflect the actual site conditions, thereby improving both structural safety and design efficiency.

Finally, it is recommended that detailed seismic microzonation studies be carried out as a subsequent step. Microzonation would enable spatial mapping of seismic hazards across the SOGIP area, allowing for more informed land-use planning, risk assessment, and infrastructure design at a finer scale.

ACKNOWLEDGEMENTS

The author thanks Khalifa Consult Sdn. Bhd., Perunding Ranhill Worley Sdn. Bhd. / Ranhill Worley Sdn. Bhd., and PETRONAS for facilitating access to the Soil Investigation report for their past FEED project in Sipitang, Sabah. Also, special thanks to the research supervisor at UTM Skudai, Johor, Prof. Ir. Ts. Dr. Ahmad Safuan Bin Abdul Rashid, for his guidance. Appreciation is extended to relevant journal publications for the opportunity to present this work. A special thanks to the Universiti Teknologi Malaysia, which supported this work under Geran Penyelidik Baharu – Enhanced Local Seismic Hazard Assessment through Borehole Data Integration and Site Response Analysis (Q.J130000.2722.04K92).

REFERENCES

1. Adnan, A., Hendriyawan, M. A., Selvanayagam, B., & Marto, A. (2008). Development of seismic hazard maps of east Malaysia. Advance in earthquake engineering applications. Penerbit UTM.
2. Adnan, A., Hendriyawan, H., & Irsyam, M. (2004). Selection and development of appropriate attenuation relationship for Peninsular Malaysia. Malaysian Science and Technology Congress.
3. Alexander, Y., Liau, A., Hamzah, M., Ramli, M. Y., Mat Taib, M. B., Ali, A., & Tjia, H. D. (2008). JMG MAGDM assessment of the seismic threats to Malaysia from major earthquakes in the Southeast Asian region.
4. Cao, T., & Petersen, M. D. (1996). Seismic hazard estimate from background seismicity in southern California. Bulletin of the Seismological Society of America, 86, 1372–1381.
5. Dobry, R., Borcherdt, R. D., Crouse, C. B., Idriss, I. M., Joyner, W. B., Martin, G. R., & Seed, R. B. (2000). New site coefficients and site classification system used in recent building seismic code provisions. Earthquake Spectra, 16(1), 41–67.
6. Erdik, M., & Durukal, E. (2004). Strong ground motion. In Recent advances in earthquake geotechnical engineering and microzonation (pp. 67–100). Springer.
7. Giardini, D., Grünthal, G., Shedlock, K., & Zhang, P. (2003). The GSHAP global seismic hazard map. In International geophysics (Vol. 81, pp. 1233–1239). Academic Press.
8. Harith, N. S. H., Tongkul, F., & Adnan, A. (2025). Investigation of peak ground acceleration on the Kuala Penyu fault and its influence on the Malaysia National Annex. International Journal of Sustainable Construction Engineering and Technology, 16(1), 154–166.
9. Hutchings, S. J., & Mooney, W. D. (2021). The seismicity of Indonesia and tectonic implications. Geochemistry, Geophysics, Geosystems, 22(9), e2021GC009812.
10. Idriss, I. M. (1990). Response of soft soil sites during earthquakes. In Proceedings of the H. Bolton Seed Memorial Symposium.
11. Idriss, I. M. (1991). Earthquake ground motions at soft soil sites. In Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics.
12. Kramer, S. L., & Stewart, J. P. (2004). Geotechnical aspects of seismic hazards. In Earthquake engineering: From engineering seismology to performance-based engineering. CRC Press.
13. Leyu, C. H. (2009). Seismic and tsunami hazards and risks study in Malaysia: Summary for policy makers. MOSTI.
14. Lizurek, G. R. (2015). Mining-induced seismic event on an inactive fault. Acta Geophysica, 63, 176–200.
15. Lillie, R. J. (2015). Beauty from the beast: Plate tectonics and the landscapes of the Pacific Northwest. Wells Creek Publishers.

16. Mayne, P. W., & Kemper, J. B. (1988). Profiling OCR in stiff clays by CPT and SPT. Geotechnical Testing Journal, 11(2), 139–147.
17. Michel, G. W., Becker, M., Angermann, D., Reigber, C., & Reinhart, E. (2000). Crustal motion in East and Southeast Asia from GPS measurements. Earth, Planets and Space, 52, 713–720.
18. Michel, G. W., Yu, Y. Q., Zhu, S. Y., et al. (2001). Crustal motion and block behaviour in Southeast Asia from GPS measurements. Earth and Planetary Science Letters, 187, 239–244.
19. Mohd Zainudin, M. Z. (2015). Geological map of Sabah (4th ed.). Minerals and Geoscience Department Malaysia.
20. MS EN 1998-1. (2017). Malaysia National Annex to Eurocode 8: Design of structures for earthquake resistance—Part 1. Department of Standards Malaysia.
21. Nabilah, A. B., Ahmadi, A., Harith, N. S. H., Adnan, A., & Suhatril, M. (2023). Development of elastic design response spectra for low to moderate seismic regions. Asian Journal of Civil Engineering.
22. Nguyen, V. Q., Aaqib, M., Nguyen, D. D., Luat, N. V., & Park, D. (2020). Site-specific response analysis: A case study in Hanoi, Vietnam. Applied Sciences, 10.
23. Pagani, M., Garcia-Pelaez, J., et al. (2018). Global earthquake model seismic hazard map (Version 2018.1). GEM Foundation.
24. Parham, P. R. (2016). Late Cenozoic sea-level record from Malaysia. Bulletin of the Geological Society of Malaysia, 62, 91–115.
25. Pacheco, J. F., Scholz, C. H., & Sykes, L. R. (1992a). Changes in frequency–size relationship. Nature, 355, 71–73.
26. Pacheco, J. F., & Sykes, L. R. (1992b). Seismic moment catalog of large earthquakes. Bulletin of the Seismological Society of America, 82, 1306–1349.
27. Petersen, M. D. (2007). Documentation for Southeast Asia seismic hazard maps. USGS.
28. Petersen, M. D. (2008). New USGS Southeast Asia seismic hazard maps. Proceedings of WCEE.
29. Pitilakis, K. (2004). Site effects. In Recent advances in earthquake geotechnical engineering. Kluwer.
30. Rodriguez-Marek, A., Bray, J. D., & Abrahamson, N. A. (2000). Geotechnical seismic site response evaluation. WCEE Proceedings.
31. Rosaidi, M. (2001). Earthquake monitoring in Malaysia. Seismic Risk Seminar.
32. Seed, H. B., Murarka, R., Lysmer, J., & Idriss, I. M. (1976). Relationships between acceleration and distance. Bulletin of the Seismological Society of America, 66, 1323–1342.
33. Simons, W. J. F., Socquet, A., Vigny, C., et al. (2007). GPS in Southeast Asia. Journal of Geophysical Research, 112, B06420.
34. Surat, T. (2001). Case history of earth tremors in Malaysia. Seismic Risk Seminar.
35. Tongkul, F. (2017). Active tectonics in Sabah. Universiti Malaysia Sabah.
36. Tongkul, F. (2021). Earthquake science in Malaysia. ASM Science Journal, 14, 1–12.
37. Vucetic, M., & Dobry, R. (1991). Effect of soil plasticity on cyclic response. Journal of Geotechnical Engineering, 117(1), 89–107.
38. Wang, P. C., & Zhang, S. Z. (2016). Accretionary processes in Borneo. Geological Journal, 51, 464–489.
39. Wannier, M. (2017). Geological mapping in Sabah. Bulletin of the Geological Society of Malaysia, 64, 37–49.
40. Zikiri, M. F., Roslee, R., & Madri, A. N. (2020). Landslide hazard identification using geoelectrical mapping. Earth Sciences Pakistan, 4(2), 81–87.