Development of Peak Ground Acceleration Map of Penang Island, Malaysia Using Probabilistic Seismic Hazard Analysis

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Evaluation of peak ground accelerations (PGA) for Penang Island, Malaysia was done using probabilistic seismic hazard analysis. The PGA results on the bedrock were based on Young *et al.* attenuation relationship for moment magnitude (Mw) lower than 8.0 and Petersen *et al.* attenuation relationship for moment magnitude (Mw) larger than 8.0. Amplification factors for ground acceleration were determined by using the correlation between shear-wave velocities in the upper 30m (Vs30) and standard penetration test N-number. SHAKE program was used to obtain amplification factor using ground motion data collected at a nearby station. The results are peak ground acceleration maps of Penang Island for 40% and 10% probability of occurrences in 50 years. For 40% probability, the highest PGA value is 0.44g and the lowest is 0.1g. For 10% probability of occurrences in 50 years, the highest value of PGA is 0.79g and the lowest value is 0.18g.

Key Words: *Probabilistic seismic hazard analysis; ground motion analysis; Penang Island, Malaysia*

1. INTRODUCTION

Penang Island is situated at the northeast of Peninsular Malaysia and has a population of 1.5million (**Fig.1**). The Malaysian peninsula is said to be located in a low-seismic region with low and moderate seismic activity, depending on the distance from the site to the epicenter[2–4]. However, recently there have been a number of earthquakes that affected the island, including the Great Sumatran–Andaman earthquake in 2004, which generated a tsunami as well as severe shaking on high ground in Penang Island.

There are no known reports of structural damage, but records from the Malaysia Meteorological Agency and mass media reported swaying of tall buildings, especially in highly-developed states such as Kuala Lumpur, Selangor, Penang, and Johor[4–7].

In order to develop good prediction, historical data is one of the most important inputs needed. However, these data are scarce and limited. Therefore, data to estimate the probability of earthquakes were taken from the U.S. Geological Survey and the Indonesian Meteorology Agency, BMG. These data include the following about earthquakes from 1871 to 2011: date, location, magnitude, and depth.

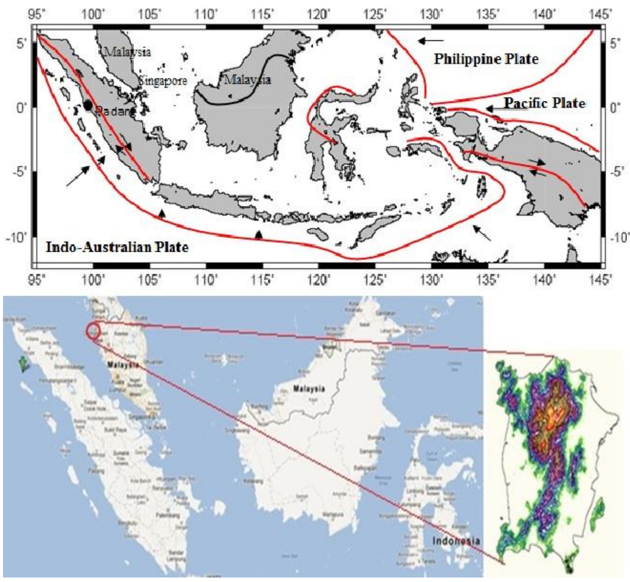

Fig.1 Location of Penang Island and subduction plates surrounding Malaysia

This paper attempts to develop a peak ground acceleration map for Penang Island, Malaysia using PSHA and ground motion analysis. The result indicates the maximum peak ground acceleration for Penang Island for probability of occurrences of 40% and 10% in 50 years.

Peak ground acceleration for bedrock can be determined using probabilistic seismic hazard analysis (PSHA). Using suitable empirical attenuation relationships and historical data for nearby locations, predictions on peak ground acceleration can be made. This mathematical approach can solve prediction of potential earthquakes caused by prospective earthquakes [1].

Assessment of ground response during an earthquake under ideal conditions is based on the assumption that response on the ground surface is based on the upward propagation of stress waves from bedrock formation. Factors affecting ground response include soil conditions and geologic features such as depth of soil deposits, bedding planes of soils overlying bedrock, changes of soil types, and faults crossing soil deposits.

2. PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)

Any structure should be able to withstand a certain amount of shaking, but knowing what level the structure can withstand is always a challenge. PSHA is a mathematical method that can quantify uncertainties in determining the amount of shaking and its result. PSHA is able to describe the distribution of future shaking by using historical earthquake data for an area. Quantifying ground motion is important to understand the behavior of a site during an earthquake[1].

Attenuation models are used to predict probability distribution of ground intensity as a function of variables such as magnitude, distance, faulting mechanism, near-surface site conditions, etc. Attenuation models can represent complicated and time-consuming simulations using a simple equation. A previous study by the author concluded that for Penang Island, it is suitable to use Young *et al*[8] attenuation model for moment magnitude less than 8.0 and Petersen *et al*[9] attenuation model for moment magnitude more than 8.0.

Young *et al*[8] attenuation model is built based on regression analysis of recorded ground motions from inter-plate earthquakes in Alaska, Chile, Cascadia, Japan, Mexico, Peru, and the Solomon Island. The relationship is valid for moment magnitude Mw≥5.0 and distance R from 10 to 500km and is shown in Equation 1 with *y* in g. Penang Island is located on granite bedrock, hence the equation is based on rock conditions.

$$\begin{aligned}\ln(y) &= 0.2418 + 1.414M + \\ &C_1 + C_2(10-M)^3 + \\ &C_3\ln(r_{rup} + 1.7818e^{0.554M}) + \\ &0.00607H + 0.3846Z_T\end{aligned} \qquad (1)$$

with standard deviation, $\varepsilon_{\ln(y)} = C_4+C_5$, C_1 and $C_2 = 0$, $C_3 = -2.552$, $C_4 = 1.45$ and $C_5 = -0.1$.

For moment magnitude more than 8.0, Petersen *et al*[9] is recommended for use, as shown in Equation 2. This attenuation model was built based on Sumatran earthquakes and the data used are suitable for Penang Island usage. The equation is for distances beyond 200km and modified using Young *et al* attenuation model.

$$\begin{aligned}\ln Y_{MODIFIED} &= \ln Y_{YOUNGS}(M,R) + \\ &[-0.0038*(R-200)]\end{aligned} \qquad (2)$$

with R is the distance and Y_{YOUNGS} is equal to equation (1).

In this paper, the Penang Island area is divided into 49 points. For each point, historical records for 600km radius are collected, and only those with moment magnitude more than 5.0 are used for analysis (**Fig.2**). These data are then used with the attenuation relationship as mentioned above to determine the peak ground acceleration.

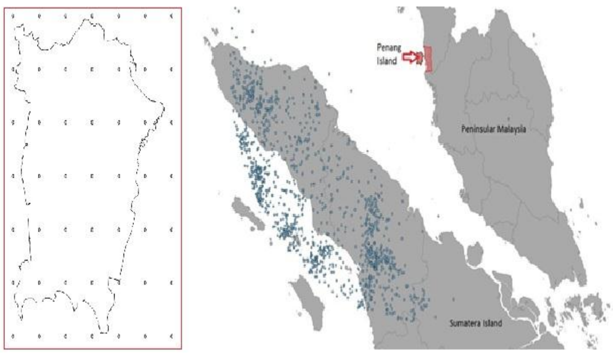

Fig.2 Data collection for each grid on Penang Island

Using total probability theorem, a hazard map for Penang Island can be built. The map is based on the peak ground acceleration distribution for Penang Island with respect to probability of occurrences for 40% and 10% in 50 years. From **Fig.3**, it can be seen that for 40% probability of occurrences in 50 years (98 years return period), the highest PGA for Penang bedrock is 0.058g and the minimum value is 0.049g. For 10% probability of occurrences in 50 years (475 years return period), the highest value is 0.103g and the lowest value is 0.087g. These values are then used to determine the surface PGA for Penang Island by using ground motion analysis.

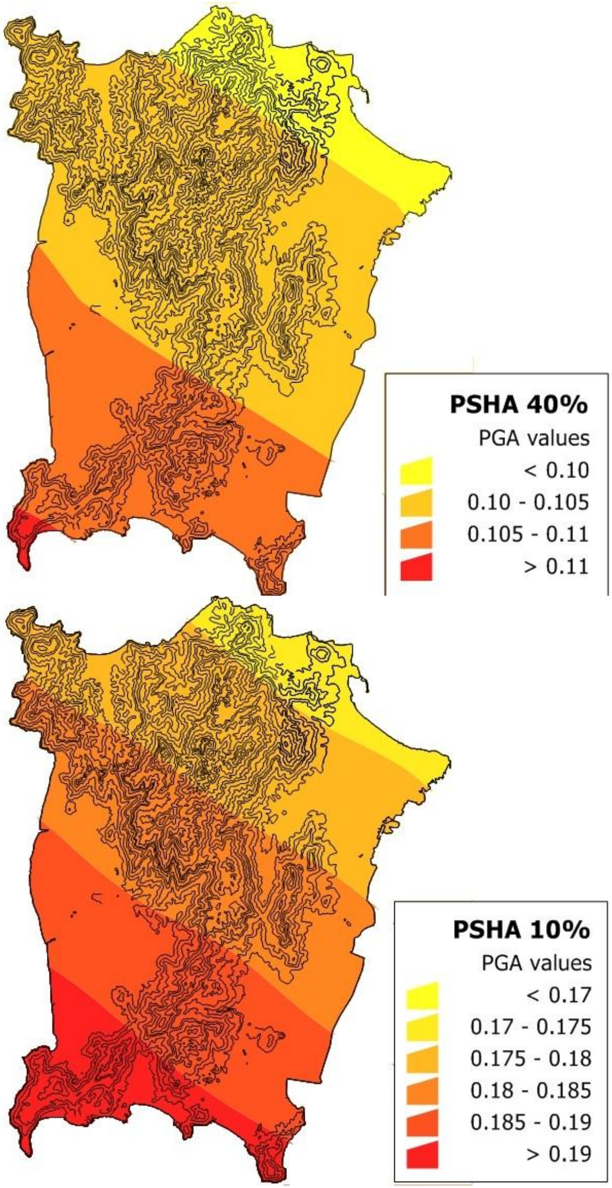

Fig.3 PSHA of Penang Island for probability of occurrences of 40% in 50 years (top) and 10% in 50 years (bottom)

3. GROUND MOTION ANALYSIS

In order to develop PGA map, ground response analysis is used to determine the surface ground motion at a specific site. For purposes of simplification, this paper uses the analysis to determine the ground motion at a site and does not describe the response. Ground response analysis can model the mechanism of an earthquake at the source, propagate the stress wave through earth to the top of the bedrock beneath a particular site, and determine the surface motion based on the influence of the soil layer beneath the surface[10].

Factors affecting the ground response include soil condition and geologic features. Depth of soil deposits and bedrock play important roles in determining the amplification of waves from source to site. In order to analyze ground motion, a soil profile of the site should be known and a reliable source of ground motion should be used.

(1) Input ground motion

In this study, ground motion of a nearby earthquake was used. The input ground motion was collected from the Malaysian Meteorological Agency seismic station in Serdang, Kulim, Kedah (Lat 5.29, Long 100.65). The distance from Penang Island to this station is about 50km. The input ground motion used came from an earthquake with moment magnitude of 8.6 on 28 March 2005 in Pulau Bangkaru, Indonesia (Lat 2.09, Long 97.11). Sherliza *et al*[5] has made the correction needed for this ground motion to be used in the analysis. **Fig.4** shows the ground motion record for the analysis.

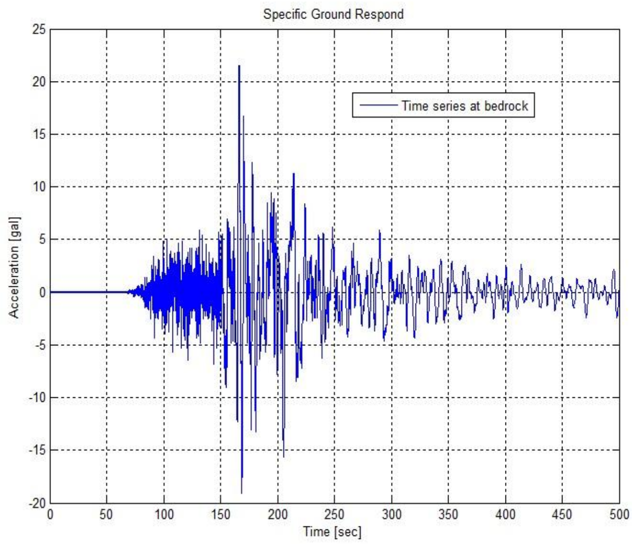

Fig. 4 28 March 2005 Indonesia (Lat 2.09, Long 97.11) earthquake record in N-S direction

(2) Soil profile

Penang Island soil profiles were collected from local consultants for several projects on Penang Island. The soil profiles came from site investigation reports. Standard Penetration Tests (SPT) were done for each borehole, N numbers were recorded, and soil samples taken to determine characteristics. Sites were Batu Ferringhi, Tanjung Bungah, and Bukit Jambul.

From these soil profiles, each layer type was determined and shear-wave velocities were calculated. Lists of the boreholes and calculated shear-wave velocities are presented in Appendix A.

(3) Analytical procedures for predicting groun response within soil deposits

The procedure involve in predicting ground re sponse involves several step. First is to determine th characteristics of motion likely to develop in roc formations underlying the site. Maximum accelera tion, predominant period, and effective duration ar the parameters important to use from the inpu ground motion chosen earlier. An empirical rela tionship from these parameters and the distance fror fault to site is determined[10].

Then, using the soil profile informatio (N-number) from the SPT, dynamic properties o each layer of the soil are determined. This paper use 5% damping for all soil types. There are many rela tionships between shear-wave velocity and SPT N-number available. For this paper, the Japanese Highway Bridge Design Code is adapted, since it is generally used[11]. Equations 3 and 4 show the relationship between shear-wave velocity and N-number for sand and clay type soils.

$$V_s = 80N^{1/3}, (m/s) \text{ for Sand} \quad (3)$$

$$V_s = 100N^{1/3}, (m/s) \text{ for Clay} \quad (4)$$

Then, by using soil parameters (unit weight, shear-wave velocity, and the depth of each layer), computation is performed on the response of the soil deposit to the base-rock motion.

SHAKE program computes the responses in a system of homogeneous, visco-elastic layers of infinite horizontal extent subjected to vertically travelling shear waves. The software is based on a continuous solution to wave-equation adapted for use with transient motions through the Fast Fourier Transform algorithm[10].

Taking one borehole (BH14) in Batu Ferringhi (see borehole descriptions in Appendix A), the ground response for that point is as shown in **Fig.5**. The blue line represents the time series for bedrock and the red line represents the time series for the surface. The difference between the peaks of each point on these time series is the amplification factor for the site.

The amplification factor for BH14 is shown in **Fig.6**. For this borehole, the amplification factor is 3.2. This amplification factor will be used to determine the peak ground acceleration for the site.

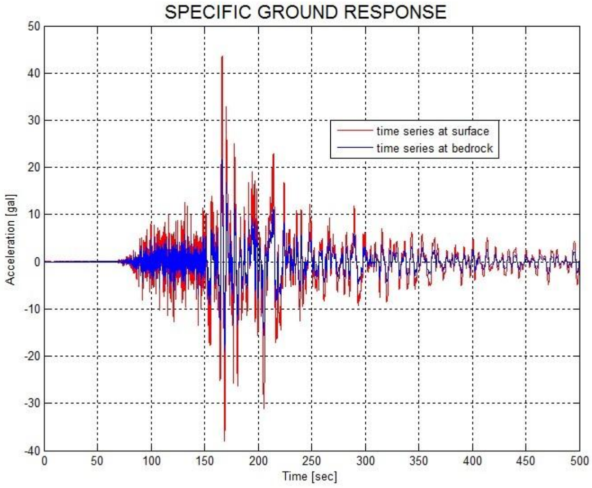

Fig.5 Ground motion for borehole BH14, Batu Feringhi, Penang

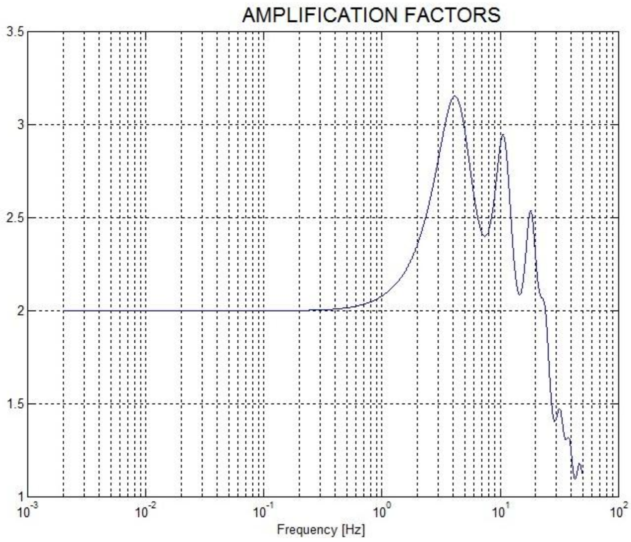

Fig.6 Ground motion for borehole BH14, Batu Feringhi, Penang

For each borehole in Penang Island, separate calculations for ground motion and amplification factor were done. The results were then tabulated and average values for the amplification factor are used for different elevations on the contour map of Penang Island, depending on the location of the boreholes.

4. PEAK GROUND ACCELERATION MAP FOR PENANG ISLAND

From the analysis of PSHA, each location on the contour line was amplified using the result from the SHAKE program as mentioned. Assumptions were based on the idea that soil layers at the tops of hills in Penang Island are the same. From there, a map was made. **Fig.7** shows that for 40% probability of occurrences in 50 years (98 years return period), the highest value of peak ground acceleration is 0.44g and the lowest is 0.1g. For 10% probability of occurrences in 50 years (475 years return period), the highest value of peak ground acceleration is 0.79g and the lowest value is 0.18g.

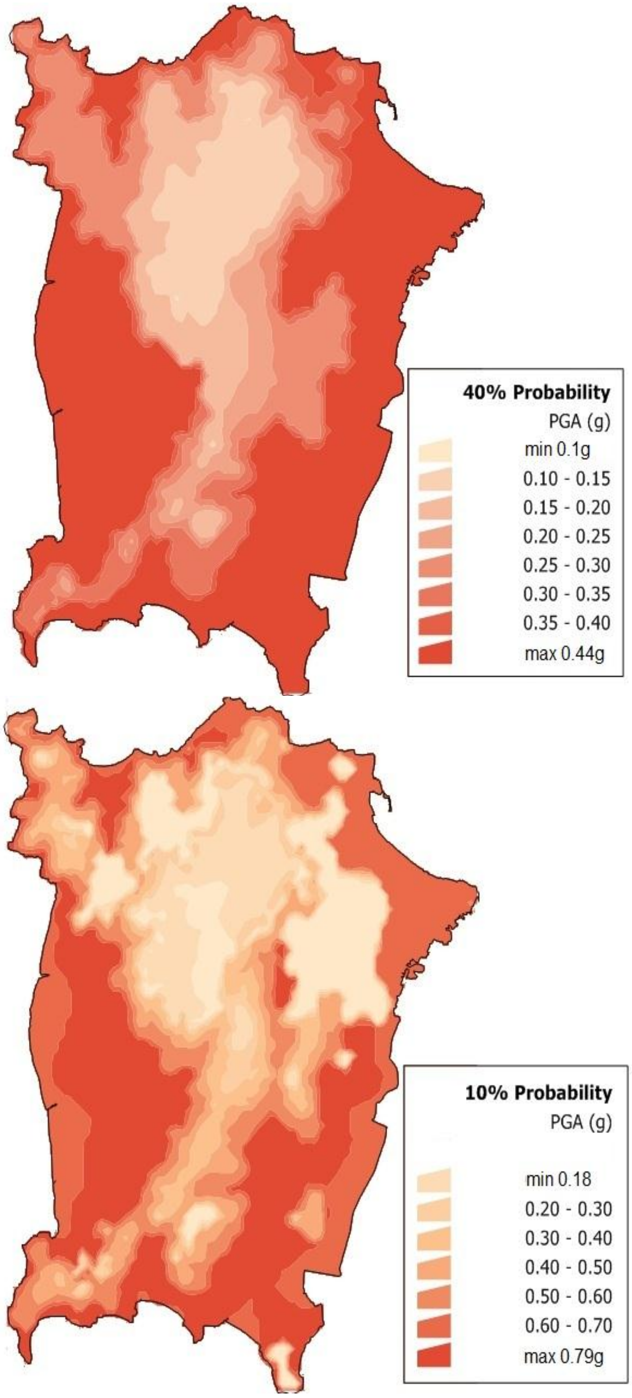

Fig.7 PGA map for 40% probability (top) and 10% probability (bottom) of occurrences in 50 years

In **Fig. 7**, the distributions of peak ground accelerations are highly concentrated in lowlands, especially near the seacoast. This is because the amplifications on lowlands are higher than on hillsides. It is safe to say that most of the slopes on Penang Island can be regarded as safe from the probability of failure due to earthquake for a maximum return period of 475 years.

5. CONCLUSIONS

From the analysis, peak ground accelerations for Penang Island were mapped based on 40% and 10% probability of occurrences in 50 years (98 year and 475 year return periods, respectively). It can be seen that the results are lower if compared to highly seismic regions. For the 98 year return period, the PGA values are 0.1g – 0.44g and for the 475 year return period, the values are 0.18g – 0.79g.

Higher values are concentrated on lowland areas, since they contain softer soils that amplify earthquakes more than the soil types on higher ground. This is because hill soil layers are shallow and stronger bedrock (granite) is available, giving lower amplification factors.

It is believed that from these results, it is safe to say that Penang Island is safe from earthquakes for a maximum 475 year return period. However, further analysis on longer return periods is needed to predict stability of Penang Island hills and slopes against earthquake-induced landslides.

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APPENDIX A –List of boreholes used in analysis

Batu Ferringhi											
Borehole number	**Depth (m)**	**N-number**	**Description**	**Unit weight (g/cm^3)**	**V_s (m/s)**	**Borehole number**	**Depth (m)**	**N-number**	**Description**	**Unit weight (g/cm^3)**	**V_s (m/s)**
BH1	3.6	12	Gravelly sand	1.92	183	BH6	2.4	11	Clay	1.8	178
	6.6	28	Gravelly sand	1.94	242		2.4	50	Granite boulder	2.65	295
	8.25	35	Gravelly sand	1.95	262		1.8	20	Sandy clay	1.85	217
	9.45	44	Gravelly sand	1.97	282		0.65	32	Sandy clay	1.88	254
	5.45	50	Granite	2.65	295		5	50	Granite	2.65	295
BH2	2.4	9	Clayey sandy gravel	1.86	166	BH7	2.55	13	Sandy clay	1.85	188
	4.35	19	Sandy silt	1.88	213		3.9	24	Sandy clay	1.87	231
	6.55	33	Gravelly sand	1.92	257		7.35	50	Granite	2.65	295
	2.65	37	Gravelly sand	1.95	267	BH8	5.7	16	Sandy clay	1.79	202
	6.45	50	Granite	2.65	295		1.55	11	Silty clay	1.83	178
BH3	3	20	Silty clay	1.80	217		1.4	24	Sandy silt	1.85	231
	1.5	38	Clayey sand	1.86	269		6.6	50	Granite	2.65	295
	6.5	50	Granite	2.65	295	BH9	2.7	18	Silty clay	1.83	210
BH4	5.4	21	Gravelly sand	1.9	221		5.4	38	Clayey sand	1.86	269
	6.6	23	Gravelly sand	1.94	228		6.05	50	Granite	2.65	295
	12.3	50	Granite	2.65	295	BH10	5.7	15	Silty clay	1.83	197
BH5	2.4	11	Silty clay	1.8	178		1.8	32	Sandy silt	1.86	258
	1.8	22	Clayey sand	1.86	224		7.8	50	Granite	2.65	295
	9.3	50	Granite	2.65	295						

Batu Ferringhi											
Borehole number	**Depth (m)**	**N-number**	**Description**	**Unit weight (g/cm^3)**	**V_s (m/s)**	**Borehole number**	**Depth (m)**	**N-number**	**Description**	**Unit weight (g/cm^3)**	**V_s (m/s)**
BH11	2.7	10	Clay	1.9	172	BH15	1.5	11	Clayey silt	1.87	178
	1.5	40	Clayey sand	1.88	274		4.5	16	Sandy silt	1.8	202
	7.2	50	Granite	2.65	295		3	39	Sandy silt	1.85	271
BH12	4.35	16	Gravelly sandy clay	1.93	202		4	40	Gravel sand	1.9	274
	0.95	23	Sandy silt	1.95	228		6	50	Granite	2.65	295
	6.0	50	Granite	2.65	295	BH16	1.5	7	Silty sand	1.8	153
BH13	1.5	10	Sandy silt	1.88	172		1.5	12	Silty clay	1.83	183
	1.2	13	Sandy gravel	1.91	188		3	14	Clayey silt	1.93	193
	2.7	28	Sand	1.95	243		3.5	25	Sandy silt	2	234
	6.6	50	Granite	2.65	295		3	50	Gravelly sand	2.1	295
BH14	1.5	5	Clayey silty sand	1.87	137		3.3	50	Very dense gravelly sand	2.3	295
	4.5	8	Clayey silt	1.73	160						
	0.6	17	Sandy silt	1.8	206						
	3	50	Granite boulder	2.65	295						
	2.4	40	Dense gravel sand	2.1	274						
	4.8	50	Sandy silt	2	295						

Tanjung Bungah											
Borehole number	**Depth (m)**	**N-number**	**Description**	**Unit weight (g/cm^3)**	**V_s (m/s)**	**Borehole number**	**Depth (m)**	**N-number**	**Description**	**Unit weight (g/cm^3)**	**V_s (m/s)**
BH1a	1.5	50	Very dense sand with gravel	1.9	295	BH6a	2	8	Loose silty sand with gravel	1.95	160
	1.5	38	Silty sand with gravel	1.85	269		1.45	7	Loose silty sand with gravel	1.99	153
	3	50	Granite	2.65	295		1.5	10	Loose silty sand with gravel	1.84	172
BH2a	2	33	Silty sand	1.8	257		2	13	Medium silty sand with gravel	1.83	188
	8	50	Silty sand with gravel	2	295		2	17	Medium silty sand with gravel	2.03	206
	3.5	50	Granite	2.65	295		1.5	21	Medium silty sand with gravel	2.01	221
BH3a	2	15	Silty sand with gravel	1.99	197		5	50	Granite	2.65	295
	1.45	16	Silty sand with gravel	2	202	BH7a	2	5	Loose silty sand	1.95	137
	1.5	32	Silty sand with gravel	2	254		1.5	8	Loose silty sand	1.95	160
	3	50	Granite	2.65	295		1.5	11	Loose silty sand	1.95	178
BH4a	2	8	Loose silty sand with gravel	2	160		5	15	Medium silty sand	2.05	197
	1.45	10	Loose silty sand with gravel	1.94	172		1	20	Medium silty sand	2.05	217
	1.5	17	Medium silty sand with gravel	1.9	206		2	25	Medium silty sand	2.05	234
	2	23	Medium silty sand with gravel	1.93	228		3	28	Medium silty sand	2.05	245
	3	50	Medium silty sand with gravel	2	295		6	50	Dense silty sand	2.15	295
	3	50	Granite	2.65	295		3	50	Granite	2.65	295
BH5a	2	10	Loose silty sand with gravel	1.95	189						
	2	12	Medium silty sand with gravel	2.03	202						
	3	50	Granite	2.65	295						

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