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Integrated seismic hazard analysis of southwest Penang Island through horizontal-to-vertical spectral ratio and probabilistic seismic hazard assessment

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Abstract: Peninsular Malaysia is susceptible to large magnitude earthquakes induced by the regional sources as it is surrounded by countries that are known for their active seismicity. Tremors were felt in Penang Island of Pulau Pinang due to earthquake events in Sumatra, Indonesia in 2005 and 2009. Presence of cracks on buildings in the island was reported caused by the earthquake on 2nd November 2002. The tsunami that hit the island on 26 December 2004 was the aftermath of the Great Sumatra-Andaman earthquake with magnitude 9.1. The investigation of earthquake risks ensures that the effect of earthquake disasters in the inclined region can be reduced effectively. This paper aims to provide a comprehensive seismic hazard assessment in Penang Island by analysing the predominant natural frequency distribution in Balik Pulau through a passive seismic survey method known as horizontal-to-vertical spectral ratio (HVSR) and evaluating the ground motion throughout the island using probabilistic seismic hazard assessment (PSHA) approach. The natural frequencies of Balik Pulau mostly falls in the range of 3 to 4 Hz which is associated with loose deposits and stiff soil layer. The amplification factor extracted from the HVSR curves ranges approximately 4 to 5. The minimum ground motions estimated for a fixed intensity in 50 years for Penang Island is 0.006 g[1] and can reach up to 0.025 g. While the minimum ground motions for a fixed return period of 98 years in 50 years is 0.016 g with maximum of 0.035 g.

Keywords: Microtremor, seismic hazard, ground motions, earthquakes, Balik Pulau

INTRODUCTION

Malay Peninsula is considered free from earthquake induced by local sources due to its location outside of the Ring of Fire region. However, it is still vulnerable towards seismic activities from the surrounding area since Malay Peninsular is bounded by active plate boundaries. Moreover, the possibility of far-field earthquake impact from Sumatra Subduction Zone (SSZ) and Sumatra Fault Zone (SFZ) cannot simply be ignored as these sources are known for their intense seismicity all year round. Penang Island had been experiencing several impacts by the earthquake originated from the Sumatra as reported by the Meteorological Department of Malaysia and several researchers (Adnan *et al*., 2004; 2005; Aghdam *et al*., 2015; Yahya *et al*., 2016) where tremors were felt by the people in the state in 2005 and 2009 as well as presence of cracks in buildings due to the earthquake on 2nd November 2002.

It is well aware that the area close to the earthquake epicenter will experience the most catastrophic damage compared to the site far from the focus. This is because the seismic waves from the earthquake will be attenuated into harmless waves after propagating for some distance. However, the Mexico City 1985 earthquake had proven that source to site distance was not the only factor controlling the degree of destruction. This incident had been discussed by many (Sun & Pan, 1995; Adnan *et al*., 2004; Tuladhar *et al*., 2004; Avar *et al*., 2019) where the most dreadful destruction occurred in Mexico City which was 400 km away from the focus. Mexico City was underlain by a former drained lakebed with soft soil deposits where the ground motions were strongly amplified by the soft soil. The common essence taken from the previous studies show that the evaluation of local site effects is significant in order to determine the impact of ground shaking towards an area.

Malaysia is a tropical country where it experiences a year-round hot and humid climate with frequent rainfalls. This promotes the process of rock weathering where temperature and rainfall are included in the factors influencing the degree of weathering and thickness of residual soils. Hence, a deep weathering profiles and soil mantles exceeding 30 m can often be found in Malaysia (Ahmad *et al*., 2006). Considering the history of far-field earthquake hazard towards Malaysia and thick weathering profiles, a profound seismic hazard assessment is required to be implemented to assist the natural disaster mitigation. This paper aims to evaluate the predominant natural frequency distributions

[1] 1g = 9.81m/s^2

in Balik Pulau district located in the southwest of Penang Island through a passive seismic survey method known as horizontal-to-vertical spectral ratio (HVSR) by generating 1-D HVSR peak amplitude map as well as to analyse the ground motion distributions throughout the island using probabilistic seismic hazard assessment (PSHA) approach.

PULAU PINANG GEOLOGICAL SETTING

Pulau Pinang (Penang in English) is considered as one of the smallest states in Malaysia with an area of 1031 km^2 and is located in the northwest area of Peninsular Malaysia. Pulau Pinang is also the second state that records a high density of population throughout Malaysia. It is divided into two parts which is Seberang Perai located within the mainland of Peninsular Malaysia and Penang Island, that are connected by bridges. Penang Island is mainly composed of granite with some marine clay and silt, and has a granitic range extending in north-south direction at the centre of the island. According to Ahmad *et al*. (2006), the granitic rocks found in Penang Island are divided into three main geological formations which was categorised based on the mineral composition of the granitic rocks. The formations are Tanjung Bungah Formation, Paya Terubong Formation, and Batu Ferringhi Formation. The northern coast of Penang Island is composed of medium to coarse-grained biotite granite with mainly orthoclase and subordinate microcline which belongs to Tanjung Bungah Formation. Whereas in the southeastern half of the island, medium and coarse-grained porphyritic muscovite biotite granite can be found which belongs to Paya Terubong Formation. The last formation present is Batu Ferringhi Formation which is at the north-western coast (Ahmad *et al*., 2006). This particular formation is composed of medium to coarse-grained biotite granite. The coastal area around the island for both east and west are low-lying plains composed of Quaternary deposits such as clay, silt and sand which is illustrated in Figure 1. A major uplifting and tilting during Oligocene/Miocene periods caused the exposure of granite hills to the highest point from sea level, except where alluvium deposits are found (Tan *et al*., 2014; Avar *et al*., 2019). The presence of alluvium deposits at the slopes and foot of granite hills are the product of weathering of granite itself.

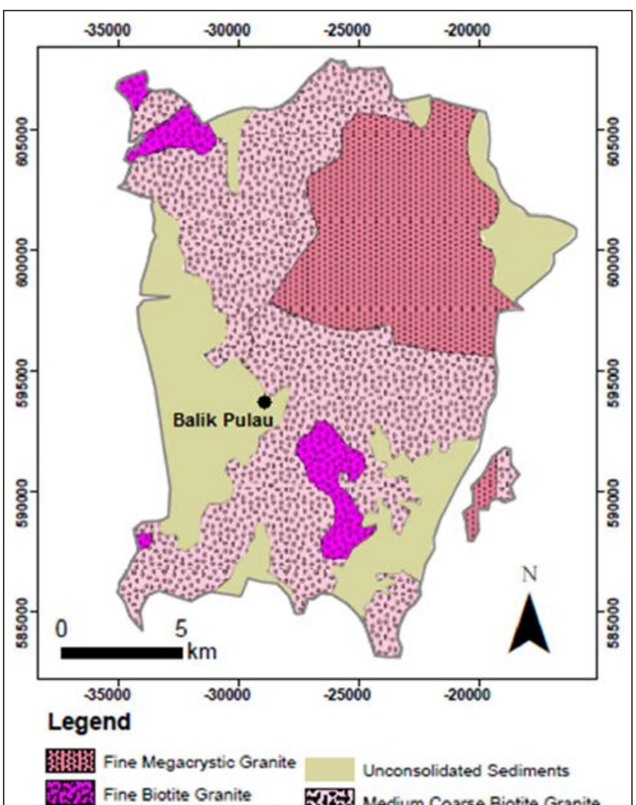

Figure 1: Geological Map of Penang Island.

SOIL PROFILE CLASSIFICATIONS

Shear-wave velocity (Vs) is often applied in the investigation of soil properties. Whereas shear-wave velocity in the uppermost 30 m layer that is based on the travel time from the surface to a depth of 30 m is known as Vs_{30} (Martin & Diehl, 2004). The application of Vs_{30} is commonly found in the process of site response characterisation in global building codes for designing earthquake-resistant structures. It is also applied in seismic hazard mapping by computing the predicted ground motions (Borcherdt, 2012). Vs_{30} enables the evaluation of subsurface characteristics in the top 30 m of the Earth's subsurface. Vs_{30} is also integrated into local seismic hazard maps in order to assess the degree of earthquake's impact towards specific site. It is well aware that the site closest to the epicenter of an earthquake will experience greater impact compared to farther site, but it had been proven that sites with very low Vs_{30} are also exposed to earthquake risks. The computation of empirical Vs_{30} was done by using the mentioned equation (Nakamura, 2000):

$$f = Vs / 4h \qquad \text{(Equation 1)}$$

where f represents the natural frequency of each site and h is the thickness of soil layer. Since the depth of each sites is unknown, the topmost layer is assumed as 30 m thick. Table 1 depicts the classes of soil profile based on the ranges of Vs_{30} that was published by the National Earthquake Hazard Reduction Program (NEHRP) (BSSC, 2003).

An average shear-wave velocity (Vs_{30}) analysis was conducted by Tan *et al*. (2014) to evaluate the soil profile in Pulau Pinang. From the analysis, it shows that Pulau Pinang is divided into three soil profile classes which are class C, class D and Class E. The mainland is predominantly class D (180 m/s $< Vs <$ 360 m/s) with the least class C (360 m/s $< Vs <$ 760 m/s), while Class E ($Vs <$ 180 m/s) can be found in the northwest and south. On the other hand, Penang Island only have two classes which are Class C and Class D. Class D can be found in the west while Class C can be found in the east of Penang Island, respectively. As depicted in Table 1, Class C is associated with very dense soil and soft rock, Class D is associated with stiff soil while Class E is representing soft soil. The Vs_{30} distributions throughout Pulau Pinang is illustrated in Figure 2.

METHODOLOGY

The methodology of this research had been divided into two main phases which are the microtremor data analysis by applying Horizontal-to-Vertical Spectral Ratio (HVSR) technique and the application of Probabilistic Seismic Hazard Analysis (PSHA) method to assess the ground motion in Penang Island. The output of HVSR method focuses in the district of Balik Pulau while the PSHA output covers the whole Penang Island.

Microtremor method using HVSR

Microtremors are defined as weak, and low amplitude vibrations recorded on the Earth's surface. Although tremors from earthquakes are absent, the Earth's surface is always in motion at seismic frequencies, hence resulting in the constant vibrations (Okada, 2003). These vibrations may either be generated by natural phenomena such as river flow, wind, ocean waves or anthropogenic which is induced by human activities such as usage of machinery in constructions, road traffic and footsteps (Okada, 2003). HVSR is one of the passive seismic method that records the seismic response from the microtremors. This approach records the vertical and two horizontals (north-south and east-west) components of the microtremors induced by either natural phenomena or anthropogenic. Geologists are able to identify the natural frequency of the local soil. Based on Bour *et al*. (1998), the data recorded by using this method is reliable to evaluate the seismic behavior of thin and gently dipping surficial layer. Microtremors are assumed to be made up of various waves but primarily surface wave known as Rayleigh waves. The effects of Rayleigh wave can be eliminated by the spectral ratio between both horizontal and vertical components of background noise. This ensures the effect from the geological structure of site is conserved (Bour *et al*., 1998). GEOPSY software is use for data processing whereby Fourier amplitude spectral transformed from three components of ambient vibration waves, then computed into HVSR as simplified in the equation (Kamarudin *et al*., 2016),

$$HVSR = \sqrt{(H^2_{N\text{-}S} + H^2_{E\text{-}W})} / 2V^2 \qquad \text{(Equation 2)}$$

Where,

$H_{N\text{-}S}$: Fourier amplitude spectra in the North-South direction

$H_{E\text{-}W}$: Fourier amplitude spectra in the East-West direction

V : Fourier amplitude spectra in the vertical direction

Table 1: NEHRP soil profile classification (BSSC, 2003).

Soil Type	General Description	Vs_{30} (m/s)
A	Hard Rock	>1500
B	Rock	760 – 1500
C	Very Dense Soil and Soft Rock	360 – 760
D	Stiff Soil	180 – 360
E	Soft Soil	<180
F	Soils requiring site-specific evaluations	

The acquisition site for microtremor data recordings is in Balik Pulau which is located in the southwest of the island. Based on the geology of Penang Island as well as the Vs_{30} discussed earlier in this paper, Balik Pulau is mainly composed of alluvium deposits and stiff soil. A total of 20 data points were acquired within four days. The interval between two points is set to 500 m. The equipment is set to record the microtremors for a period of 60 minutes. A longer recording time ensures that more undisturbed frequency windows to be selected during the data processing. The first acquisition was done from point 1 to point 9. In order to reduce the noises from vehicles on the road and residence

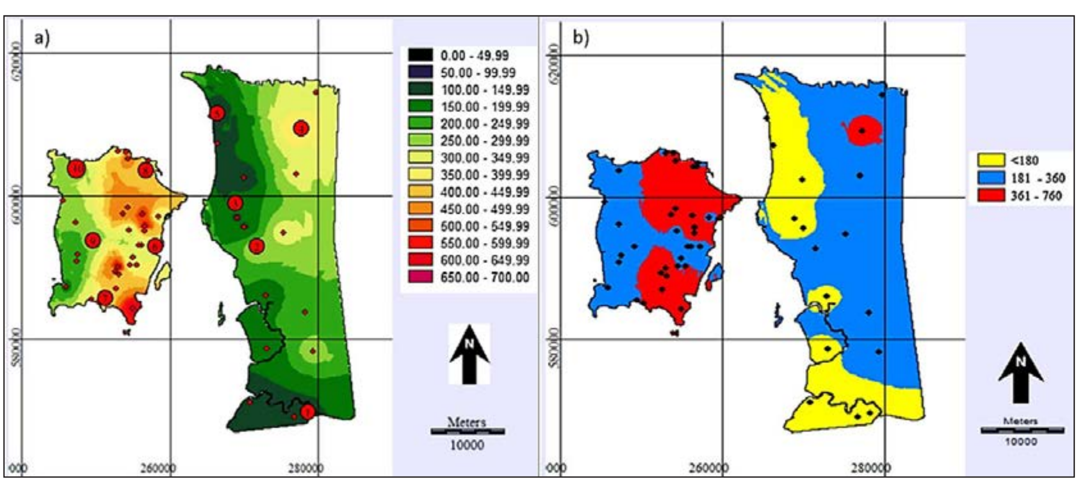

Figure 2: a) Vs_{30} distribution map b) Soil profile classes based on NEHRP (Tan *et al.*, 2014).

activities, the second acquisition starting from point 10, were done after 10.00 pm up until dawn. The first batch acquisition was done in an area that have slightly higher elevation compared to the second batch acquisition. Moving further southwest, the elevation is mostly below 50 m. The location of each acquired point is plotted below in Figure 3 with complete labels.

Probabilistic seismic hazard assessment (PSHA)

The prediction of risks at a specific site caused by the impact of earthquake induced from identified seismic source is known as seismic hazard assessment. The seismic intensity emitted will influence ground-shaking experienced by the area (Loi *et al*., 2018). The most significant elements to be considered in seismic hazard assessment are data of historical earthquakes, regional characteristics of sources and the attenuation relationships or also known as ground motion prediction equation (GMPE). Probabilistic seismic hazard assessment is applied in the study as it is able to quantify uncertainties in the extent of shaking and can be used to interpret the site behavior during occurrence of earthquakes. The distribution of future shaking can be mapped based on the past earthquake events from a particular region.

The basic steps of PSHA had been outlined by Azmi *et al*. (2013) as follows :

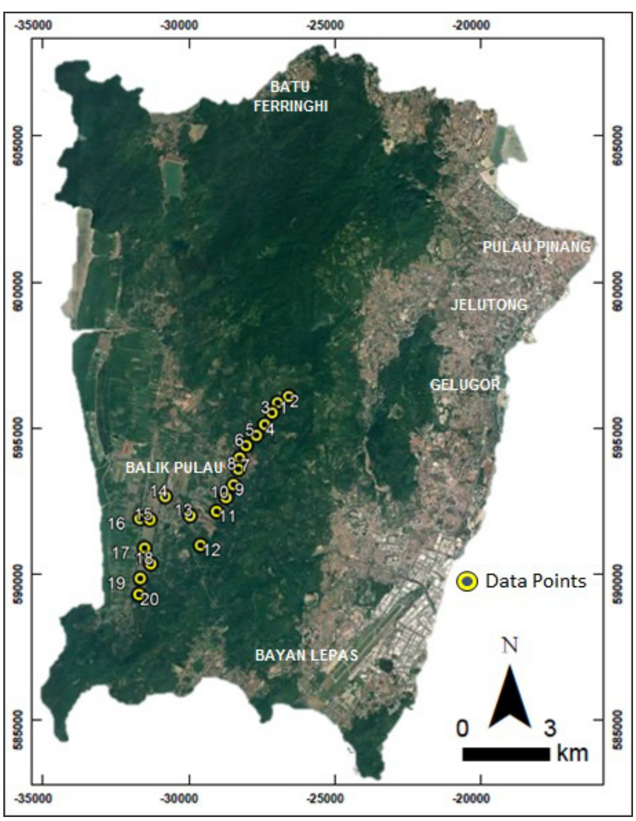

Figure 3: HVSR acquisition points location within Balik Pulau district.

i- Collection of past earthquake records
ii- Identification of earthquake sources
iii- Earthquake characterisation
iv- Source-to-site distances
v- Determination of suitable GMPE
vi- Computation of ground motion

Past earthquake records were extracted from International Seismological Centre (ISC) open source that was set at 600 km radius around Balik Pulau with magnitude minimum of 4 starting from the year 1900 up to 2017. Approximately 6800 earthquake records with various magnitude measurements such as body magnitude (Mb), moment magnitude (Mw) and surface magnitude (MS) were extracted. The events mainly occurred in the Sumatra Subduction Zone and Sumatra Fault Zone which are the regional sources of earthquake for Peninsular Malaysia. Further steps are done to complete an earthquake catalogue which is homogenisation of magnitudes into moment magnitude (Mw) and declustering of events that only preserves the main shocks of earthquakes by removing foreshocks, aftershocks and any duplicates in the events.

Ground motion is defined as the shaking phenomenon on the Earth's surface due to the arrival of earthquake waves. Ground motion can be described in various acceleration expressions such as Peak Ground Velocity (PGV), Peak Ground Acceleration (PGA) and Spectral Acceleration (SA). Ground motions is calculated by adopting the suitable GMPE. This function shows the relationship between the intensity of local ground movement (a), the magnitude of earthquake (M), and the distance between one point in the source of an earthquake (Irwansyah *et al*., 2013). A suitable GMPE had been assigned to each of the earthquake sources which complies the parameters of the sources. The most appropriate GMPE that fulfills most of the subduction zone criteria in this study is the equation that was built by Lin & Lee (2008). The distance of earthquake did not meet the given value where Rmax is 250 km, whereby the distance exceeds 250 km for this study. The equation introduced by Boore *et al.* (2014) was applied to the fault zone since all the parameters listed were fulfilled and was also suggested by Ahmad (2016).

The final outcome for PSHA is the expected ground motions in certain return period. The ground motions are commonly represented in hazard maps. There have been several hazard maps generated by researchers such as by Azmi *et al*. (2013) and Weijie Loi *et al.* (2018) having various ranges of PGA as illustrated in Figure 4 and Figure 5 for 10% probability of exceedance (475-years return period) respectively. For example, the seismic hazard maps in the draft Malaysian national annex (NA) to Eurocode 8 (NA-2017 to MS EN 1998-1:2015 yielded probabilistic PGA for 10% probability of exceedance (PE) for Penang Island is 0.03 g to 0.04 g (Avar *et al*., 2019), while Loi *et al.* (2018) yielded PGA values of 0.011 g to 0.056 g for 10% PE.

RESULTS AND DISCUSSIONS

Microtremor data distribution

The output from the processed data using GEOPSY software is a HVSR curve for each point. A clean data with minimum noise will have a single, clear peak. However, several points show multiple peaks or unclear peak depending on the degree of noise recorded during acquisition. The two significant measurements that can be extracted from the generated H/V curve are natural frequency and amplification factor. These values can be extracted from the highest peak of the curve where natural frequency is the *x-axis* and amplification factor are the *y-axis*. The curves of HVSR are illustrated as shown in Figure 6. The variation in the generated curves at each point may be due to the disturbances such as vehicles, footsteps and wind that was recorded during acquisition. Sine the measurement was done following the roadside, most of the disturbances might come from the traffic. The selection of windows during data processing also influences the final H/V curves generated. In theory, the resonant frequency below 2 Hz is representing area with sediments. Lower frequency is associated with thicker sediment deposits. While frequency higher than 2 Hz may reflects the underlying rocks. The frequency surpassing 12 Hz should be disregard due to high noises.

The distribution of natural frequency for the 20 points acquired in Balik Pulau are between 0.9 Hz and 5.99 Hz as listed in Table 2. The natural frequencies of Balik Pulau mostly falls in the range of 3 to 4 Hz with an exception of one point having measurement more than 5 Hz. The data distributions for natural frequency in Balik Pulau suggested that loose

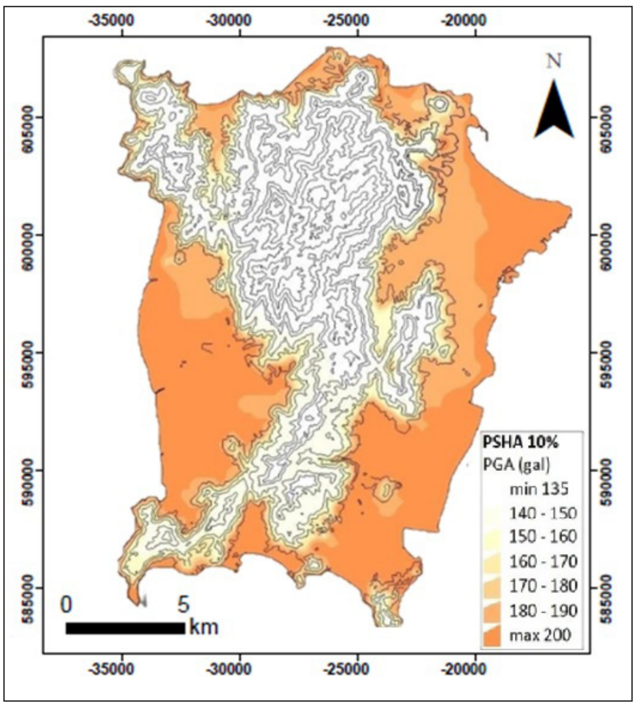

Figure 4: PSHA Map of Penang Island showing the probability of events at 10% PE in 50 years (Azmi *et al*., 2013).

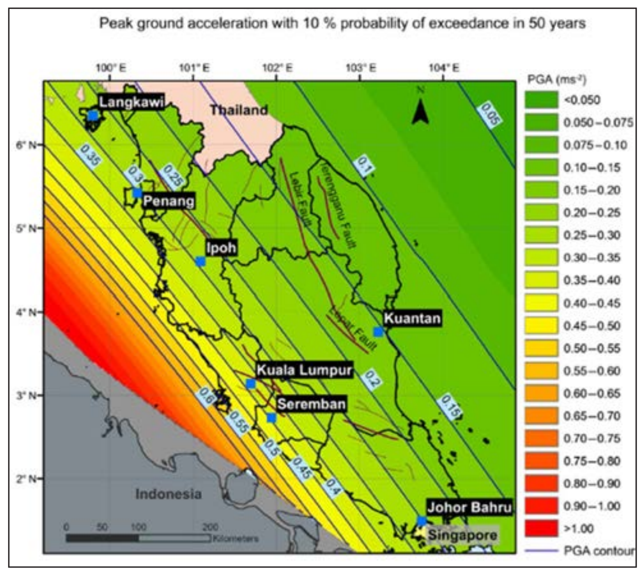

Figure 5: PGA Map of Peninsular Malaysia at rock site condition affected by the Sumatran sources at 10% in 50 years probability of exceedance (Loi *et al.*, 2018).

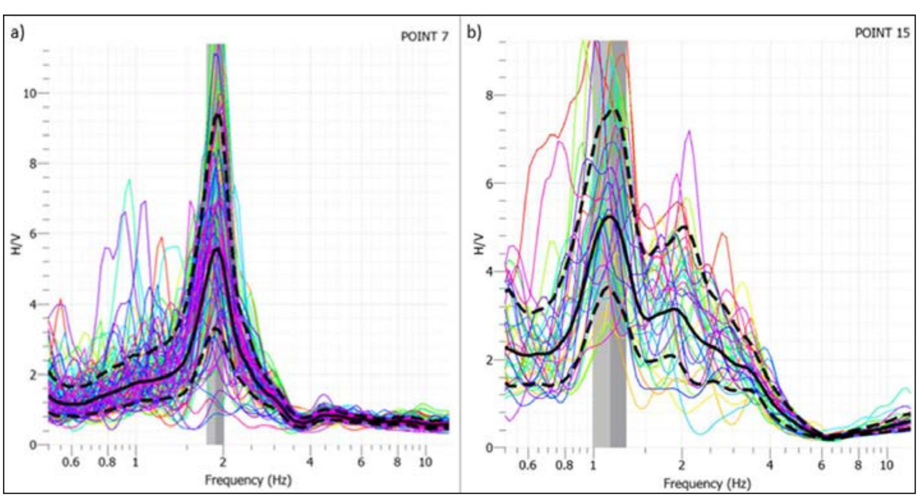

Figure 6: HVSR curves example generated from acquisition in Balik Pulau. a) Single clear peak at Point 7 b) Multiple curves at Point 15.

deposits and stiff soil is predominant in the area. The points that are located in the considerably flat area has a relatively lower natural frequency (f_0) values compared to the points that are in a slightly elevated area (near to the contour lines) as illustrated in Figure 7. The value of f_0 decreases from northeast to southwest, moving further away from the contour lines.

Furthermore, the amplification factor (A_m) distributions in Balik Pulau is approximately 4 to 5 as portrayed in Figure 8. Lower amplification factor is measured in the slightly elevated area which are near the contour lines. On the contrary, the ones in the flat area show a much greater amplification factor relatively. The flat area that is composed

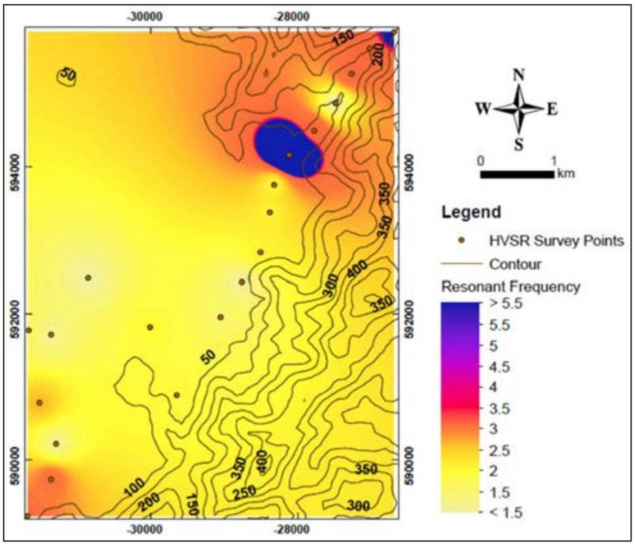

Figure 7: Resonant frequency (f_0) distribution based on 20 points recorded in Balik Pulau.

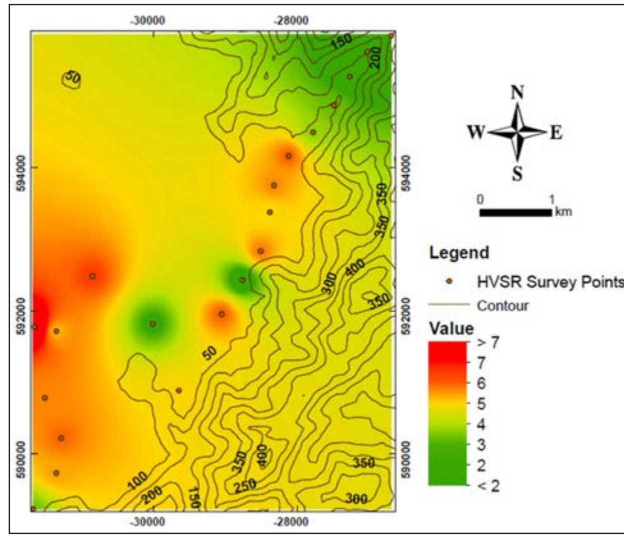

Figure 8: Amplification factor (A_m) distribution based on 20 points recorded in Balik Pulau.

Table 2: Summary of HVSR processing output.

No.	Latitude	Longitude	Resonant Frequency, F0 (Hz)	Amplification Factor, A0	Shear wave Velocity, Vs_{30} (m/s)	Vulnerability Index, K_j
1	5.3700	100.2480	3.360	1.49	403.20	0.66
2	5.3719	100.2514	3.706	2.24	444.72	1.35
3	5.3669	100.2464	3.340	2.50	400.80	1.87
4	5.3633	100.2442	0.944	3.51	113.28	13.05
5	5.3600	100.2417	3.340	3.84	400.80	4.41
6	5.3569	100.2386	5.999	5.88	719.88	5.76
7	5.3531	100.2367	1.925	5.56	231.00	16.06
8	5.3497	100.2364	2.001	4.97	240.12	12.34
9	5.3450	100.2350	2.040	5.68	244.80	15.81
10	5.3411	100.2328	1.021	2.38	122.52	5.55
11	5.3369	100.2300	1.479	5.87	177.48	23.30
12	5.3267	100.2253	1.835	4.96	220.20	13.41
13	5.3356	100.2219	1.925	2.89	231.00	4.34
14	5.3414	100.2142	0.981	6.11	117.72	38.06
15	5.3344	100.2097	1.134	5.20	136.08	23.84
16	5.3347	100.2067	1.558	7.66	186.96	37.66
17	5.3258	100.2083	2.570	5.61	308.40	12.25
18	5.3211	100.2103	1.134	5.81	136.08	29.77
19	5.3167	100.2072	3.117	5.37	374.04	9.25
20	5.3119	100.2069	3.270	3.58	392.40	3.92

of soft soil from Quaternary deposits can be inferred as more susceptible towards seismicity as the amplification of waves occurring in soft soil is much bigger compared to an area with rock layer overlaid by thin soil layer.

Seismic hazard maps

The steps that was outlined by Azmi *et al*. (2013) were followed including a completeness analysis and generation of recurrence model. This is to ensure a complete and reliable seismic hazard map is produced. The seismic hazard maps in this study are produced by using R-CRISIS and ArcGIS software. Two seismic hazard maps were developed for the whole Penang Island which are fixed returned period and fixed intensity in 50 years. It is shown in both Figure 9 and Figure 10 that the value for ground motions are increasing as it moves towards the southwest of the island. This happens as the southwest is much closer to the seismic sources in Sumatra. This clearly shows that shorter distance between the site and the seismic sources influence the susceptibility of the area towards the danger of high magnitude earthquake due to the higher ground motions generated by the seismic activity. The minimum ground motions estimated for a fixed intensity in 50 years for Penang Island is 0.006 g and can reach up to 0.025 g which can be observed in Figure 9.

On the other hand, the PGA values dispersion for a fixed return period of 98 years or 40% probability of exceedance can be observed in Figure 10. The minimum ground motions for a fixed return period of 98 years in 50 years is 0.016 g with maximum of 0.035 g. The greatest ground motion value calculated in Balik Pulau is 0.035 g.

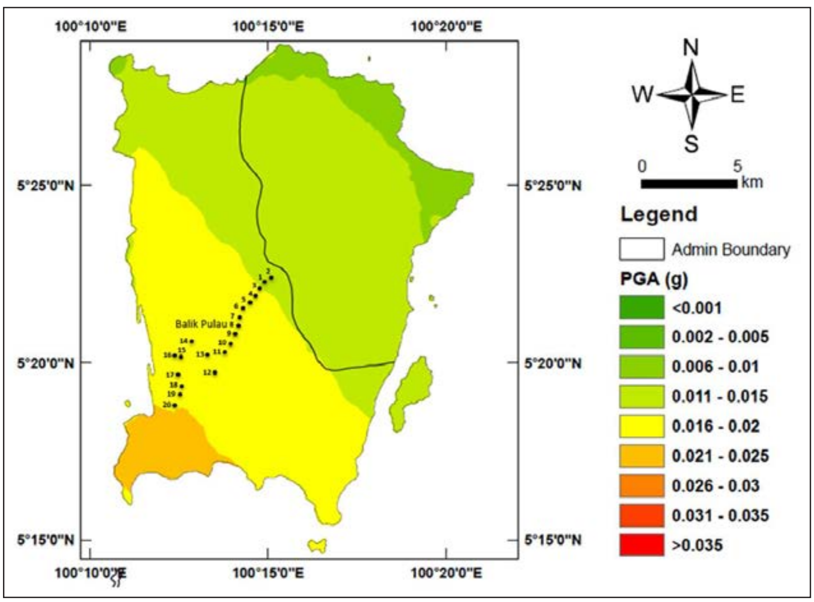

Figure 9: PSHA of Penang Island for fixed intensity in 50 years.

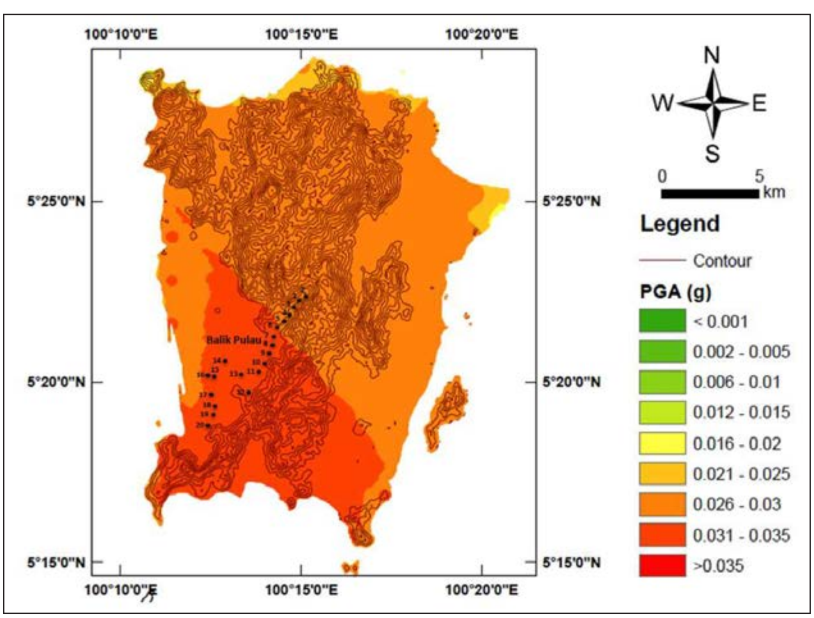

Figure 10: PSHA of Penang Island for fixed return period in 50 years.

The lowest value calculated for overall of Penang Island is in Georgetown area with 0.016 g. By referring to the contour lines shown in Figure 10, it indicates that greater ground motions are found in the alluvial plain area and the values start to decrease in the highland area. This output agrees with the result produced by Azmi *et al*. (2013), area with thicker superficial soil layer are more susceptible to strong ground motion compared to area with thin soil.

CONCLUSIONS

Based on the analysis of substantial data of microtremors acquired in Balik Pulau, the natural frequencies mostly fall in the range of 3 to 4 Hz which is commonly associated with loose deposits and stiff soil layer. A much higher frequency may suggest soft rock. The amplification factor extracted from the HVSR curves ranges approximately 4 to 5. From the maps presented, the low natural frequencies will mostly have a slightly higher amplification factor and they are located in the flatlands area. This outcome shows that loose sediments site will amplify the waves more than the site with hard rock.

Two seismic hazard maps were constructed for Penang Island which are fixed intensity and fixed return period in 50 years. The minimum ground motions estimated for a fixed intensity in 50 years for Pulau Pinang is 0.006 g and can reach up to 0.025 g. While the minimum ground motions for a fixed return period of 98 years in 50 years is 0.016 g with maximum of 0.035 g. As presented in the seismic hazard maps, the highest ground motions are calculated at the area that have the shortest site to source distance.

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