DETERMINATION OF GROUND STRUCTURE USING MICROTREMOR ARRAY METHOD

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DETERMINATION OF GROUND STRUCTURE USING MICROTREMOR ARRAY METHOD

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ABSTRAK

Ciri struktur tanah ialah parameter yang penting dalam penilaian kesan tapak seismik untuk reka bentuk struktur gempa bumi. Banyak kaedah geofizik boleh digunakan untuk menganggar struktur tanah. Kaedah pengukuran tapak terbaik yang memerlukan usaha kerja tapak yang minimum dan memberikan anggaran yang tepat adalah perhatian utama dalam kajian ini. Kajian ini menggunakan kaedah pemerhatian gegaran mikro tatasusunan untuk menyiasat ketepatan profil gelombang ricih (V_S) yang dianggarkan dengan kaedah Autokorelasi Ruangan *(SPAC)* dan Tatasusunan Bulat Tanpa Pusat *(CCA)* dengan pelbagai jejari tatasusunan. Berdasarkan profil V_S yang diperolehi, kesan mempertimbangkan ketebalan sedimen melebihi 30m ke atas pengkelasan tanah telah disiasat. Pemerhatian gegaran mikro tatasusunan telah dijalankan di sembilan tapak yang berada di Kuala Lumpur dan Pulau Pinang dengan menggunakan jejari tatasusunan besar (10m dan ke atas), sederhana (5m) dan kecil (1m). Dengan menggunakan kaedah *SPAC*, tatasusunan besar memberi anggaran profil V_S yang terbaik. Dengan menggunakan kaedah *CCA*, keputusan tatasusunan sederhana memberi anggaran yang terbaik antara tiga saiz tatasusunan. Kaedah *CCA* mampu memberi anggaran yang lebih tepat berbanding dengan kaedah *SPAC* semasa tatasusunan sederhana digunakan dalam pemerhatian. Oleh itu, kaedah *CCA* adalah lebih memuaskan dalam kecekapan kerja tapak. Empat daripada lima tapak yang mempunyai ketebalan sedimen melebihi 30m mengalami perubahan kelas tanah menurun sebanyak satu ke dua kelas, manakala kelas tanah satu tapak kekal sama. Walaupun kelas tanah kekal sama, tetapi sambutan pecutan bertambah. Perubahan ini dalam pengkelasan tanah telah memberikan kesan ketara terhadap bangunan ketinggian rendah dan sederhana kerana sambutan pecutan bangunan dengan kala asas daripada 0.1s ke 1.0s bertambah secara drastik semasa ketebalan sedimen melebihi 30m dipertimbangkan.

ABSTRACT

Ground structure characteristic is an important parameter in seismic site effect evaluation for earthquake structural design. Many geophysical methods can be used to estimate ground structure. The best field measurement option that requires least field effort and yet producing accurate estimation is the main concern of this study. This study applies microtremor array observation method to investigate the accuracy of V_S profile estimated using Spatial Autocorrelation (SPAC) and Centerless Circular Array (CCA) methods of various array radii. Based on V_S profile obtained, the effect of considering sediment thickness of more than 30m on ground classification is investigated. Microtremor array observation was conducted at a total of nine sites in Kuala Lumpur and Penang with large (10m radius and above), medium (5m radius) and small (1m radius) array. When using SPAC method, larger array gives better V_S profile estimation. When using CCA method, medium array gives better estimation among three array sizes. CCA method gives better estimation as compared to SPAC method when medium array is used in observation. Thus, CCA method is more favourable in term of fieldwork efficiency. Out of five sites with sediment thickness more than 30m, four sites exhibit ground type changes by reducing one to two classes and the other one remains unchanged. Although the ground type remains unchanged, but the acceleration response increases. These changes in ground type have affected low to medium rise buildings within the fundamental periods of 0.1s to 1.0s significantly because the acceleration response increases drastically when sediment thickness more than 30m is considered.

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LIST OF ABBREVIATIONS

SPAC	**Sp**atial **A**uto**c**orrelation
CCA	**C**enterless **C**ircular **A**rray
N_{SPT}	**N**umber of blows of **S**tandard **P**enetration **T**est
V_S	Shear wave velocity
$V_{S,10}$	Average shear wave velocity for top 10m sediment
$V_{S,30}$	Average shear wave velocity for top 30m sediment
T_S	Site natural period
c_u	Undrained shear strength

LIST OF SYMBOLS

$\rho(r,\omega)$	SPAC coefficient
ω	Angular frequency
θ	Azimuth between two observation points
$\emptyset$	Azimuth of incidence for incoming plane waves
γ_I	Importance factor
η	Damping correction factor with a reference value of $\eta = 1$ for 5% viscous damping
a_g	Design ground acceleration on type A ground
a_{gR}	Reference ground acceleration on type A ground
c	Phase velocity of surface wave
d_i	Sediment thickness of i-th layer
k	Wavenumber
r	Inter-station distance
$C_{A,B}(\omega)$	Cross spectra of the records obtained at x_a and x_b
$E[\ ]$	Ensemble average over the time
G	Power spectral density
H_S	Sediment thickness
J_0	Zero order Bessel function
J_1	First order Bessel function
N_{SPT}	Number of blows of Standard Penetration Test
$N_{SPT,i}$	N_{SPT} of i-th layer
S	Soil factor

$S_e(T)$	Elastic response spectrum
T	Vibration period of a linear single-degree-of-freedom system
T_B	Lower limit of the period of the constant spectral acceleration branch
T_C	Upper limit of the period of the constant spectral acceleration branch
T_D	Value defining the beginning of the constant displacement response range of the spectrum
T_S	Site natural period
V_S	Average shear wave velocity
$V_{S,i}$	Shear wave velocity of i-th layer

CHAPTER 1

INTRODUCTION

1.1 Background

Malaysia is located out of Pacific Ring of Fire. However, Malaysia is still subjected to distant earthquake, especially in Peninsular Malaysia. Recent years, more tremors are felt in Peninsular Malaysia as a result of earthquake happened in Sumatra. There is one tremor reported in 2016 and two tremors reported in 2017. Since the epicenter is located hundred kilometers away from Peninsular Malaysia, these tremors can be considered as far field earthquake. Meanwhile, local site effect is one of the major concerns in far field earthquake. Figure 1.1 shows the tremor felt reported in Peninsular Malaysia reported in newspaper.

Indonesia Earthquake: Residents report tremors felt in PJ, Shah Alam, Kajang

Astro Awani | March 02, 2016 22:20 MYT

The locations of where tremors were felt in Selangor, as claimed by members of the public.

KUALA LUMPUR: The Selangor Fire and Rescue Department received several reports from members of the public in Petaling Jaya, Shah Alam and Kajang who claimed they felt some tremors tonight.

The department said the first report was received by the Petaling Jaya Section 7 Fire and Rescue Department on claims that some tremors were felt at the PKNS flats there.

The Shah Alam Fire and Rescue Department also received distress calls, at 9.09pm, on reports of tremors felt at Block A of the Kampung Baru Hicom flat in Section 26.

As for the Kajang Fire and Rescue Department, their distress calls came in at 9.16pm on reports that tremors were felt at the Tiara Park Homes in Taman Bukit Ria.

Figure 1.1: Newspaper cuttings on tremor felt in Peninsular Malaysia

Tremors felt in Peninsular Malaysia following Sumatra quake

Share this story Share Tweet Share

Parts of Peninsular Malaysia experienced tremors following an earthquake which struck North Sumatra at 8.42pm.

By NST ONLINE - January 16, 2017 @ 9:40pm

KUALA LUMPUR: Parts of Peninsular Malaysia experienced tremors following an earthquake which struck North Sumatra at 8.42pm.

The Malaysian Meteorological Department, in a statement issued tonight via its Facebook page, said the medium-sized earthquake bore a magnitude of 5.5.

It struck at a depth of 10km in Northern Sumatra, south west of Binjai, Indonesia.

Sumatra quake: Tremors felt in Johor Baru

SHARE

Posted on 13 August 2017 - 07:19pm

Last updated on 13 August 2017 - 08:08pm

Johor Fire and Rescue Department (JBPM) arrives at the Inland Revenue Board (LHDN) building in Jalan Padi Emas 1, after a report on tremors felt at 11.10am, in Johor Baru, on August 13, 2017. — Bernama

JOHOR BARU: Minor tremors following the earthquake in Sumatra were felt in several places in Johor Baru this morning.

According to a Fire and Rescue Department (JBPM) spokesman, so far, three reports on tremors were received, namely at the Inland Revenue Board (LHDN) building in Jalan Padi Emas 1, Menara Kastam in Jalan Tun Razak and Menara Tabung Haji at Jalan Ayer Molek.

However, no injuries or cracks to buildings were reported.

Figure 1.1: Continued

Local site effect is the effect of local geological condition on the seismic wave. One of the examples of geological condition is the soft sediment thickness. Soft sediment thickness can modify the nature of the seismic wave. When seismic waves travel from bedrock to soft sediment, the amplitude of seismic wave will be amplified due to reflection and refraction of wave at the boundary of soft sediment and bedrock. Figure 1.2 illustrates the process of reflection and refraction of seismic waves. The ground motion amplification can cause devastated seismic hazard to the local community, where the site is few hundred kilometers away from the epicenter. One of the good examples of this incident is the Michoacan Earthquake in Mexico City in 1985. Figure 1.3 illustrates the amplification of Michoacan Earthquake in Mexico City. The PGA at Campos, which is nearest to the epicenter, is 150cm/s^2. It is then attenuated to 18cm/s^2 at Teacalco. However, due to amplification, the PGA at SCT appears to be 170cm/s^2, which is higher than PGA at Campos. (Singh et al., 1988) In order to evaluate local site effect on seismic structural design, ground structure of the site must first be estimated.

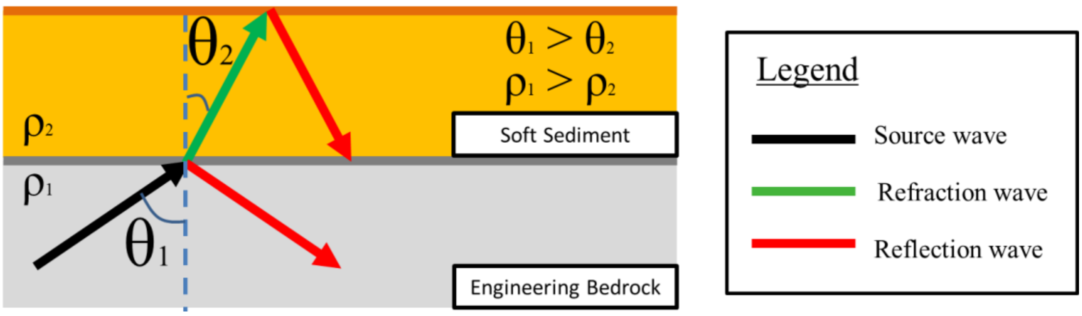

Figure 1.2: Process of reflection and refraction of seismic wave

There are many geophysical methods to estimate ground structure such as reflection survey, refraction survey, PS-logging, microtremor survey, electromagnetic survey, gravity survey and magnetic survey. One of the non-invasive methods to estimate ground structure is microtremor survey method. Microtremor is ambient vibration of the ground surface. Its amplitude ranges from 10^{-4} to 10^{-2} mm and it is far below human sensing (Okada, 2003). The sources of microtremor can be due to human activity and natural phenomena such as oceanic waves and variation of atmospheric pressure. Microtremor due to human activity has frequency above 1 Hz while microtremor due to natural phenomena has frequency below 1 Hz (Okada, 2003).

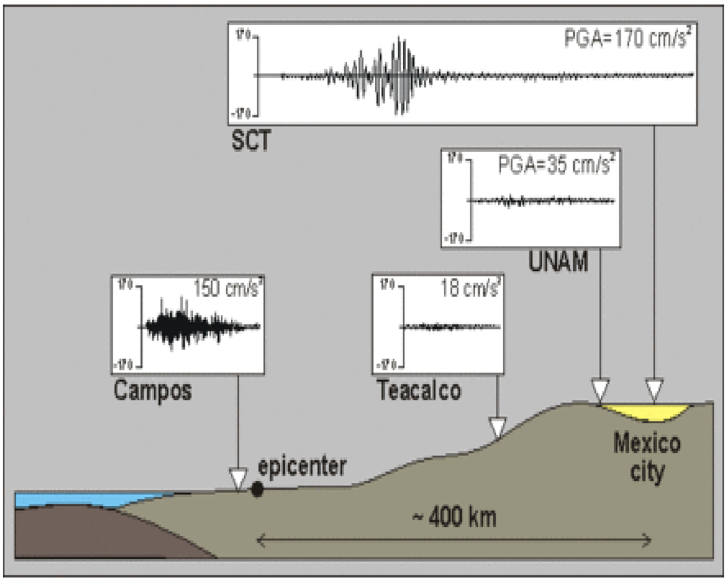

Figure 1.3: Amplification of Michoacan Earthquake in Mexico City in 1985 (Singh et al., 1988)

Microtremor observation can be conducted in single point observation and array observation. Microtremor single point observation requires only one sensing instrument while microtremor array observation is a measurement method using a series of microtremor sensing instruments and deploying them in an array formation. Active seismic source is not needed for microtremor measurement. As compared to other geophysical methods, this method is relatively simple, non-destructive and economical.

Shear wave velocity profile (V_S profile) represents to ground structure profile. In order to estimate ground structure, V_S profile must be obtained from dispersion curve of surface wave by performing inversion. Surface wave in this case is referred to Rayleigh wave. Therefore, data measured must be analysed to obtain dispersion curve. Many data analysis methods can be employed. In this study, two analysis methods which are Spatial Autocorrelation (SPAC) method and Centerless Circular Array (CCA) method are adopted. SPAC method was developed by Keiiti Aki in 1957. It requires minimum of four sensors. Three sensors are placed on the vertex of the equilateral triangle and one sensor is placed at the center of the circle. CCA method was developed by Ikuo Cho in 2004. Cho et al. (2004) claimed that sensor at the center is not needed and it can give promising accuracy with smaller array size as compared to SPAC method.

Due to the frequent tremors felt in Malaysia, the government has decided to implement seismic design code in construction industry. Thus, Malaysia National Annex (NA) to MS EN 1998-1:2015 has been published in December 2017. Two types of ground classification are introduced based on sediment thickness. Table A1 is introduced in this national annex to supplement Table 3.1 in MS EN 1998-1:2015 for ground type classification of sediment thickness more than 30m. Ground classification is based on shear wave velocity of top 30m sediment ($V_{S,30}$), number of blows of standard penetration test (N_{SPT}) or undrained shear strength (c_u) in Table 3.1 (MS EN 1998-1:2015) while it is based on natural period of site (T_S) in Table A1 (NA,2017).

1.2 Study Area

This study was carried out at selected sites in Kuala Lumpur Federal Territory and Penang State. Kuala Lumpur and Penang are two main cities in Malaysia due to its economy status and highly densed population. These two cities also have highest building structures density in Malaysia. Thus, they are more susceptible to earthquake disaster risks as compared to cities in other states.

1.3 Problem Statement

Acquiring the accurate estimation of ground structure using the smallest array in microtremor observation is the upmost priority in field measurement. Larger array size and more sensors will result in higher field effort and lower survey efficiency. Moreover, large array is challenging to be employed in cities where most spaces are fully occupied. Thus, it is more preferable to use smaller array size in practice. SPAC method requires more than three sensors and larger array radius to obtain higher accuracy in dispersion curve estimation. CCA method only requires minimum of three sensors to give similar dispersion curve estimation (Tada et al., 2006). Cho et al. (2004) claimed that CCA method has advantage in analysing data recorded using a smaller array size. However, the accuracy of the V_S profile estimation result based on CCA method is still not well studied as compared to SPAC method. This has sparked an idea to carrying out this research that involving microtremor observation using various radii.

Seismic loading applied to structures is determined based on ground classification. Ground classification is normally based on Table 3.1 in MS EN 1998-1:2015 by considering sediment thickness of 30m. It is also the common practice that soil boring is conducted up to 30m from ground surface. However, Table A1 in Malaysia National Annex has suggested to consider sediment thickness more than 30m in ground classification if the site has sediment thickness more than 30m. The effect of considering sediment thickness more than 30m in ground type classification is still not known yet, either it will improve or worsen the overall ground type. This has initiated the intention to include this topic in the research.

1.4 Objectives

The main objectives of this study are:

i. To investigate the accuracy of ground structure estimated using Spatial Autocorrelation (SPAC) and Centerless Circular Array (CCA) methods of various array radii.

ii. To assess the effect of considering sediment thickness of more than 30m in ground classification based on Table A1 in Malaysia Annex to MS EN 1998-1:2015.

1.5 Scope of Study

This research focuses on the ground structure estimation using microtremor array observation method. Field work were conducted at nine sires in Kuala Lumpur and Penang State due to the availability of borelog for comparison with the estimated ground structure. To determine the best option of field measurement, three array radii namely large (≥ 10m), medium (5m) and small (1m) were considered and the data were analysed using SPAC and CCA methods. The accuracy of the ground structure prediction is assessed through comparison with corresponding soil investigation report that is assumed to be the true ground structure at the site. The best ground structure estimated from SPAC method is further analysed to investigate the effect of considering sediment thickness of more than 30m in ground classification.

1.6 Dissertation Outline

This dissertation consists of five chapters:

Chapter 1 presents the background, study area, problem statement, objectives, scope of study and dissertation outline. This chapter gives an overview of this research.

Chapter 2 discusses the theory of microtremor array measurement, relationship of shear wave velocity profile and dispersion curve, reliability and application of SPAC and CCA methods. This chapter also reviews previous work done using SPAC and CCA methods.

Chapter 3 covers the methodology used in this research. This chapter discusses the approach used in desk study, geotechnical data screening, survey site selection, microtremor array observation, estimation of dispersion curve using SPAC and CCA methods, comparison of estimated ground structure and ground type classification for site with sediment thickness more than 30m.

Chapter 4 discusses the results obtained from the research. The results are presented in four main sections, namely, ground structure estimated using SPAC method, ground structure estimated using CCA method, comparison of dispersion curves using SPAC and CCA methods with theoretical dispersion curve and effect of considering sediment thickness more than 30m in ground classification.

Chapter 5 concludes the important findings together with recommendations for improvement for future study. List of references and appendices are attached in the last part of dissertation.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter discusses about the theory and application of microtremor array measurement in estimating shear wave velocity (V_S) profile. It also provides a basic idea about the relationship of V_S profile and dispersion curve. The analysis method, which is also the core of this research is also discussed. Two methods involved in this research to determine dispersion curve are Spatial Autocorrelation (SPAC) method and Centerless Circular Array (CCA) method. Their reliability and application are summarized in the following sections.

2.2 Microtremor Array Measurement (MAM)

Records of microtremor show that microtremor is highly variable and irregular vibratory phenomena by the means of temporarily and spatially due to the uncontrolled natural phenomena source such as oceanic wave and variation in atmospheric pressure. Microtremor array measurement (MAM) utilises the microtremor caused by these natural sources and treats various aspect of microtremor spectra in accordance to theory of stochastic process. Most of the microtremor sources are identified to be acting on the Earth's surface or oceanic sea bed. Thus, the dominant wave component is considered to be surface wave over the body wave. Since dispersion curve of surface wave is a function of subsurface structure, MAM makes use of the dominant surface wave in microtremor to estimate V_S profile by inverting the dispersion curve of surface wave. In recent years, MAM has gained more interest due to its advantages as compared to conventional geophysical methods. It is popularly known that MAM provide useful information of sub-soil dynamic properties. The main advantages of MAM are its low operation cost and capability to provide non-destructive measurements at every corner of a highly populated city with relatively large penetration depth (Ohrnberger et al., 2004). Many researchers have used this method to estimate V_S profile of their study area such as Horike (1985), Yamanaka et al. (1994), Horike (1996), Tokimatsu (1997), Chouet et al. (1998), Ishida (1998), Miyakoshi et al. (1998), Scherbaum et al. (1999), Bettig et al. (2001), Satoh et al. (2001), Asten and Dhu (2002), Estrella and González (2003), Asten et al. (2004), Maresca et al. (2006), Davoodi et al. (2008), Morikawa et al. (2009), Kiyono et al. (2011), Zaineh et al. (2012), Hamasaki et al. (2013), Su et al. (2015) and Setiawan et al. (2016).

2.3 Shear Wave Velocity Profile and Dispersion Curve Estimation

By assuming that the ground structure at site is horizontally stratified and the microtremor is predominantly consists of surface wave, the analysis of MAM allows us to obtain dispersion curve of the surface wave (Okada, 2003). In order to estimate a reliable shear wave velocity profile using inversion of dispersion curve, a method that can retrieve an acceptable quality of dispersion curve is needed. Considering that the microtremor consists mainly of Rayleigh wave in the vertical plane, thus analysis the vertical component in MAM is sufficient to obtain the dispersion curve of Rayleigh wave. The estimation of dispersion of Rayleigh wave can be carried out using two methods, which are SPAC method and CCA method.

2.4 Reliability of SPAC and CCA Methods

Since the introduction of microtremor array observation to estimate shear wave velocity profile, many methods have been proposed and modified to determine the dispersion curve of surface wave. One of the most applicable method is SPAC method. SPAC method can be found in many articles and a number of studies, such as Estrella and González (2003), Asten et al. (2004), Ohrnberger et al. (2004), Davoodi et al. (2008) and Lal Shrestha (2011), have been conducted to compare the shear wave velocity profile estimated using SPAC method with other conventional methods such as PS logging, gravity survey and geological data. Meanwhile, CCA method is a new method developed by Cho et al. (2004) based on the SPAC method by Aki (1957). As compared to SPAC method, relatively less studies were done to validate CCA method.

In aspect of site evaluation, the vital component of these methods is the accuracy in estimating the shear wave velocity profile at site. Since shear wave velocity for 30m sediment thickness is needed for ground classification, thus the accuracy of shear wave velocity profile for first 30m is utmost important to be achieved by these estimation methods. Asten et al. (2004) stated that SPAC method has achieved a precision of ±10% or better in the $V_{S,30}$ zone of unconsolidated but moderately homogeneous sediments. They concluded that SPAC method has the potential to provide shear wave velocity profile of soils and near-surface basement rocks and suitable for input into a site response model. Cho et al. (2008) applied CCA method to analyse data of a 0.3m radius miniature array. Their study has shown that the Rayleigh wave phase velocity estimated has reasonable accuracy up to wavelengths of several ten meters. The average shear velocities to depths of 10m, 20m and 30m were consistent with available PS-logging data and known geologic structure. As a reconnaissance survey, this accuracy within sediment thickness 30m appears to be convincing for preliminary site effect evaluation.

Lal Shrestha (2011) conducted a validation of SPAC method with PS-logging data at Toyota Community Baseball Ground, Jyoso City, Ibaraki Prefecture, Japan. The study found out that dispersion curve determined from a triangle array of 40m side length has a close match with the one calculated from PS-logging data.

Nakai et al. (2011) validated CCA method with past literature by estimating the shear wave velocity profile at Chiba City, Japan. Their research demonstrates that the observation-based phase velocity based on CCA method using 44m and 22m side length arrays agrees fairly well with the one computed from existing soil profile. Thus, an array of seismometers can effectively be used to estimate the deep soil structure using CCA method.

In short, most of the studies have shown that SPAC method is capable to give reasonable accuracy of estimated shear wave velocity profiles with several 10m of array radius. However, application of SPAC method on miniature array has not studied yet as well as comparing with CCA method. The previous works done to validate SPAC and CCA methods are summarized in Table 2.1.

2.5 Application of SPAC and CCA Methods

Morikawa et al. (2009) adopted SPAC method to model V_S profile in Hsinchu, Taiwan. Figure 2.1 shows shear wave velocity profiles at each site in Hsinchu City, Taiwan, where the profile arrangement order is from seashore area to Hsinchu City. Their findings have shown that four layers are determined around Hsinchu City and five layers are determined at seashore area around Hsinchu City. These four layers sediment ranges from 500 m/s, 800 m/s, 1200 m/s and 2000 m/s. At around seashore area, a very soft soil layer is presence with velocity of 250 m/s. The depth of bedrock is about 1000m below ground level with velocity of 3000 m/s.

Table 2.1: Validation of SPAC and CCA methods

Author	Site	Target Method	Validation Method	Array Size (m)	Number of Sensors	Velocity Profile
Estrella and González (2003)	Mexico City, Mexico	SPAC	F-K Method	1000 (SL)	4	Comparable
Asten et al. (2004)	Perth, Australia	SPAC	SCPTs	25 – 50 (R)	7	Comparable
Ohrnberger et al. (2004)	Lower Rhine Embayment, Germany	SPAC	Wavefield Simulation	150 – 900 (SL)	12	Comparable
Cho et al. (2008)	-	CCA	PS-logging, Existing Soil Profile	0.3 (R)	6	Comparable
Davoodi et al. (2008)	Tehran Site, Shaghayegh Park, Iran	SPAC	PS-logging	25, 35, 50 (R)	4,6,7	Slightly Deviate
Lal Shrestha (2011)	Jyoso City, Japan	SPAC	PS-logging	40 (SL)	7	Comparable
Nakai et al. (2011)	Chiba City, Japan	CCA	Existing Soil Profile	1500 – 4500 (SL)	4	Comparable

Note : SL = side length; R = radius; SCPTs = Seismic cone penetration tests

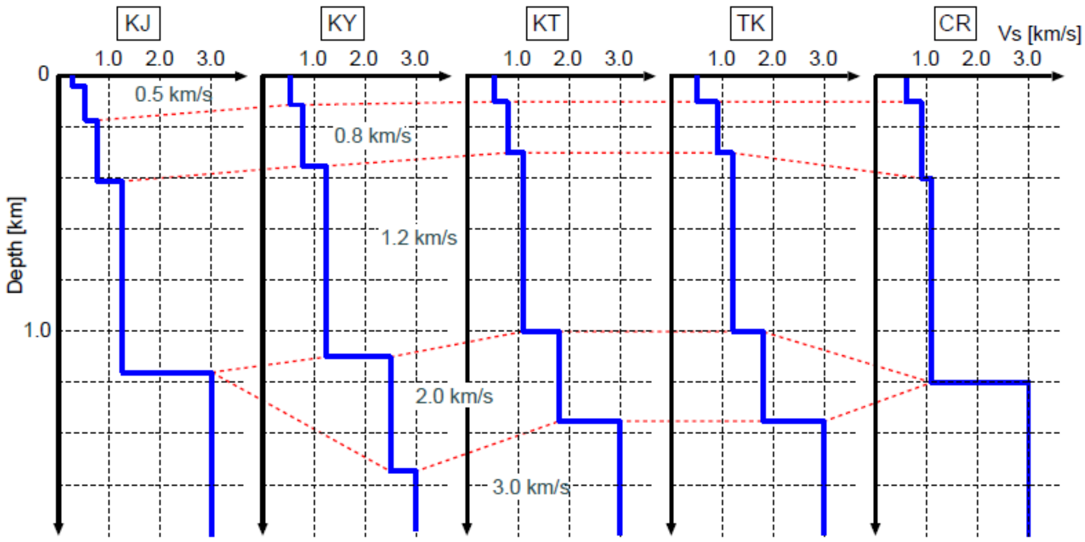

Figure 2.1: Shear wave velocity profiles at each site in Hsinchu City, Taiwan (Morikawa et al., 2009)

Kiyono et al. (2011) adopted both SPAC and CCA method to estimate subsurface structure at Padang, Indonesia. Microtremor array observation was at a total of 11 sites, which covers almost the whole city. They averaged the dispersion curve obtained from both methods to determine the subsurface structure profile. A 30m thick sedimentary layer with V_S less than 300 m/s was found uniformly accumulated along the coast as shown in Figure 2.2. The sediment layer became thinner away from coast to hilly area. The intermediate layer was in between 250m to 35m with V_S of 300 m/s to 3000 m/s.

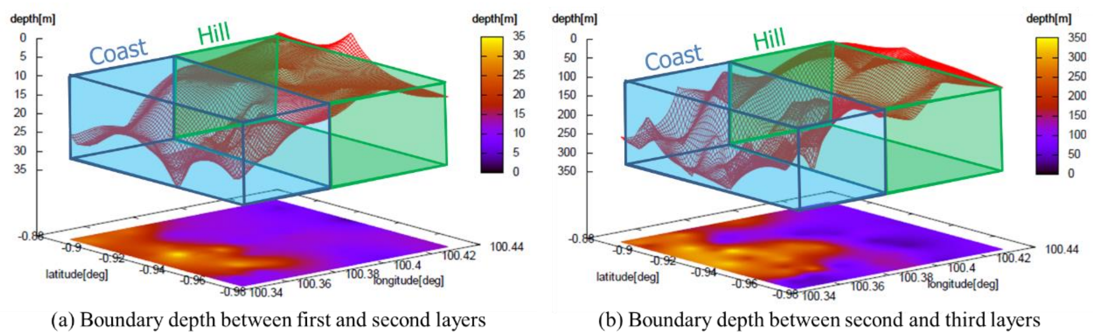

Figure 2.2: Three-dimensional shape of the estimated subsurface structure (adapted from Kiyono et al., 2011)

In the research done by Zaineh et al. (2012), they applied SPAC method to estimate shear wave velocity structure profile in Damascus City, Syria. Figure 2.3 shows the microtremor array observation sites. The resultant profiles (Figure 2.4) show that the engineering bedrock is located at a shallow depth, which is only less than 10m for sites located at the outbound of Damascus City, and the depth gradually increases toward the center of the basin, which is about 15m depth. Another significant finding is shear wave velocity of top 10m sediment ($V_{S,10}$) shows a much better correlation with averaged site amplification as compared to shear wave velocity of top 30m sediment ($V_{S,30}$). This concluded that the shallow low velocity layer governs the amplification factors in Damascus City.

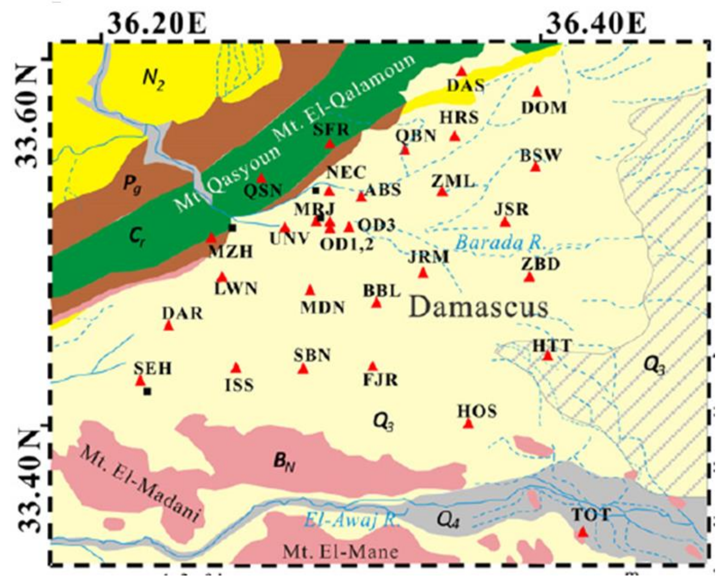

Figure 2.3: Location of microtremor array observation sites in Damascus City (Zaineh et al., 2012)

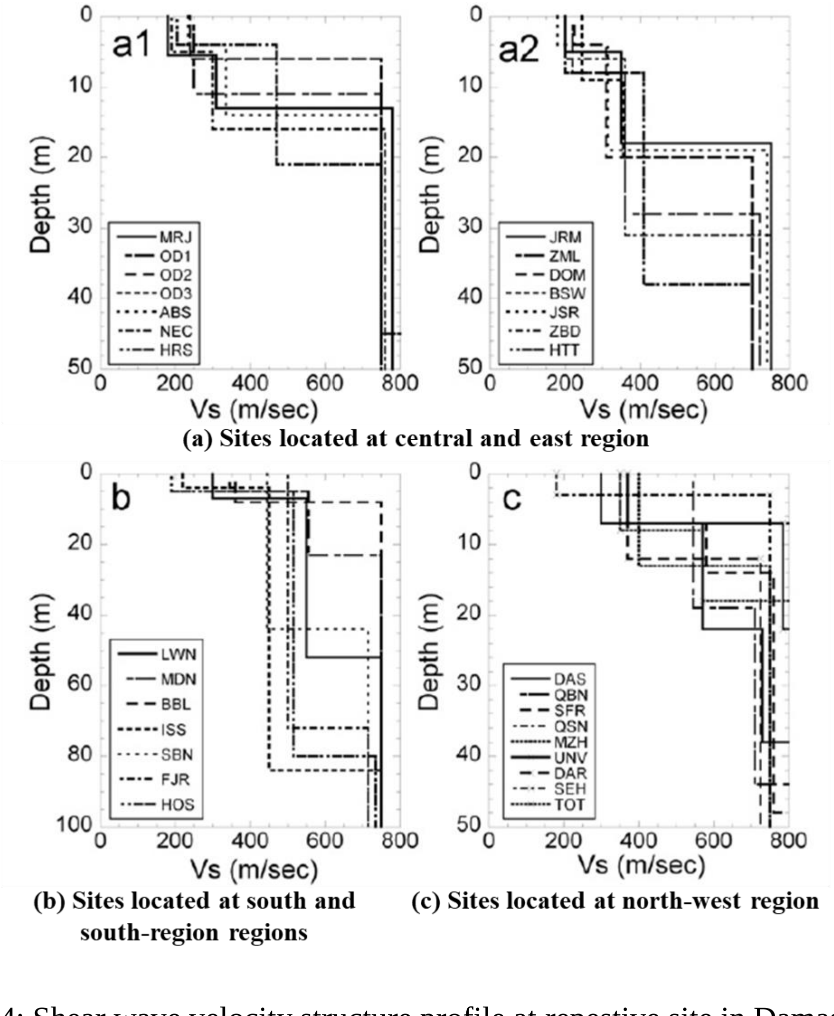

Figure 2.4: Shear wave velocity structure profile at repestive site in Damascus City (Zaineh et al., 2012)

The previous estimation works conducted by other researchers are summarized in Table 2.2. The array radius used in previous works ranges from few meters to few hundred meters. Although a few meters radius array has been used in the previous studies, but verification was not made on the result. Thus, the quality of the estimation using small size array is still not clearly studied.

Table 2.2: Application of SPAC and CCA methods in estimating V_S profile

Author	Site	Target Method	Array Radius (m)	Number of Sensors
Noguchi and Nishida (2002)	Tottori Plain, Japan	SPAC	3 – 70	4
Maresca et al. (2006)	Vesuvius Area, Italy	SPAC	30 – 90	13
Morikawa et al. (2009)	Hsinchu City, Taiwan	SPAC	60 – 500	4
Kataoka (2011)	Chile	SPAC	5 – 6	4
Kiyono et al. (2011)	Padang, Indonesia	SPAC & CCA	NA	NA
Zaineh et al. (2012)	Damascus City, Syria	SPAC	12 – 40	7
Hamasaki et al. (2013)	Penang Island, Malaysia	SPAC	1 – 73	4
Su et al. (2015)	Xishan village, Sichuan province, China	SPAC	15	7
Jirasakjamroonsri and Poovarodomb (2015)	Bangkok, Thailand	SPAC & CCA	5 – 250	4
Setiawan et al. (2016)	Adelaide City, South Australia	SPAC	NA	7
Koesuma et al. (2017)	Central Java, Indonesia	SPAC	100 – 400 (SL)	9

Note : NA = Not available; SL = Side length

2.6 Ground Classification for Seismic Site Effect Evaluation

Ground classification is one of the most important parameters to evaluate the seismic site effect. In term of ground classification parameters, many countries, including Australia, China, European countries, India and United States of America, adopted average shear wave velocity for top 30m sediment, $V_{S,30}$, standard penetration test N value, N_{SPT}, and undrained shear strength, c_u.

Pitilakis et al. (2006) summarized the ground classification system based on $V_{S,30}$, in modern seismic codes worldwide as shown in Figure 2.5. Although $V_{S,30}$ is considered to be a sound parameter for site classification, but site classification exclusively based on $V_{S,30}$ is a simplified hypothesis and it can be misleading in many cases. It can lead to erroneous result especially in the cases of deep soil formations and abrupt stiffness change between soil layers within 30m in depth (Seed et al., 1991). Based on Figure 2.5, New Zealand and Japan also adopted natural period of site in site classification.

$V_{S,30}$ (m/s)	180	360	760		1500
UBC/97 IBC/2000	S_E	S_D	S_C	S_B	S_A
GREEK SEISMIC CODE EAK2000	D – C	C B	A	A	
EC8 (ENV1998)	C	C B	A	A	
EC8 (prEN1998) (Draft4, 2001)	D	C	B	A	
New Zealand, 2000 (Draft)	D (T>0.6s→$V_{S,30}$<200)	C (T<0.6s →$V_{S,30}$>200)	B	A	
Japan, 1998 (Highway Bridges)	III (T>0.6s→$V_{S,30}$<200)	II (T=0.2-0.6s→$V_{S,30}$=200-600)	(I)	I (T<0.2s→ $V_{S,30}$>200)	
Turkey/98	$Z_4 – Z_3$	$Z_3 – Z_2$	$Z_3 – Z_2 – Z_1$	Z_1	
AFPS/90	$S_3 – S_2$	$S_3 – S_2 – S_1$	$S_1 – S_0$	S_0	

Figure 2.5: Comparison of soil classification in modern seismic codes worldwide (Pitilakis et al., 2006)

Since $V_{S,30}$ is average shear wave velocity for sediment thickness 30m, thus $V_{S,30}$ value will be higher at site with a shallow bedrock depth due to the reason that bedrock has high shear wave velocity. On the other hand, $V_{S,30}$ is also not able to represent the site characteristic if the site has sediment thickness more than 30m. In the past research by Molnar et al. (2017), site classification has been carried out at Alberta, Canada. Figure 2.6 shows that site class reduces by one or two class when site dominant frequency is considered in site classification at Alberta. Site dominant frequency is the dominant frequency of soft sediment at site. In the other words, only sediment layers are considered in site classification when site dominant frequency is used. Hence, V_S of site will not be overestimated by omitting bedrock layer in average V_S computation.

Station Name	Lat. [^{0}N]	Long. [^{0}E]	Depth to Bedrock (H) [m]	H/V Peak Freq. (f_{peak}) [Hz]	f_{peak} Site Class*	Topographic Proxy+		Earthquake H/V	
						V_{S30} [m/s]	Site Class (NEHRP)	$V_Z = 4{*}H{*}f_{peak}$ %	Site Class (NEHRP)
TD013	52.518	-115.024	5.3	3	SC II	760	C	63.2	E
TD016	51.210	-114.836	5.0	5	SC II	292	D	100.0	E
TD022	51.177	-114.229	13.5	5	SC II	357	D	270.4	D
TD023	51.111	-114.305	14.1	2	SC III	760	C	113.0	E
TD024	51.048	-114.362	13.6	4	SC II	358	D	218.0	D
TD025	51.161	-114.676	5.0	2.5	SC III	657	C	50.0	E
TD08A	52.948	-115.278	2.1	3	SC II	760	C	24.7	E
TD09A	52.925	-116.390	1.6	2.5	SC III	760	C	15.9	E
TD13A	52.008	-114.768	12.5	1.8	SC III	394	C	90.0	E
WALA	49.059	-113.912	0.0			760	C		
WAPA	55.183	-119.254	14.6	3	SC II	655	C	175.3	E
WTMTA	55.694	-119.240	3.8	2	SC III	760	C	30.6	E

Figure 2.6: Selected Alberta seismograph stations and corresponding site classification (Molnar et al., 2017)

In conjunction to the implementation of seismic design in Malaysia, Malaysia National Annex to MS EN 1998-1:2015 has been published. In national annex (NA), site classification is based on both sediment thickness 30m and sediment thickness more than 30m. Site classification for sediment thickness more than 30m is the same as EC8. However, site classification for site with sediment thickness more than 30m is different from that adopted in New Zealand and Japan. The site period, T_S ranges for each ground type in NA are T_S = 0.7 – 1.0s for class D, T_S = 0.5 – 0.7s for class C, T_S = 0.15 – 0.5s for class B and T_S < 0.15s for class A. Meanwhile, the site period limits for class D and class A used in Japan and New Zealand are 0.6s and 0.2s, respectively. There are 0.1s and 0.05s difference in T_S for those two classes as compared to NA. Moreover, the elastic response spectrum for both these two cases are also different. Thus, this study is meant to provide a clear picture on the effect of considering sediment thickness more than 30m in ground classification for sites in Peninsular Malaysia.

2.7 Summary

Microtremor array observation has become more popular for determining the V_S profile over the decades due to its simplicity in both operation and analysis. Basically, V_S profile can be obtained from the dispersion curve of Rayleigh wave estimated from microtremor array data by mean of inversion. In the aspect of analysis, many researches have been done to validate the SPAC method. SPAC method has high accuracy to estimate V_S profile with an array of minimum several ten meters. Lately, CCA method was developed based on SPAC method. In accordance to the developers of CCA method, CCA method is superior to SPAC method as CCA method does not need that large array to estimate shear wave velocity within a same wavelength range. No research has been done to compare both methods together with other conventional methods. In seismic site effect evaluation, $V_{S,30}$ has been a simplified parameter used in many design codes to classify ground type. Some past research shown that considering V_S for 30m in depth is not sufficient for ground classification, especially for site with deep soil formation. Meanwhile, Malaysia National Annex to MS EN 1998-1:2015 has suggested to consider sediment thickness more than 30m in ground classification for site with deep soil deposit. Thus, it is necessary to study the effect of considering sediment thickness more than 30m in ground classification for sites in Peninsular Malaysia.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter discusses the activities carried out throughout the research period. The process in this research is divided into six main stages, which are desk study, field measurement, data analysis and result interpretation. The flowchart in Figure 3.1 summarizes all the activities performed for this research.

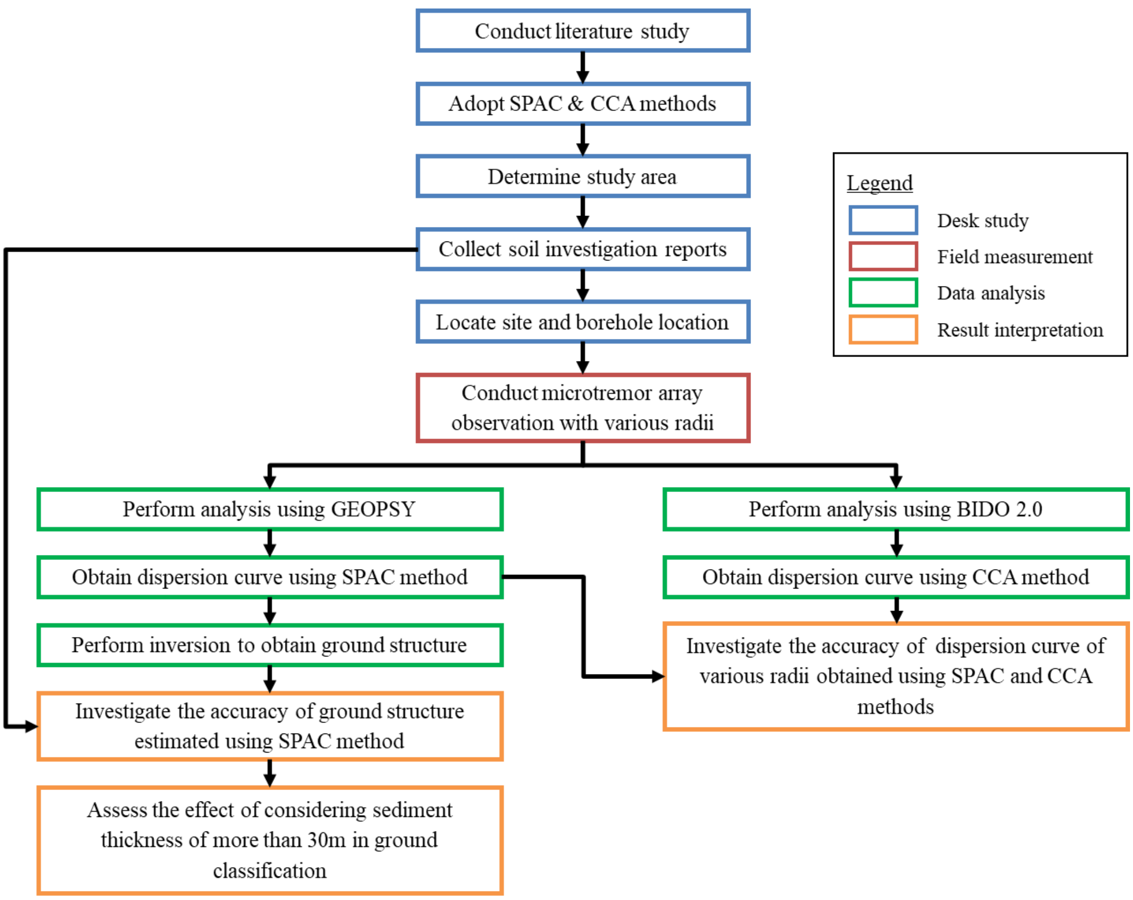

Figure 3.1: Flowchart of methodology

3.2 Desk Study

3.2.1 SPAC and CCA Methods

In this stage, related literatures on microtremor array observation method were studied. SPAC method and CCA method were adopted to estimate the V_S profile in this research. Previous work done by researchers in validating and applying SPAC and CCA methods in V_S profile estimation were also reviewed.

Extraction of phase velocities from microtremor using SPAC method is based on the theory proposed by Aki (1957). The Spatial Autocorrelation (SPAC) coefficient is defined as the azimuthal average of the coherence between the vertical component (Rayleigh wave) records of a central sensor with each sensor on the array circumference, and may coincide to a known function shown in the fourth member of Equation 3.1. The wavenumber, $k(\omega)$ is estimated by fitting to $J_0(kr)$ with the measured SPAC coefficient at each inter-station distance for each frequency.

$$\rho(r,\omega) = \frac{1}{2\pi}\int_0^{2\pi} exp[ikr\cos(\theta\text{-}\emptyset)]d\theta = \frac{R_e\left[E\left(C_{A,B}(\omega)\right)\right]}{\sqrt{E\left[C_{A,A}(\omega)\right]E\left[C_{B,B}(\omega)\right]}} = J_0(kr) \qquad (3.1)$$

where,

$\rho(r,\omega)$	=	SPAC coefficient
ω	=	angular frequency
r	=	inter-station distance
θ	=	azimuth between two observation points
$\emptyset$	=	azimuth of incidence for incoming plane waves
k	=	wavenumber
J_0	=	zero order Bessel function
$E[\,]$	=	ensemble average over the time
$C_{A,B}(\omega)$	=	cross spectra of the records obtained at x_A and x_B

CCA method was developed by Cho et al. (2004). They uses a spectral representation which may be considered a general case to SPAC method. The vertical component of microtremor records are used to determine the phase velocities of Rayleigh waves from sensors located on a circle without using a sensor at the center. The CCA coefficient is defined in Equation 3.2. The wavenumber, $k(\omega)$ is estimated by fitting to $[J_0(kr)/J_1(kr)]^2$ with the measured CCA coefficient at each inter-station distance for each frequency.

$$\frac{G_0(\omega,r)}{G_1(\omega,r)} = \frac{J_0^2[rk_1(\omega)]}{J_1^2[rk_1(\omega)]} \tag{3.2}$$

where,

r = inter-station distance

ω = angular frequency

k = wavenumber

J_0 = zero order Bessel function

J_1 = first order Bessel function

G_0, G_1 = power spectral density

After obtaining SPAC and CCA coefficient, the phase velocity of surface wave is calculated based on Equation 3.3.

$$c(\omega) = \frac{\omega}{k(\omega)} \tag{3.3}$$

where,

ω = angular frequency

$c(\omega)$ = phase velocity of surface wave

$k(\omega)$ = wavenumber

3.2.2 Study Areas and Site Locations

The research study areas are Kuala Lumpur and Penang due to many experience of ground tremor felt and both cities are economically important. Soil investigation reports on these two areas were then collected and filtered to locate the suitable survey sites. Out of over hundreds of investigation reports, nine sites were chosen to conduct microtremor array observation, which is four sites in Kuala Lumpur and five sites in Penang as shown in Figure 3.2. The coordinate of site was determined using Leica Viva CS10 Field Controller GPS system. Locations and coordinates of selected sites are shown in Table 3.1. Borelog for all nine sites are attached in Appendix A. Suitable sites were selected based on some criteria such as least human activities, away from traffic, flat terrain and accessible. Sites with multiple sediment layers and sediment thickness more than 30m have higher priority to be chosen as suitable sites. Sediment layers were defined based on N_{SPT} for site classification in Table 3.2. Site sediment was separated into three main layers, which are soft, medium and hard layer, with N_{SPT} value of 0 – 15, 15 – 50 and > 50, respectively. Figure 3.3 illustrates the soil properties at sites with single sediment layer and multiple sediment layers. In the current practice, all borelog were conducted for the depth up to 30m only.

Table 3.1: Location of sites

No.	Location code	Location	Coordinate (°)	
			Latitude	Longitude
1	KBSS	Kampung Baru Salak Selatan, Kuala Lumpur	3.090228	101.705981
2	TSJ	Taman Salak Jaya, Kuala Lumpur	3.093900	101.705808
3	PTC	Taman Cheras, Kuala Lumpur	3.101739	101.745144
4	TBR	Taman Bunga Raya, Kuala Lumpur	3.210469	101.727442
5	TMH	Taman Seri Putra, Nibong Tebal	5.143164	100.479194
6	HGR	Hangar, USM Engineering Campus	5.148081	100.495922
7	SERC	SERC, USM Engineering Campus	5.148744	100.494069
8	PUMA	PUMA, USM Engineering Campus	5.149236	100.498058
9	JCH	Jalan Chai, Balik Pulau, Pulau Pinang	5.356758	100.231061

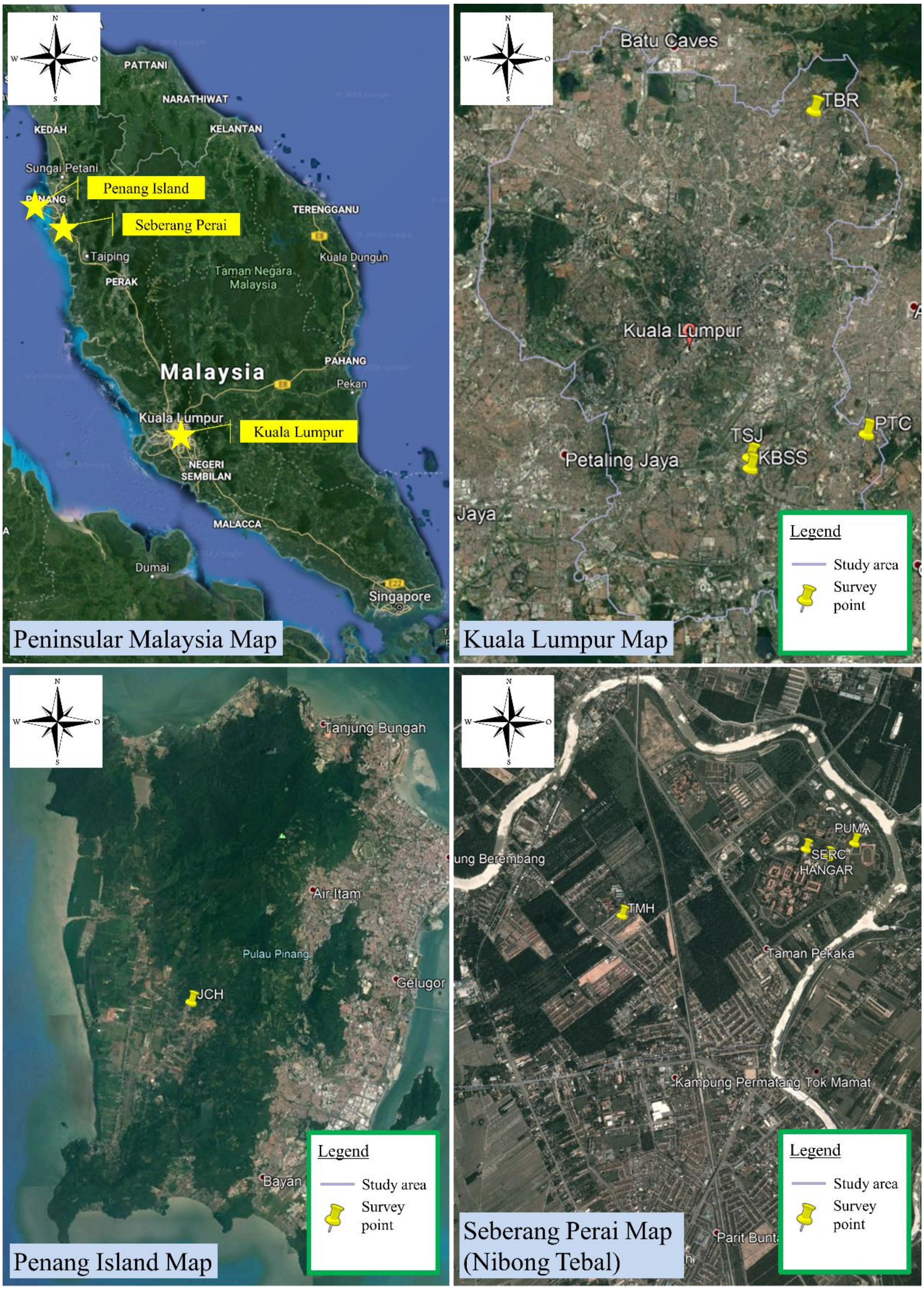

Figure 3.2: Microtremor array survey points