Estimation of the subsurface structure in Georgetown, Penang Island using single point microtremor observation technique

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Abstract. In this paper, the subsurface structure was estimated using single point microtremor observation technique in Penang Island, Malaysia. Malaysia is located out of Pacific Ring of Fire hence no active tectonic activity happens. However, numerous earthquakes that happened at neighbouring countries act contrary to the myth that Malaysia is seismic free. Tremors from far field earthquake events in Sumatra can be felt at Penang Island. The local site condition is investigated in this study in order to predict the damages on buildings when the earthquake strikes. The study area focused on Georgetown as it is the heart of Penang Island where the economy and population concentrated on. The objective of this study is to determine $V_s$ profile at Georgetown area. Microtremor single point measurements were conducted to estimate the $V_s$ profile at Georgetown area. For estimating the ground structure, Rayleigh wave ellipticity method was adopted to single point measurements. From the results, it is found that Georgetown area has $V_s$ of 216.4 m/s to 286.6 m/s and the predominant frequency ranging from 1.7 Hz to 2.43 Hz. Hence, the ground type of Georgetown area is classified as Class C in accordance to Eurocode 8.

1. Introduction

Local site effect is one of the main concerns in seismic design of structures. The local geologic condition at the site could amplify the seismic wave even though at far distance from the epicentre. The 1985 Mexico City earthquake event is the example of seismic amplification that has caused severe damage to structures and enormous loss of life [1]. Generally, the intensity of the earthquake decreases when the location is further away from the epicentre of the earthquake. However, the earthquake waves can be amplified when the waves propagate through soft sediment layer of soil.

Although Malaysia is located out of the Pacific Ring of Fire, there are still many long-distance earthquake tremors felt in Peninsular Malaysia. Figure 1 demonstrates the historical earthquakes happened in neighbouring country. A total of 73 earthquakes with moment magnitude larger than 5 was recorded from July 2004 to July 2013 [2]. An example of more recent event is the tremor felt in Penang and Kedah after the earthquake in Aceh, Indonesia on 7th December 2016 with $M_w$ of 6.5. The earthquake that occurred on 16th January 2017 in Medan, Indonesia with $M_w$ of 5.7 is another example as its tremor could be felt in Penang. Both incidents had been reported in news, raising concern about the effect of distant earthquake to Penang Island. In fact, there is still lack of seismic study on the local geological condition being done in Penang Island.

There are many methods that had been introduced over the past decades to determine the soil condition. Among them all, the best approach to obtain highly accurate data was found to be boring
exploration. However, this method requires tremendous number of borings to be done in order to determine the soil layer over a wide area, rendering it to be considered as an uneconomical method. Due to this reason, microtremor measurement will be a better alternative due to its simplicity. It can be done even in the presence of some certain degree of artificial tremor [3]. For microtremor single point observation, only one sensing instrument is required. The vertical and horizontal components of microtremor were recorded and used to derive horizontal to vertical (H/V) ratio. The validity of H/V method has been proven to be able to estimate the dynamic characteristics of ground surface layers [4].

Single point microtremor observation has been adopted in seismic microzonation study in world wide. Related past researches in this field includes studies [5] to [11]. In Malaysia, few past studies [12] to [16] have been initiated to investigate the local ground condition in Penang Island and other states in Malaysia using single point microtremor observation. However, these studies are mainly focus on the determination of predominant frequency and sediment thickness of the site. No study on the estimation on subsurface structure using Rayleigh wave ellipticity method has been done in Malaysia.

![Figure 1. Major earthquake events from July 2004 to July 2013 [2]](image)

2. Method

2.1. Microtremor observation
In this study, field observation was done by the microtremor instruments to estimate the subsurface structure of the study area, as shown in Figure 2. The instruments consist of velocity sensor, data logger, velocity sensor, GPS time sensor, power supply and LAN cable. The velocity sensor instrument measures the velocity time history in three axes, North-South (NS) in X axis, East-West (EW) in Y axis and Up-Down (UD) in the Z axis. In order to obtain more consistent data, duration of microtremor measurement varies from 20 minutes to 1 hour depending on the site condition.

A total of eight single point microtremor measurements were carried out at different location, as shown in Figure 3 to study the subsurface structure of the sites. The details of the survey sites are summarised in Table 1. H/V Spectral Ratio was obtained and compared with the ellipticity curve of proposed shear wave velocity profile.
Figure 2. Microtremor instrument set

Table 1. Location of survey sites

| No | Location Code | Coordinate |   |   |
|----|---------------|------------|---|---|
|    |               | Latitude   | Longitude |
| 1  | G11           | 5.43357    | 100.30758  |
| 2  | G21           | 5.42457    | 100.29858  |
| 3  | G35           | 5.42007    | 100.3256   |
| 4  | G43           | 5.41557    | 100.3166   |
| 5  | G47           | 5.41557    | 100.3346   |
| 6  | G63           | 5.40657    | 100.30759  |
| 7  | G67           | 5.40657    | 100.3256   |
| 8  | G94           | 5.39307    | 100.3211   |

Figure 3. Location of single point measurement sites
2.2. Data analysis
For single point microtremor analysis, the processed data files will be analysed by a MATLAB Program to generate H/V Spectral Ratio. Next, different shear wave velocities and thicknesses of soil layers were proposed and used to generate theoretical ellipticity of Rayleigh curve. Both ellipticity curve and H/V spectral ratio should match to validate the estimated shear wave velocity profile. The general procedure for single point microtremor analysis is illustrated in Figure 4.

![Figure 4. General procedure for single point microtremor analysis](image)

2.2.1 Generation of H/V Spectral Ratio graph
The recorded data was analysed using a program written in MATLAB to produce H/V spectral ratio. After loading the data into MATLAB Program, velocity time history in three axes were plotted, as shown in Figure 5. From the velocity time history, five sets of data with interval more than 30 seconds that shows low level of non-stationary transient noise were selected. The datasets were differentiated with respect to time, followed by performing Fast Fourier Transform to generate H/V spectral ratio versus frequency, as shown in Figure 6. The predominant frequency of the ground was determined from the graph.

Among ten sets of graphs plotted for both X and Y axes, the best set of H/V spectral ratio graph was selected, with an obvious peak and frequency near to the average frequency of all the graphs. The selected graph was used to compare with ellipticity of Rayleigh curve as explained in the following subsection.
Figure 5. Graph of velocity time histories in X (top), Y (middle) and Z (bottom) components

Figure 6. H/V spectra ratio of five selected time intervals in X and Y axes
2.2.2 Generation of ellipticity of Rayleigh wave curve

Estimation of subsurface structure starts with proposing the shear wave velocity profiles. The soil thickness and shear wave velocity of each layer was first proposed and to generate the ellipticity curve of Rayleigh wave by means of inversion. The proposed soil layers were altered until the ellipticity curve match with the H/V spectral ratio graph. Figure 7 shows an example of matching ellipticity curve with H/V spectral ratio graph. Finally, the estimated soil thickness and shear wave velocity was established at that study site.

![Figure 7](image_url)

**Figure 7.** Plotting of ellipticity curve and H/V spectral ratio graph

3. Results and Discussion

3.1. Analysis of single point measurement based on Rayleigh wave ellipticity curve method

Single point measurement was conducted at eight sites around Georgetown area, as shown in Figure 2. The ellipticity curve produced from the estimated ground structures at eight measuring sites, as shown in Figure 8 to Figure 11 match well with the H/V Spectral Ratio of the measured data. Estimated shear wave velocity profile of the sites are summarised in Table 2. The ground classification was defined based on $V_{s,30}$ as specified in EC8 (Table 3.1, MS EN 1998-1:2015) [17].

The proposed shear wave velocity profile is considered to be acceptable when the peak of ellipticity curve coincide with the predominant frequency of the H/V Spectral Ratio. Hence, all the acceptable shear wave velocity profile proposed are summarised in Table 2.

![Figure 8](image_url)

**Figure 8.** Comparison of H/V Spectral Ratio and ellipticity curve at G11 and G21
**Figure 9.** Comparison of H/V Spectral Ratio and ellipticity curve at G35 and G43

**Figure 10.** Comparison of H/V Spectral Ratio and ellipticity curve at G47 and G63

**Figure 11.** Comparison of H/V Spectral Ratio and ellipticity curve at G67 and G94
| Location Code | Layer               | Thickness (m) | $V_s$ (m/s) | Predominant Frequency (Hz) | $V_{s,30}$ (m/s) |
|---------------|---------------------|---------------|-------------|---------------------------|------------------|
| G11           | Soft                | 9             | 160         |                           |                  |
|               | Medium              | 20            | 310         |                           |                  |
|               | Hard                | 10            | 550         | 2.20                      | 244.7            |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
| G21           | Soft                | 7.5           | 150         |                           |                  |
|               | Medium              | 18            | 300         | 2.43                      | 253.9            |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
| G35           | Soft                | 13            | 230         | 2.10                      | 255.9            |
|               | Medium              | 18            | 280         |                           |                  |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 800         |                           |                  |
| G43           | Soft                | 14            | 160         | 1.70                      | 218.2            |
|               | Medium              | 26            | 320         |                           |                  |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
| G47           | Soft                | 14            | 200         | 1.84                      | 250.0            |
|               | Medium              | 26            | 320         |                           |                  |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
| G63           | Soft                | 8             | 120         | 2.13                      | 221.5            |
|               | Medium              | 24            | 320         |                           |                  |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
| G67           | Soft                | 9             | 120         | 2.03                      | 216.4            |
|               | Medium              | 23            | 330         |                           |                  |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
| G94           | Soft                | 10.5          | 240         | 2.40                      | 286.6            |
|               | Medium              | 22            | 320         |                           |                  |
|               | Hard                | 10            | 550         |                           |                  |
|               | Engineering Bedrock | 15            | 1000        |                           |                  |
4. Conclusion
This study was carried out to determine the substructure of Georgetown, Penang using microtremor observation technique. Microtremor single point measurement was carried out at eight selected locations in Georgetown. Rayleigh wave ellipticity method was adopted to estimate $V_s$ profile for single point measurement. Based on the results, it is found that Georgetown area has $V_{s,30}$ of 216.4 m/s to 286.6 m/s and the predominant frequency ranging from 1.7 Hz to 2.43 Hz. Hence, the ground type at the selected sites in Georgetown area is classified as Class C ($180 < V_{s,30} < 360$) in accordance to Eurocode 8 (EN 1998-1:2004).

Acknowledgments
The authors gratefully acknowledge that the present research is supported by Universiti Sains Malaysia. The support is under Research University Grant (Grant Number 1001.PAWAM.8014107).

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