INTEGRATING MULTICHANNEL ANALYSIS OF SURFACE WAVES AND HORIZONTAL TO VERTICAL SPECTRAL RATIO TECHNIQUES FOR DYNAMIC SITE CHARACTERISATION AT PULAU PINANG, MALAYSIA

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by

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A	Relative amplification
A_b	Incide wave at base layer
A_S	Incident wave at ground surface
b	Bandwidth coefficient
f	Frequency
f_1	Frequency of interest
f_0	Fundamental resonance frequency
f_0 _1-D TF	Fundamental resonance frequency from 1-D SH transfer function computation
f_0 (HVSR)	Fundamental resonance frequency from HVSR measurements
f_c	Central frequency
h	Depth to bedrock
h_i	The thickness of the i'th layer (within the top 30 m)
R^2	Regression coefficient
T_n	Site period
$Tn_{(HVSR)}$	Site Period derived from HVSR measurements
$Tn_{(MASW)}$	Site Period derived from MASW measurements
Vs	Shear wave velocity
V_S30	Time average shear-wave velocity form the surface to a depth of 30 m
$\overline{V_s}, Vs_{avg}$	Average shear-wave velocity of the soil above the bedrock
V_{sb}	Shear wave velocity at the base layer
$V_{S,i}$	The shear-wave velocity of the i'th layer
V_{SR}	Shear Wave Velocity of bedrock to soil
Vp	P-wave velocity
V_R	Rayleigh wave phase velocity

Qp	P-wave quality factor
Qs	S-wave quality factor

LIST OF ABBREVIATIONS

1-D	One dimensional
2-D	One dimensional
3-D	Three dimensional
AF	Amplification factor
$AHSA$	Average Horizontal Spectral Acceleration
AM_{FS}	First Amplification Magnitude
AM_L	Largest amplification magnitude
DFA	Diffuse Field Assumption
GRG	Generalized Reduced Gradient
HVSR	Horizontal to Vertical Spectral Ratio
MASW	Multichannel Analysis of Surface Waves
NEHRP	National Earthquake Hazard Reduction Program
SASW	Spectral Analysis of Surface Waves
PVA	Peak velocity Amplification

INTEGRASI ANALISIS PELBAGAI SALURAN AKTIF OLEH GELOMBANG PERMUKAAN DAN TEKNIK NISBAH SPEKTRA MENDATAR KE MENEGAK UNTUK PENCIRIAN TAPAK DINAMIK DI PULAU PINANG, MALAYSIA

ABSTRAK

Pulau Pinang mudah terdedah kepada kesan pelbagai bentuk pergerakan tanah yang boleh menyebabkan kerosakan, dan pemahaman tentang ciri-ciri dinamik tanahnya adalah penting untuk anggaran kesan tapak, terutamanya kerana ia merangkumi penguatan tapak. Teknik HVSR adalah cara murah dan mudah untuk menganggarkan parameter kesan tapak, bagaimanapun, tidak ada konsensus mengenai penggunaan amplitud puncak HVSR sebagai pengganti penguatan tapak. Tumpuan kajian ini adalah untuk menentukan kesesuaian penggunaan amplitud puncak HVSR sebagai proksi untuk penguatan tapak, dengan membangunkan formula empirik untuk penganggaran penguatan tapak. Juga, pentingnya adalah untuk membangunkan model empirik untuk mengagih kedalaman ke pangkalan rasuk kejuruteraan dan peta mikrozonasi untuk kawasan kajian. Dalam Fasa I kajian ini, pemodelan berangka telah dilaksanakan untuk memahami kesan lithologi pada spektrum halaju fasa frekuensi (f-c) dan lengkung HVSR. Dalam Fasa II, bidang MASW dan pengukuran HVSR dijalankan di seluruh kawasan kajian dan keputusannya dianalisis untuk membangunkan persamaan untuk penguatan tapak (AF) dan kedalaman kepada asas batuan kejuruteraan (h). Akhir sekali, fasa III kajian menumpukan kepada pembangunan peta mikrozonasi untuk kawasan kajian. Hasil daripada pemodelan berangka mencadangkan bahawa kerumitan pada spektrum f-c berkaitan dengan kehadiran penyongsangan halaju, kontras kekakuan yang tinggi dan batuan dasar yang

cetek dalam profil tanah. Walau bagaimanapun, bagi kes-kes ini, lengkung HVSR tidak menunjukkan kerumitan. Penemuan ini memberikan pandangan untuk analisis keputusan dari Tahap II. Perbandingan f_0 yang dianggarkan dari pengukuran HVSR, MASW dan pemindahan gelombang SH yang dikira untuk setiap lokasi mendedahkan korelasi yang sangat baik ($R^2 > 0.9$). Hubungan korelasi yang baik diperolehi antara amplitud puncak HVSR dan faktor penguatan tapak ($R^2 \approx 0.5$), dengan hubungan linear yang terhasil, $AF = 0.5693(A0_{(HVSR)}) + 2.4521$. Persamaan regresi yang dikembangkan untuk kawasan kajian didasarkan pada f_0 dan kedalaman untuk batuan kejuruteraan yang diperolehi dari pengukuran MASW adalah $h = 38.5{f_0}^{-0.73025}$. Peta mikrozonasi yang berbeza telah dibangunkan untuk kawasan kajian berdasarkan keputusan dari Fasa II. Sedangkan Vs30, f_0 dan mendalam ke peta dasar kejuruteraan menunjukkan konsistensi dengan peta geologi untuk kawasan kajian, tetapi tidak pada peta penguatan tapak. Hubungan empirikal yang dibangunkan dalam kajian ini membolehkan kaedah pengukuran dan kedalaman tapak cepat dan mudah untuk mendalami batuan kejuruteraan dari teknik HVSR. Lebih penting lagi, f_0 tanah di kawasan kajian berada dalam lingkungan kepentingan kejuruteraan (1-10Hz), yang menunjukkan kemungkinan tinggi resonans struktur tanah. Sehubungan dengan penguatan tapak, tanah di bahagian selatan dan di kawasan yang ditebang di kawasan kajian lebih cenderung untuk menguatkan gerakan tanah.

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ABSTRACT

Pulau Pinang is susceptible to the effects of various forms of ground motion capable of causing damages, and an understanding of the dynamic characteristics of its soils is important for site effects estimation, especially as it concerns site amplification. The HVSR technique is a cheap and easy means of estimating site effect parameters, however, there is no consensus on the use of the HVSR peak amplitude as a substitute for site amplification. The focus of this study is to determine the suitability of utilizing the HVSR peak amplitude as a proxy for site amplification, by developing empirical formulae for site amplification estimation. Also, of importance is the development of an empirical model for estimating the depth to engineering bedrock and microzonation maps for the study area. In Phase I of this study, numerical modelling was implemented to understand the effect of the lithology on the frequency-phase velocity (f-c) spectrum and the HVSR curve. In Phase II, field MASW and HVSR measurements were conducted across the study area and the results analysed to develop equations for site amplification (AF) and depth to engineering bedrock (h). Finally, phase III of the study focused on the development of microzonation maps for the study area. Results from the numerical modelling suggest that complexities on the f-c spectrum are related to the presence of velocity inversions, high stiffness contrast and relatively shallow bedrock within the soil profile. However, for these cases, the HVSR curve showed no complexity. These findings provided insights for the analysis of the results from Phase II. A comparison of the f_0 estimated from the HVSR

measurements, MASW and SH-wave Transfer computed for each location revealed an excellent correlation ($R^2 > 0.9$). A fair correlation was obtained between the peak amplitude of the HVSR and the site amplification factor ($R^2 \approx 0.5$), with the resulting linear relationship, $AF = 0.5693(A0_{(HVSR)}) + 2.4521$. The regression equation developed for the study area is based on f_0 and depth to engineering bedrock derved from MASW measurements is $h = 38.5{f_0}^{-0.73025}$. Different microzonation maps were developed for the study area based on the results from Phase II. Whereas the Vs30, f_0 and depth to engineering bedrock maps showed consistency with the geological map for the study area, the site amplification map did not. The empirical relationships developed in this study allows for a rapid and easy means of estimating site amplification and depth to engineering bedrock from the HVSR technique. More significantly, the f_0 of the soils in the study area is within the range of engineering interest (1-10Hz), suggesting a high possibility of soil-structure resonance. As regards site amplification, soils in the south-eastern part and on reclaimed areas of the study area are more likely to amplify ground motion.

CHAPTER 1

INTRODUCTION

1.1 Background

Dynamic site characterisation entails the classification of the soil based on its response to ground motion. Forms of ground motion such as seismic events, machine vibration, blasting, etc., pose a significant threat to the stability of structures and induce other forms of hazards such as liquefaction and landslides. Studies of past seismic events have shown that the local geological characteristics, i.e. the soil condition at the site, play a significant role in modifying ground motion in terms of its amplitude, frequency content and duration (Lacave et al., 2014, Fan et al., 2019). These local geological characteristics are termed as site effects.

The recorded ground motion at a site is a combination of various factors such as the source effects, propagation effects, instrumental effects and site effects (Figure 1.1). However, site effects play a significant role in determining how the input ground motion varies (Abbott, 2005, Mihalić et al., 2011, Bowden and Tsai, 2017) as it tends to amplify or attenuate ground motion. As such, understanding and characterizing site effects is an integral part of evaluating the ability of an infrastructure to withstand any form of amplification (Nakamura, 1997).

One of the factors responsible for site effects is the occurrence of soft sediments over stiff bedrock (Shingaki et al., 2018). Generally, the subsurface of the earth is made from elastic properties that vary from soft to hard, implying a variation in velocity. The velocity of seismic waves increases with compaction, and as such, seismic velocities are higher in hard rocks than in softer rocks or sediments. This difference in velocity gives rise to impedance contrast that allows for the trapping of seismic waves.

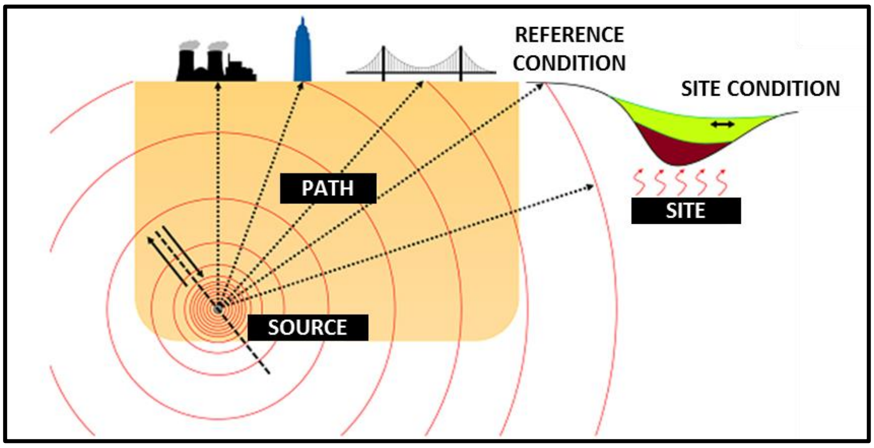

Figure 1.1: Illustration of source, path and site effects to the global seismic hazard (Foti et al., 2019).

For a simple horizontal layered structure (1-D Structure), only the body waves travelling through the soft sediments are affected. However, for cases of lateral heterogeneities within the sediments (2-D or 3-D structures), the trapping affects the surface waves also (Lacave et al., 2014). The interference of the trapped waves within the sediments leads to resonance, the shape of which is dependent on the characteristics of the sediments structure. The complexity of the resonance shape is a function of the sediment structure, with 1-D structures having a simple resonance shape as compared to that for 2D and 3D structures (Lacave et al., 2014). Figure 1.2 shows the resonance effect of a 2-D sediment structure. In general softer soils tend to amplify ground motion as compared to hard soils.

Apart from the influence of soft sediments on site effects (stratigraphical amplification), surface topography (geometrical amplification) is also another factor responsible for site effects (Foti et al., 2019). Studies on the distribution of ground shaking intensities as a result of earth's features have identified variance in the intensity of the shaking, with the hilltops having higher amplification than flat surfaces.

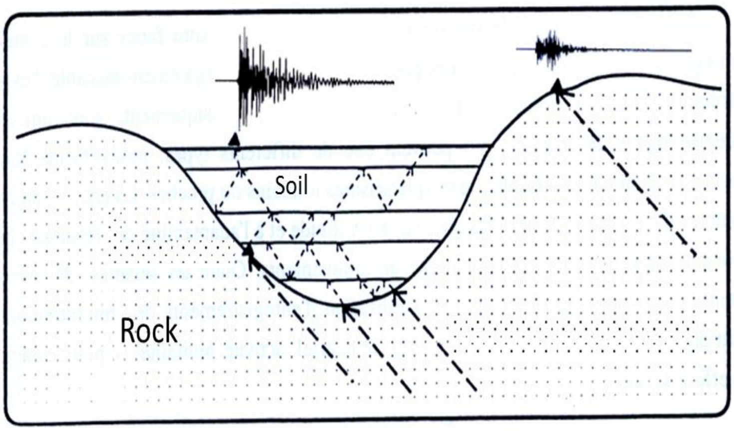

Figure 1.2: Site effects as a result of the trapping of waves by a sedimentary basin. Higher amplitude is observed on the basin than at adjacent rock site (Lacave et al., 2014).

Site effects studies involve the estimation of the site's amplification and fundamental frequency. The site amplification is expressed as the ratio of the ground motion between the ground surface and at the bedrock for a given site (Kokusho and Sato, 2008, Navidi, 2012). The frequencies at which these amplifications are observed are the resonance frequencies and the first frequency is the fundamental frequency – f_0 (natural frequency).

To estimate these parameters, the knowledge of the dynamic properties of the soil is critical. The dynamic properties determine the behavior of the soil when subjected to dynamic loading (Dammala et al., 2017) and are influenced by the shear modulus (G), damping, Poisson's ratio (D) and density (mass). However, the stiffness (shear modulus) and damping are the most important parameters that control the soil's dynamic response (Madabhushi, 1994). The soil's stiffness is a function of the shear-wave velocity, Vs, and it has been shown to significantly influence the amplitude and frequency content of predicted ground motion (Li and Assimaki, 2010, Barani et al., 2013, Teague and Cox, 2016). This makes the knowledge of Vs important, as it is a necessary input for site effects estimation.

A range of methods (both invasive and non-invasive) exists by which the shear wave velocity (Vs) of the subsurface can be obtained. For geotechnical investigations, invasive methods (e.g. boring, sampling, sounding and laboratory testing) are most often utilized. However, these invasive methods raise questions that range from the ability of a point measurements to be representative of the area investigated given the variability of near-surface geology, disturbance of the sample investigated, empirical relations utilized for the determination of the soil properties and finally the cost involved (Karray et al., 2009). Non-invasive methods utilized for estimating Vs usually involves the use of geophysical techniques such as the seismic refraction and surface waves analysis. These techniques have the advantages of in-situ sampling and provision of better sampling of a representative volume of the ground at a relatively low cost (Bard, 1999, Lin et al., 2004, Martin and Diehl, 2004, Comina et al., 2010, Dey, 2015). Of the two geophysical techniques routinely utilized (seismic refraction and surface waves analysis), the surface waves techniques are is commonly used as it is not affected by the problem of the 'hidden layer' and velocity reversals. Furthermore, the field procedure associated with the surface wave techniques (MASW) is usually less cumbersome. The high energy of surface waves on seismic records and the fact that the propagation velocity is dependent on the shear wave velocity of the medium (Park et al., 2007) makes the surface wave technique more attractive.

Surface waves analysis utilizes the dispersive characteristics of surface waves to infer the properties of the medium by inverting the dispersion curve to obtain the model parameters. Any of the different types of surface waves can be deployed for such investigations, however, the Rayleigh wave is commonly utilized due to its ease of generation and detection (Socco et al., 2010, Foti et al., 2015) (Foti et al., 2015, Miller et al., 2012; Socco et al., 2010), as well as its effectiveness and reliability (Liang et al., 2008). The surface wave technique is routinely applied in seismological studies to characterise the inner structure of the earth(e.g. the crust and upper mantle) since the mid 50s (Socco and Strobbia, 2004). However, its use for near surface characterisation did not commence until the early 1980s, with the introduction of the Spectral Analysis Of Surface Waves (SASW) technique (Heisey et al., 1982, Nazarian and Stokoe, 1985, Park and Ryden, 2007). In any form of surface wave analysis adopted, three steps are usually followed: 1. The acquisition of the seismic data record, usually by deploying low-frequency geophones; 2. The data processing to extract the dispersion curve from the shot gather, using various processing schemes and algorithms; 3. The inversion of the obtained dispersion curve to yield the shear wave velocity of the medium.

For the case of The SASW, the spectral analysis of ground-roll generated by an impulsive source and recorded by a pair of receivers is utilized. Subsequently, the Rayleigh waves dispersion curves obtained are inverted to obtain the Vs of the subsurface. However the inherent shortcomings of this method: inability to account for higher modes, contamination by body waves, reflected waves, etc. as well as phase unwrapping; led to the development of the Multichannel Analysis of Surface wave (Park et al., 1997, Xia et al., 1999, Socco and Strobbia, 2004). Unlike the SASW that uses only two geophones, the MASW deploys multiple geophones, making the field acquisition faster, with minimal processing and less sensitivity to cultural interference (Miller et al. 1999). The introduction of the MASW technique resulted in a wider application of surface waves techniques to near surface problems ranging from engineering to environmental investigations (Lin et al., 2004, Song and Gu, 2007, Schokker et al., 2008, Craig and Hayashi, 2016, Rehman et al., 2016, Mi et al., 2017). In spite of the success of this technique, limitations such as the phenomenon of mode misidentification, modal superposition and influence of higher modes which might result in the overestimation of the Vs model (Cercato et al., 2004) still exists. Also, the information obtained from the surface wave tends to decrease with depth. As a result of these challenges, there is the need for proper analysis and if possible an integration of methods to reduce the uncertainty inherent in estimating Vs from MASW measurements.

The Horizontal to vertical spectral ratio (HVSR) on the order hand provides a simple and cheap means by which the resonance frequency of a site can be inferred (Harutoonian et al., 2012, Bard, 1998) and although still debatable, the site amplification. The HVSR technique utilizes microtremor vibrations as a means by which the effect of surface geology on seismic motion can be estimated (Nakamura, 2008). This implies that it can be utilized in areas with low or no seismicity, (e.g. Pulau Pinang, Malaysia). Apart from the direct estimation of the site effect parameters from the HVSR technique, the average shear wave velocity of the soil (Ibs-von Seht and Wohlenberg, 1999, Guéguen et al., 2007, Tuan et al., 2016).

Notwithstanding the popularity of the technique and its application to a variety of problems, there is still no general consensus on the nature and source of the microtremor signals that result in the observed HVSR curve (Mucciarelli and Gallipoli, 2001, Lunedei and Malischewsky, 2015), as well as it reliability in estimating the site amplification. While experiments, theoretical and numerical investigations have shown the consistency of the technique to provide a satisfactory estimate of the fundamental frequency, its use in estimating site's amplification is still questionable (Seekins et al., 1996, Mucciarelli, 1998, Bard, 1999, SESAME, 2004, Haghshenas et al., 2008, Imposa et al., 2018). Successful estimation of the site amplification from

HVSR measurements would be of immense benefits in site effect studies given its advantages in terms of simplicity, cost-effectiveness and easy deployment in urban areas in comparison to the MASW method. The determination of the site effect parameters and the consequence of the results would be explored in this work. Furthermore, a comparison of both the frequency and site amplification estimates from both techniques would be evaluated with the sole aim of scaling the HVSR amplitude to be representative of the site's amplification. By comparing the site amplification estimated via the use of both techniques, a relationship can be developed to estimate the site amplification using the HVSR method.

1.2 Problem Statement

The geology of the near-surface plays a critical role in determining the response of a site to ground motion and its ability to withstand the load resting on it. To evaluate the effect of loading and ground motion at a locality, the characterisation of the dynamic properties of the soil is essential. The shear wave velocity (Vs) is an important dynamic property of the soil and has been routinely utilized for seismic microzonation and site effect studies. The determination of Vs can be done using a variety of techniques, however the multichannel analysis of surface waves (MASW) have been routinely utilized over the years (Foti, 2000, Harutoonian et al., 2012) for various applications. For site effect studies, parameters such as Vs30, site period and site amplification are usually computed using 1-D Vs model derived from MASW measurements. To achieve an accurate estimate of Vs from the MASW data, the resolution of the spectrum from which the dispersion curve can be extracted is of great importance. A common approach is to transform the field data from the time-space domain (t-x) into the frequency-velocity domain (f-v) using phase-shift transform

(Park et al., 1998), as it provides a convenient and effective means by which the dispersion trend can be imaged (Dal Moro et al., 2003, Ivanov et al., 2015). Unfortunately, this process is not trivial due to the phenomenon of mode misidentification, modal superposition and influence of higher modes, which can result in complicated dispersion curve trend on the resulting f-c spectrum, making the inversion into shear wave velocity of the soil inaccurate. Understanding the influence of the soil profile on the f-c spectrum can help improve the overall inversion process to achieve a robust and accurate Vs model.

The HVSR technique is a simple and reliable means to investigate the effect of near-surface geology on seismic motion independent of other geological information. Measurements are obtained via the use of a 3-component single station measurement, with microtremor signals as the source, making it a passive method. However, there is no consensus on its theoretical basis, as the source of the microtremor field that results in the observed HV curve has been attributed to Rayleigh waves, SH waves and diffuse field (a combination of both body and surface waves). The result of the HVSR measurement is an HVSR curve that usually exhibits peaks. There is a consensus that the frequency at which the first peak occurs is the fundamental resonance frequency of the soil (Tuan et al., 2016, Ibs-von Seht and Wohlenberg, 1999, Guéguen et al., 2007). Whereas, the amplitude of the peak has been argued by some authors to provide an estimate of a site's amplification (S-wave amplification factor) (Nakamura, 2000, Mucciarelli and Gallipoli, 2004, Ghofrani and Atkinson, 2014). Others maintain that the peak of the fundamental frequency of the HV curve differs from the true site amplification. Notwithstanding the lack of consensus on the use of the HVSR peak amplitude for site amplification estimation, it is possible to obtain a local relationship that is empirically obtained from local observations (Bard, 1998, Haghshenas et al., 2008, Kawase et al., 2018). Such empirical relationship can provide a fast and easy means by which site amplification can be directly estimated from HV measurements for the locality. Furthermore, a comparison of the outputs from both techniques can be used to develop empirical relationships, such as that between the fundamental frequency of the soil and the overburden thickness (engineering bedrock) can be proposed (Maresca and Berrino, 2016, Morton et al., 2018, Aswad and Massinai, 2018).

A critical issue in geophysics is that of solution non-uniqueness (Dal Moro, 2011, Foti et al., 2015, Dal Moro et al., 2015), which implies the existence of ambiguities in the obtained model. It is therefore expected that the information obtained from the use of both the MASW and HVSR technique/datasets will reduce the inherent ambiguity in the interpretation and is also capable of addressing the limitations posed by the use of just one technique. Also, it is expected that the resulting near-surface model obtained by the integration of both techniques is capable of improving the accuracy and robustness of the retrieved subsurface model. This is particularly important for a more accurate dynamic site characterisation of the study area – Pulau Pinang, which is necessary for the assessment of seismic and geotechnical hazards.

There has been an increase in seismic activities in Peninsular Malaysia due to the reactivation of ancient major fault zones (Bukit Tinggi fault zone), events from far-field earthquakes (Sumatra Subduction Zone and the 1900 km long Sumatra fault that runs through the Sumatra Island) and induced seismicity near major dams (Marto et al., 2013, Shuib, 2009, Koh et al., 2009). Some of these events have resulted in damages and destructions to both lives and properties on Peninsular Malaysia (Marto et al., 2013). Pinang state, in particular, has witnessed firsthand the disastrous effect that can arise from such seismic activities, which as in the case of the great Sumatra-Andaman Earthquake of 26 December 2004, was most affected in terms of causalities and destruction (Colbourne, 2005). Apart from the threat posed by seismic activities on Pinang State as a whole, Pulau Pinang, located in the state has witnessed tremendous infrastructure development over the years, with the level of urbanization put at 90.8 percent, an all-time high after only Kuala Lumpur, Putrajaya and Selangor. The population density is also higher in Pulau Pinang (45.8 % of the population of 1.2 million for the state) (Mok, 2016). The implication is an increase in housing needs, which has led to massive land reclamation exercise, deforestation and other activities capable of affecting the geological equilibrium and resulting in various types of seismic hazards. Therefore, there is a need to constantly appraise the sustainability of the present infrastructure to mitigate the effects of any kind of ground motion.

1.3 Research Objectives

The major objective of this study is to determine the existence or otherwise of a relationship between the peak amplitude as obtained from HVSR measurements and the site amplification.

The specific objectives are to:

i. Evaluate the effect of soil complexities on the observed phase velocity – frequency spectrum and HVSR curve.
ii. Develop empirical relationships for site amplification and peak HVSR amplitude (A_0); as well as depth to engineering bedrock and fundamental resonance frequency (f_0).

iii. Produce seismic microzonation maps (Vs30, site period, site amplification and depth to engineering bedrock) for the study area

1.4 Significance and Novelty of Study

This study implements two geophysical methods: Multichannel Analysis of Surface Waves (MASW) and Horizontal to Vertical Spectral Ratio (HVSR) for dynamic site characterisation of soils in Pulau Pinang. The utilization of a multi-method approach allows for a robust determination of the site effect parameters fundamental site frequency (f_0) and site amplification. Also, microzonation maps (Vs30, fundamental site frequency, site amplification and depth to engineering bedrock) will be developed for the study area. These maps will provide means by which areas susceptible to ground motion amplification and other hazards can be evaluated. They can also provide be used for seismic hazard analysis studies, ground motion prediction equations and analysis involving soil-structure resonance of various infrastructure.

Furthermore, the integration of the MASW and HVSR techniques allows for a comparison of the output parameters of both techniques. An attempt will be made at developing empirical formulae that can be used to predict the amplification factor of the soil and depth to engineering bedrock respectively. This will be based on the relationship between HVSR peak amplitude and the amplification factor (derived from MASW measurements), as well as depth to engineering bedrock and fundamental frequency. This would allow for an easy determination of the site amplification and depth to engineering bedrock by the direct use of the relatively cheap and less cumbersome HVSR technique. These relationships would be the first of its kind for the study area. Furthermore, an investigation of the correlation between the HVSR peak amplitude and site amplification would be an addition to the body of knowledge on utilization of the HVSR peak amplitude as a proxy for site amplification.

1.5 Thesis Arrangement

This thesis is arranged as follows:

In Chapter 2, a review of the literature related to the scope of this research is presented. Insight into previous work done is detailed with a focus on identifying research gaps that need to be addressed. The chapter commences with a summary of the MASW and HVSR techniques, after which the previous studies are presented. The previous studies commence with a review of literature related to numerical modelling, earthquake studies and seismic events in Peninsular Malaysia, with a focus on the study area. Subsequently, research works utilizing MASW and HVSR for dynamic site characterisation are reviewed, highlighting the limitations associated with the use of just one technique. The advantages of integrating more than one technique are outlined by the review of past works utilizing a multi-technique approach. As the major goal of the study is to utilize the HVSR as a proxy for site amplification, previous works on site amplification are presented. In conclusion, a summary of the literature review is presented highlighting the identified research gaps.

Chapter 3 covers the materials and methods utilized for the research are presented. It commences with a description of the geological setting and geomorphology of the study area - Pulau Pinang. Subsequently, the methodology adopted for each phase of the research is presented. Phase I outlines the methods utilized in numerical modelling. The numerical modelling involved the generation and analysis of synthetic seismograms from different models and their corresponding

HVSR curves. This is followed by Field implementation (Phase II), where the processes utilized for the MASW and HVSR measurements and data analysis are presented. A comprehensive report on the field equipment and design/parameters utilized for data acquisition; step by step processing techniques; inversion schemes deployed and criteria that help define their interpretation. For Phase III, the analytical tools and empirical formulae utilized for the analysis of the result and in the production of the final results (maps) are presented. For each Phase, the flow chart is presented to help visualize the entire process.

Chapter 4 presents the preliminary results consisting of results obtained from all phases of the study. The discussions surrounding the results are also presented. Phase I reports the result from the Numerical studies, which highlights the influence of the geology on the f-c spectra and HVSR curve. Results of Phase II gives the preliminary output from the MASW and HVSR technique. As such, the elastic parameters determined for the soil profile at each site (Vs), site fundamental frequency and peak amplitude are presented. The secondary outputs of the measurements are presented. This consists of further analysis of the preliminary results and the results from Phase IIII of the study. The output parameters from both techniques are compared and implications presented. Also presented in this chapter are the developed empirical relationships between the peak HVSR and site amplification, as well as the fundamental frequency and thickness of the unconsolidated sediments (depth to engineering bedrock). Furthermore, the seismic zonation maps developed are presented and the implications on infrastructure discussed. Also presented in this chapter are the developed empirical relationships between the peak HVSR and site amplification, as well as the fundamental frequency and thickness of the unconsolidated sediments (depth to engineering bedrock).

A general summary of the research work, the conclusions, and recommendations for further studies are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The utilization of seismic waves for probing the subsurface is one of the oldest geophysical techniques. Seismic waves are elastic waves that occur in the earth as a result of an earthquake or a disturbance. The two classes of seismic waves are the body waves and surface waves. While body waves can traverse and "probe" all depth levels of the subsurface, surface waves, on the other hand, propagates along the boundary of a medium and diminish as they travel farther from the boundary (Socco and Strobbia, 2004). For this study, the two geophysical techniques employed are the multichannel analysis of surface waves MASW and the horizontal to vertical spectral ratio (HVSR). This chapter focuses briefly on the general procedure for both techniques, as well as a review of previous studies in line with the outlined objectives.

2.2 General Procedure - Multichannel Analysis of Surface Waves Technique

The Multichannel Analysis of Surface Waves (MASW) is a technique made popular after the works by the researchers of Kansas Geological Survey (Park et. al., 1999; Xia et. al., 1999). Since then, the technique has grown in popularity, as the derived S-wave velocity information from MASW has proven useful in various applications ranging from geotechnical engineering application, site response studies, environmental studies, mineral exploration amongst others (Socco and Strobbia, 2004, Park and Ryden, 2007, Socco et al., 2010, M. Papadopoulou, 2018).

The MASW technique utilizes the dispersive nature of surface waves, with the Rayleigh waves most commonly utilized (see Appendix B). Generally, three steps are involved: Data acquisition, Data Processing (Delineation of Dispersion Curve) and Data Inversion (Generation of the Subsurface Model). The MASW technique can either be passive or active. For active MASW, the source is an impact source, while passive MASW utilizes surface waves generated passively (traffic noise, air, microtremor). For this study, the adopted approach is the active MASW technique, using the Rayleigh waves.

2.2.1 Data Acquisition

The goal of the data acquisition step for active MASW technique is to effectively record the surface waves that are generated as a result of the source impacted on the ground. The receiver usually consists of low-frequency vertical geophones planted on the surface of the site in a linear array and evenly spaced. A total of twelve or more (more commonly 24 and 48 geophones) are deployed with an in-line end off configuration. The array length and receiver spacing determine the spatial sampling of the data, and as such can affect the wavenumber (k) resolution and possibly mode separation (Park et al., 1998, Socco and Strobbia, 2004, Strobbia, 2003). However, in practical application, it is more often than not determined by the global site parameters and frequency content generated by the signal (Foti et al., 2015).

The source for MASW active data acquisition is usually a vertical source such as sledgehammer or weight drop. A common source of concern for MASW data acquisition is the source offset (distance between the source and the array), with various recommendations proposed for the optimum offset (Xu et al., 2006, Zhang et al., 2004b). Notwithstanding the recommendations proposed on the possible optimal source-offset, it is strongly dependent on site conditions and experimental set-up. It is however recommended that a preliminary survey be acquired or the data acquired with different source-offset to determine the best source-offset that can be employed (Socco and Strobbia, 2004, Zhang et al., 2004b). The sampling time of the recorded data is chosen to ensure that the time-window is long enough to detect the surface waves.

2.2.2 Processing

The processing step is a critical step of the MASW techniques. The step aims to retrieve from the waveform all information about the surface wave as embedded in the data. Here, the aim is to extract the dispersion curve from the shot-gather obtained during data acquisition. This can be done using different processing schemes, however, for this study, the Phase-Shift transform is utilized Park et al. (1998). Details on the different processing schemes utilized in MASW analysis, including the Phase-Shift transform is presented in Appendix C.

2.2.3 Inversion

The inversion of the extracted dispersion curve is the final stage of the surface wave analysis. It involves the generation of a 1-D Vs model for the subsurface from the extracted dispersion curve. A variety of inversion schemes can be used, ranging from simple empirical schemes to complex inversion algorithms. This study utilizes both forward modelling and least square and Monte Carlo inversion schemes (Refer to Appendix D)

2.3 General Procedure - Horizontal to Vertical Spectral Ratio Method

The HVSR technique is a simple and reliable means to investigate the effect of near-surface geology on seismic motion independent of other geological information. The technique is implemented using single-station measurements taken on the earth's surface. Information of interest includes the site's resonance frequency, amplification, shear wave velocity and possible thickness of the overburden material. These parameters are useful for site response studies, seismic zonation and other engineering interests (Mucciarelli and Gallipoli, 2001, Nath, 2007, Eskişar et al., 2013).

Notwithstanding the popularity of the technique and its application to a variety of problems, there is still an absence of consensus on the theoretical background of the technique, especially as regards the nature and source of the microtremor signals that is responsible for the observed HVSR curve (Lunedei and Malischewsky, 2015, Mucciarelli and Gallipoli, 2001). Similar to the MASW technique procedure, the HVSR techniques involve the following steps: Data Acquisition, Processing and Interpretation.

2.3.1 Data Acquisition

Instrumentation for the HVSR includes a properly calibrated 3-component (3C) geophone (two horizontal and one vertical) and a Digitizer. The instrumentation is mounted at the site of interest and the parameters set according to the desired specification and data acquired. The experimental conditions required for accurate measurement are elaborately outlined in the Site Effects Assessment Using Ambient Excitations (SESAME) report (SESAME, 2004). The sampling rate and acquisition duration are set according to the purpose of the survey. Recommendations for the duration, window analysis (I_w) and the number of windows are presented in Table 2.1.

Table 2.1: Recommended record length for HVSR measurements

f_0 (Hz)	Minimum value for l_w [s]	Minimum number of windows	Recommended minimum record duration [min]
0.2	50	10	30'
0.5	20	10	20'
1	10	10	10'
2	5	10	5'
5	5	10	3'
10	5	10	2'

2.3.2 Data Processing

Depending on the data, filtering can be applied and other offset removal techniques. The window selection parameters are to be considered and usually can be done automatically using the aid of software. The main interest in data processing is to ensure that the part of the signal used for computation is free from transients (i.e. the most stationary part of the signal is kept). For window selection, necessary parameters to be considered include STA (Short time Average), LTA (Long time Average), STA/LTA minimum, STA/LTA maximum and Window length. The computation of the HVSR curve as outlined in the SESAME guidelines is given in Appendix E.

2.3.3 Data Interpretation

Site effect studies require the determination of the natural frequency of the soil deposits, which corresponds to the frequency of the first peak on the HVSR curve. Also, the corresponding peak amplitude at that frequency can be determined. In doing this, the reliability of the identified peak needs to be assessed. For this study, the guidelines for the reliability of the f_0 as proposed and outlined in the SESAME report (SESAME, 2004) was adopted. Furthermore, the azimuthal power can be checked via HV rotation to determine the reliability of the peak f_0 obtained to ensure it is not a result of industrial noise such as machinery, underground pipes, roots, etc. A further test on the HV frequency peak involves the computation of the damping. This helps to determine the origin of the peak, to identify if it is polluted by a monochromatic or continuous signal. An undamped peak of less than 1% indicates an anthropogenic source and such frequency needs to be discarded.

2.4 Previous Studies

This section describes past works related to this research. The aim is to highlight the research gaps expected to be addressed by the outlined objectives.

2.4.1 Numerical Modelling

Numerical modelling simulates geological scenarios using computational methods to better understand complex geological cases. It allows for an analysis of the propagation of seismic waves through an earth model having varying elastic properties. Such modelling entails the simulation of the various parameters that control the propagation of the seismic wave such as the source parameters, attenuation coefficient estimation, source-receiver geometry, and soil-receiver coupling (Socco et al., 2010). The product of such modelling is a synthetic model, which can be used as an effective reconnaissance tool and for other engineering site investigations (Peck, 1985). Several studies have utilized numerical modelling to study different aspects related to MASW. Cercato et al., (2009) utilized synthetic models to mimic conditions expected from real sites. The study aimed to understand the peculiarities of the surface wave techniques. In their study, different earth models were investigated, consisting of a normally dispersive profile, an inversely dispersive profile and a profile with a stiff bottom. From their results, the normally dispersive profile yielded f-c spectrum with fundamental frequency dominant over the entire frequency range. For the inversely dispersive profile, higher mode dominance was observed at certain frequencies, while modal jump charactersied the profile with a stiff bottom layer. The results from the numerical modelling were utilized to obtain a better understanding of the real field scenarios.

Similarly, Shen et al. (2016) carried out a study on the sensitivity of the phase velocity dispersion curve for profiles having irregular layers (high-velocity-layer

(HVL) and low-velocity-layer (LVL)). Synthetic seismograms were generated to obtain the f-c spectra, as well as the theoretical dispersion curves. They studied the sensitivity of Rayleigh waves and Love waves in the presence of these irregular layers. Their results indicate that the surface waves phase velocities are sensitive to variations of S-wave velocity for LVL and insensitive to that of an HVL. Also, beneath these layers (HVL or LVL), there is no sensitivity. These features can affect the inversion of the phase-velocity dispersion curve, resulting in an inaccurate Vs model for the subsurface. They recommended the need for a-priori information about the subsurface layer and great care observed during inversion.

Using numerical modelling, Mi et al. (2017) evaluated the resolution horizontal resolution of the MASW method. The authors simulated synthetic multichannel records, from which dispersion curves were extracted, inverted to retrieve the Vs profiles and corresponding pseudo 2-D Vs section. The results from the numerical simulations were also observed on real data sets. The findings showed that the horizontal resolution of the MASW method reduced with increasing depth. Furthermore, they recommended the use of numerical modelling to study the horizontal resolution of MASW measurements using Love waves.

This study will adopt numerical analysis to study the effect of the lithology on both MASW and HVSR measurements. Synthetic seismograms and theoretical HVSR curves will be computed for different earth models. It is expected that the observations from the numerical modelling would help in a better interpretation of the field data.

2.4.2 Earthquake Studies

Earthquake-induced ground motion has resulted in tremendous damages to lives and properties in different parts of the world (Naghii, 2005, Choudhury et al., 2016, Whitney and Agrawal, 2016). Studies of past earthquakes have shown that local site effects can significantly alter ground motion, resulting in greater destruction. In a review of the effect of geology on seismic ground motion, Sánchez-Sesma and Crouse (2015) chronicled the history of earthquake damages and its relationship to the geology at the site. According to the review, the suggestion of a correlation between the damage and the geology was first alluded to by John Milne (Milne, 1887), who observed that higher amplitudes motion occurred on soft ground as against hard ground. Great earthquakes such as the one that occurred in April 1906 in San Francisco, California and that of Kanto, Japan, 1923 both with a moment magnitude of M7.9 resulted in a more rigorous study of the correlation, with the conclusion that the damage is dependent greatly on the nature of the shallow soils. Sextos et al. (2018) carried out a comprehensive study on the impact of local site effects on the damages recorded by buildings in Central Italy as a result of a sequence of earthquakes that occurred in 2016. In their study, they considered geological, topographical and HVSR measurements, alongside building by building assessment of the damage patterns. In carrying out their work, they utilized both satellite-based assessment and on-site inspections. The major findings from their work indicated that a major contributor to the damages observed on the buildings in the area is site effects, particularly the amplification of the seismic waves as a result of stratigraphic and topographic effects. The stratigraphic effects are related to the material makeup of the near-surface deposits.

2.4.3 Ground Motion in Peninsular Malaysia

Peninsular Malaysia is considered aseismic, however, it is prone to the effect of regional seismic events, especially those originating from the Sunda arc subduction zone and the Sumatra fault. Apart from the effect of regional seismic events, there can be a triggering of inactive fault lines running through the Peninsular which can result in seismic activities on the Peninsular. As regards regional earthquake events, Adnan et al. (2005) reported that the 2002 and 2003 earthquakes of Sumatra caused panic in Pinang and Kuala Lumpur, both in Peninsular Malaysia, with cracks observed on buildings in Pinang for the 2002 Sumatra earthquake. According to the analysis of Adnan et al. (2002), (Adnan et al., 2005), one to two - storey buildings in Pinang and Kuala Lumpur would experience the greatest effect of Sumatra earthquakes of 2002 and 2003. Similarly, the results obtained by Loi et al. (2018) in their study of seismic hazard assessment of Peninsular Malaysia, indicates that the source of hazards affecting Pinang originates majorly from the Sumatran subduction zone. Apart from seismic events originating from afar, microseismic activities occurring within the Peninsular due to the reactivation of existing faults zones is a cause for concern. Record of earthquakes within the Peninsular shows occurrence in different areas– Bukit Tinggi, Kuala Lumpur, Kuala Pilah, Jerantut Pahang, Manjung Perak, Kenyir Dam in Terengganu and Mersing Johor at different times spanning from the year 2007 to 2012 (Marto et al., 2013). Apart from seismic events, ground motion related to man-made activities such as blasting and mining can destroy lives and properties (Faradonbeh et al., 2016). Table 2.2 gives a list of the felt earthquakes in the study area– Pulau Pinang from 2006 to 2015. The intensity of the felt earthquakes, mostly originating from Northern Sumatra varied from II to V (Table 2.2). The records as seen in Table 2.2 suggests that the study area – Pulau Pinang is prone to the effect of far off earthquakes, especially from Northern Sumatra. The combined effect of far off earthquakes and probable seismic event occurring within the Peninsular makes it paramount that the site effects for the study area are evaluated, considering that the study area is highly urbanized and of great economic importance.

2.4.4 Dynamic Site Characterisation

Site characterisation is a compulsory step for the design, construction and use of any geotechnical project. It requires an understanding of the materials and conditions that would be encountered at the site during all stages of the project. In particular, dynamic site characterisation allows for the characterisation of the soil based on its response to ground motion such as seismic events, machine vibration and blasting. In such studies, the determination of the soil dynamic properties such as the shear-wave velocity, shear modulus, Poisson ratio and damping are critical (Jia, 2018). In determining these parameters both geotechnical and geophysical methods are employed.

Table 2.2: List of felt Earthquakes and intensity in Pulau Pinang between 2006 - 2015 (Malaysian Meteorological Department)

No.	Date	Earthquake Location	Felt Area	Intensity
1	2013-07-02	Northern Sumatera	Georgetown and Batu Feringghi, Pulau Pinang	III
2	2012-07-25	Off West Coast of Northern Sumatera	Pulau Pinang	II
3.	2012-06-23	Northern Sumatra	Perai, Gelugor, Georgetown and Tanjung Bungah, Pulau Pinang	III
			Ayer Itam, Bukit Mertajam and Sungai Ara, Pulau Pinang	II
4.	2012-04-11	Off West Coast of Northern Sumatera	Bayan Baru, Pulau Pinang	IV
5.	2012-01-10	Off West Coast of Northern Sumatera	Butterworth, Georgetown, Sungai Ara dan Tanjung Tokong, Pulau Pinang	III
			Ayer Itam dan Gelugor, Pulau Pinang	II
6.	2011-09-05	Northern Sumatera	Pulau Pinang	III
7.	2011-06-18	Northern Sumatera	Pulau Pinang	III
8.	2011-04-29	Off West Coast of Northern Sumatera	Pulau Pinang	III
9.	2010-05-09	Northern Sumatera	Pulau Pinang	IV
10.	2010-04-06	Northern Sumatera	Pulau Pinang	IV
11.	2009-09-30	Southern Sumatera	Pulau Pinang	V