SEISMIC RESPONSE ANALYSIS OF BUILDINGS IN MALAYSIA SUBJECTED TO NEAR-FIELD AND FAR-FIELD GROUND MOTIONS

TAN CHIN GUAN

SCHOOL OF CIVIL ENGINEERING
UNIVERSITI SAINS MALAYSIA
2018

SEISMIC RESPONSE ANALYSIS OF BUILDINGS IN MALAYSIA SUBJECTED TO NEAR-FIELD AND FAR-FIELD GROUND MOTIONS

By

TAN CHIN GUAN

This dissertation is submitted to

UNIVERSITI SAINS MALAYSIA

As partial fulfilment of requirement for the degree of

BACHELOR OF ENGINEERING (HONS.)
(CIVIL ENGINEERING)

School of Civil Engineering,
Universiti Sains Malaysia

June 2018

UNIVERSITI SAINS MALAYSIA

SCHOOL OF CIVIL ENGINEERING
ACADEMIC SESSION 2014/2015

FINAL YEAR PROJECT EAA492/6
DISSERTATION ENDORSEMENT FORM

Title: SEISMIC RESPONSE ANALYSIS OF BUILDINGS IN MALAYSIA SUBJECTED TO NEAR-FIELD AND FAR-FIELD GROUND MOTIONS

Name of Student: TAN CHIN GUAN

I hereby declare that all corrections and comments made by the supervisor(s)and examiner have been taken into consideration and rectified accordingly.

Signature:

____

Date :

Approved by:

____

(Signature of Supervisor)

Name of Supervisor :

Date :

Approved by:

____

(Signature of Examiner)

Name of Examiner :

Date :

ACKNOWLEDGEMENT

First and foremost, I would like to express my sincere gratitude to my supervisor, Assoc. Prof. Dr. Lau Tze Liang for the continuous support on my study. His patience, motivation, enthusiasm, and immense knowledge guided me to complete this undergraduate dissertation. The convenient environment provided and the time he had spent in assisting me are undoubtfully vital to ensure the success of this study.

Besides, I would like to thank my friend, especially Cheah Yi Ben for his constant support and assistance in doing this project. I sincerely appreciate his contribution in conducting the field works. My appreciation also extends to my roommates for their mental support throughout this project period. Without their encouragement and help, this dissertation would not be completed smoothly.

Lastly, I would like to express my deepest gratitude to all my family members. Their unbroken consideration and tolerance throughout my research greatly inspire me in finishing this dissertation. This study would not be a success without their spiritual support and understanding.

ABSTRAK

Selain mengalami gempa bumi tempatan, gegaran dari negara-negara jiran yang seismic aktif juga dirasai di Semenanjung Malaysia. Bangunan-bangunan dikenakan gempa bumi tempatan dan jauh berpotensi menghadapi kerosakan berlainan akibat daripada keadaan tapak tempatan. Disertasi ini membentangkan kesan ampifikasi tanah dengan sedimen berbezakan kelas dan tindak balas struktur bangunan berlainan ketinggian semasa dikenakan pergerakan dekat dan jauh. Profil tanah Kelas C dan E yang diperolehi daripada ukuran lapangan digunakan untuk menganggar pergerakan permukaan tanah berdasarkan tujuh pergerakan dasar dekat dan tujuh pergerakan dasar jauh yang direkodkan di berlainan stesen seismik di Semenanjung Malaysia semasa kejadian gempa bumi. Tindak balas struktur bangunan konkrit bertetulang merintangi momen yang berlainan ketinggian di tapak Kelas C dan E dikenakan pergerakan dekat dan jauh telah dianalisis dengan menggunakan perisian ETABS. Dapatan menunjukkan pergerakan dasar dekat mempunyai kandungan tempoh pendek sementara pergerakan dasar jauh mempunyai kandungan tempoh panjang. Pecutan maksima dan factor amplifikasi bagi tapak Kelas C dan E yang dikenakan pergerakan jauh adalah lebih tinggi daripada gerakan dekat. Daripada spektrum sambutan yang dibangunkan, pecutan spektrum maksimum yang dibangunkan daripada kedua-dua pergerakan dekat dan jauh di tapak Kelas C lebih tinggi daripada yang di tapak Kelas E. Dapatan tindak balas bangunan dalam reaksi asas, pesongan dan hanyutan antara tingkat menunjukkan bahawa bangunan tiga tingkat dikenakan gerakan dekat memberi tindak balas yang lebih besar sedangkan bangunan lapan dan 15 tingkat di tapak Kelas C dan E dikenakan pergerakan jauh memberi tindak balas yang lebih tinggi. Pada umumnya, Malaysia National Annex memberikan anggaran tindak balas yang lebih tinggi daripada kebanyakan bangunan di tapak Kelas C dan E yang dikenakan pergerakan dekat dan jauh.

ABSTRACT

Despite experienced earthquakes from local origin, tremors from neighbouring active seismic countries are felt in Peninsular Malaysia. The buildings subjected to local and distant earthquakes are posed with different damage potentials due to local site condition. This dissertation presents the effect of soil amplification for sediments with different soil classes and the structural responses of buildings with different heights subjected to near-field and far-field ground motions. Class C and E soil profiles determined from field measurement were considered to estimate the ground surface motions based on seven near-field and seven far-field bedrock motions recorded at different seismic stations in Peninsular Malaysia during various earthquake events. Structural responses of reinforced concrete moment-resisting frame buildings with varying heights on Class C and E sites subjected to near-field and far-field ground motions were analyzed using ETABS software. The results show that near-field bedrock motions have short period contents while far-field bedrock motions have long period contents. The calculated soil amplification factors show that the maximum acceleration and amplification factor for Class C and E sites subjected to far-field ground motions are higher than that subjected to near-field ground motions. From the developed acceleration response spectra, maximum spectral acceleration developed from both near-field and far-field ground motions on Class C site is higher than that on Class E site. The results with structural response of base reaction, storey deflection and inter-storey drift of buildings show that three-storey building that subjected to near-field ground motions give larger responses, whereas eight and 15-storey buildings on Class C and E sites that subjected to far-field ground motion result in higher responses. Generally, Malaysia National Annex gives higher prediction on the response of most of the buildings on Class C and E sites that subjected to both near-field and far-field ground motions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

2D	**2-D**imensional
3D	**3-D**imensional
EC 8	**E**uro**c**ode **8**
EERA	**E**quivalent-linear **E**arthquake site **R**esponse **A**nalysis
NA	Malaysia **N**ational **A**nnex
PGA	**P**eak **G**round **A**cceleration

CHAPTER 1

INTRODUCTION

1.1 Background

Although Malaysia is located on a stable part of Eurasian plate, tremors due to far-field effects of earthquakes in Sumatra can be felt since 1915 (MOSTI, 2009). Figure 1.1 shows 10026 records of earthquake in Malaysia and neighbouring countries between 2000 and 2018 (USGS, 2018). Numerous earthquakes that occurred due to Sumatran fault and the subduction zone cause tremors along the west coast of Peninsular Malaysia. The most severe damage happened on 26^{th} December 2004 in which 68 human casualties were reported in Penang, Langkawi and Kuala Kedah because of a huge tsunami that induced by the earthquake with magnitude of 9.0. After this mega quake, near-field earthquakes originated from the reactivation of ancient inactive fault (Bukit Tinggi Fault and Kuala Lumpur Fault in Bentong fault zone as shown in Figure 1.2) were occurred as a result of intraplate stress built up (Shuib, 2009). Besides, 6.0 magnitude earthquake happened in Ranau and Kundasang, Sabah in June 2015 killed 18 people and damaged buildings. This was mainly because of the presence of Mensaban and Lobou-Lobou active faults in Ranau-Kinabalu area which induce various level of ground motions in Sabah, as shown in Figure 1.3. Hence, Malaysia is under a certain degree of seismic impact risk.

In assessing the seismic hazard, soil amplification is one of the major concerns. Soil amplification is a process in which the seismic waves increase while propagating from bedrock to soil surface, depending on the local soil condition and thicknesses of soil. This amplification happens due to multiple reflection and refraction that are taken place when the incoming seismic waves reach the boundaries of different geological materials. The ability of soft soil to amplify the earthquake bedrock motion is well demonstrated through several earthquakes such as Mexico City in 1985, Loma Prieta in 1989, Kobe in 1995 and Chi-Chi in 1999. This effect explains the tremors felt in Peninsular Malaysia during the major earthquake events that happened few hundred kilometers away in Sumatra.

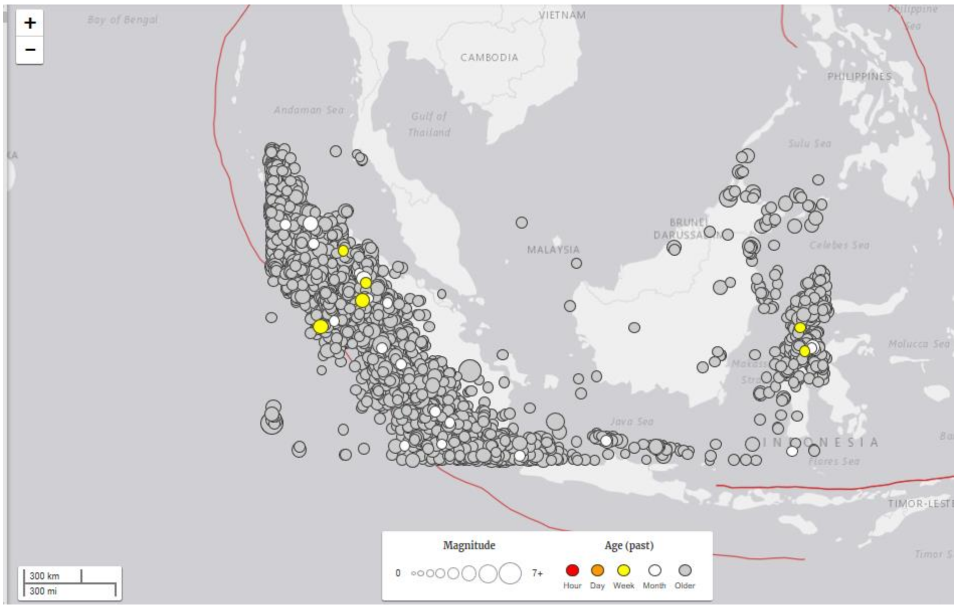

Figure 1.1: Record of earthquakes in Malaysia and neighbouring countries between 2000 and 2018 (USGS, 2018)

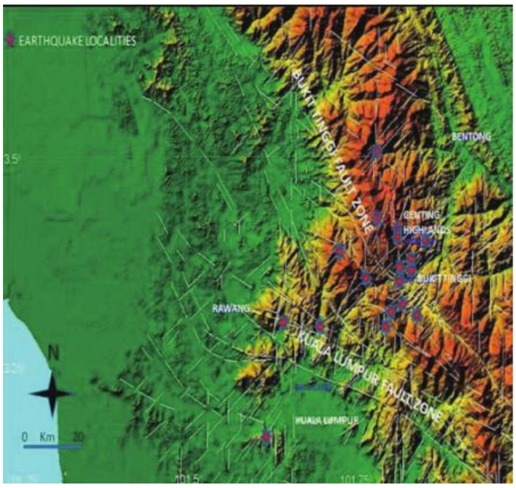

Figure 1.2: Bukit Tinggi Fault Zone in Selangor and the epicentres of earthquake occured (Shuib, 2009)

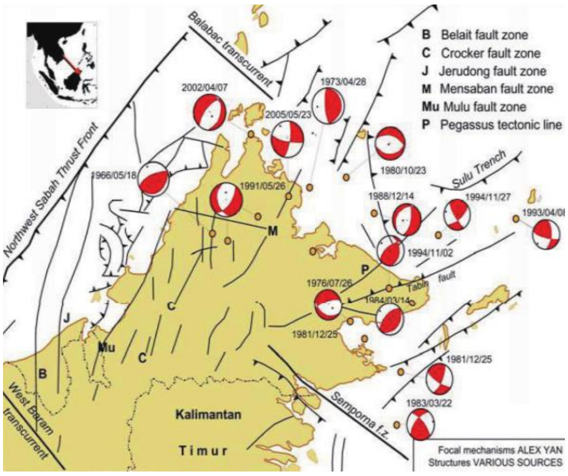

Figure 1.3: Mensaban and Lobou-Lobou Fault in Sabah (MOSTI, 2009)

There are varying intensities of tremors that have been felt in Malaysia whenever major earthquakes occurred in the neighbouring country. Soil amplification is the main effect to be considered for these earthquakes. An example of devastation caused by soil amplification effect is the 1985 Mexico City earthquake. Although the epicentre of earthquake is more than 350 km from Mexico City, the thick soft soil layer underneath greatly amplify the seismic waves, resulting in serious damage on the buildings. It can be seen that soil type and its thickness play major roles in affecting the soil amplification. Meanwhile, Eurocode 8 gives the ground classification for top 30 m whereas Malaysia National Annex that suggests another ground classification scheme with soil more than 30 m in depth. This will affect the soil type classified for a site with depth more than 30 m when considering top 30 m and more than 30 m in depth.

Moreover, even though the local earthquakes occurred in Bukit Tinggi Area are too weak to danger the buildings, precaution should be taken to ensure the safety of buildings in future. For East Malaysia, 6.0 magnitude earthquake recorded in 2015 magnifies the need to implement seismic design for the buildings in Malaysia. However, the study on the structural response of various heights of building that subjected to both effect of near-field and far-field ground motions is still lacking locally. Hence, more researches should be done for better understanding on these effects to the country.

1.2 Problem Statement

In Malaysia, most of the buildings are designed according to British Standard (BS8110) which do not have any provision to earthquake loadings. Meanwhile, Malaysia are subjected to both near-field and far-field earthquakes. Near-field ground motion has high frequency and short period, whereas the low frequency and long period ground motion is found in far-field ground motion. Based on Mohraz (1994), earthquake that happens less than 50 km from the epicentre is near-field earthquake. On the other hand, far-field earthquake occurs at a distance more than 50 km from the epicentre. Short buildings are more affected by high frequency wave whereas tall buildings are more shaken by long period ground motion. It is important to understand the effect from both near-field and far-field earthquakes in the design of structures. In Malaysia, there are various heights of buildings ranging from one-storey to skyscrapers such as Kuala Lumpur Tower and Petronas Tower. Thus, investigation of the structural response of various heights of building subjected to near-field and far-field ground motions is vital to be conducted.

Soil type has significant effect on the soil amplification. Various soil types cause different effects to soil amplification. In Eurocodes 8, identification of ground type is conducted for sediment depth of 30 m. However, Malaysia National Annex (NA) to MS EN 1998-1:2015 suggests another ground classification scheme for soil deposit exceeding 30 m in depth. These ground classification schemes may give rise to different soil types classified for a specific site, resulting in distinct soil amplifications. Both near-field and far-field ground motions that have different characteristics cause different effects on soil amplification. Moreover, there is still less study and knowledge on the investigation of effect of the soil amplification for site with different soil classes subjected to near-field and far-field ground motions . Therefore, it is essential to investigate the effect of near-field and far-field ground motions on soil amplification.

1.3 Objective

The main objectives of this study are listed below:

i. To investigate the effect of near-field and far-field ground motions on soil amplification.
ii. To assess the structural response of various heights of building subjected to near-field and far-field ground motions and design spectra in NA.

1.4 Scope of Study

This research focusses on the effect of near-field and far-field ground motions on soil amplification. Two borehole sites are analysed by considering near-field and far-field ground motions. Three near-field and three far-field ground motions recorded at the seven seismic stations by Malaysian Meteorological Department (MMD) around Kuala Lumpur are used for the analysis. The ground surface motions are generated by EERA computer program. Besides, the time step of acceleration time histories for all near-field and far-field bedrock motions is 0.01 s. The peak ground acceleration (PGA) is scaled up to 0.09 g due to the highest PGA (9 %) proposed by NA in the seismic hazard map of Peninsular Malaysia. Elastic response spectra with constant damping ratio of 5 % are then developed from the generated near-field and far-field ground surface motions. Three heights of building comprise low-rise (three-storey), mid-rise (eight-storey) and high-rise (15-storey) two-dimensional reinforced concrete moment resisting framed buildings are adopted in this research to analyse their structural response subjected to near-field and far-field ground motions and design spectra proposed in NA. Simulation of structural response of buildings is conducted by ETABS software using the ground surface motions generated and design spectra in NA. After the analysis, structural response such as base reaction, maximum storey deflection and inter-storey drift were then recorded and tabulated for further comparison and discussion.

1.5 Dissertation Outline

This dissertation consists of five chapters:

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

Chapter 2 discusses on seismicity of Malaysia and near-field and far-field earthquakes. This chapter also reviews past studies on the factors affecting ground motion amplification, ground response analysis and structural response analysis.

Chapter 3 describes the methodology used in this research. This chapter discusses the approach used in desk study, data collection, ground structure profile generation, generation of ground surface motions, design response spectrum from NA and structural response analysis.

Chapter 4 presents and discusses the results obtained from the research. Presentation of results is in the form of graph and table.

Chapter 5 concludes all the findings in this research and 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

Malaysia encounters both local and distant earthquakes. While Peninsular Malaysia has only experienced weak local earthquakes in Bukit Tinggi area since 2007, East Malaysia especially the state of Sabah has recorded local earthquake in Ranau area with magnitude of 6.0. Meanwhile, records of felt earthquakes in Peninsular Malaysia that mainly originated from Sumatra are available for events that began since 1909 (MOSTI, 2009). These clearly show the seismic hazards present in the country, in which precautions should be taken to deal with the issue.

One of the concerns in seismic hazard is the soil amplification that is a process of amplifying the incoming seismic waves through soft soil layer. There are a few areas in Malaysia that have surficial soft soil layer, which make the soil amplification effect to be critical in this country. This effect is significantly depending on the soil type and depth of soil. Besides, different characteristics shown by near-field and far-field earthquakes influence the soil amplification. The buildings on top of the soft ground are more prone to encounter damages due to the seismic motions.

Hence, this chapter discusses about the seismicity of Malaysia. It is followed by near-field and far-field earthquakes and the factors affecting soil amplification. Then, past studies on ground response analysis and structural response analysis are reviewed.

2.2 Seismicity of Malaysia

According to a seismotectonic study conducted by the Minerals and Geoscience Department of Malaysia (JMG), Malaysia is tectonically situated within relatively stable

Sundaland. Therefore, Malaysia belongs to the low-to-moderate seismicity countries, together with Singapore, Thailand and Australia. Even though Malaysia is located outside of Pacific Ring of Fire, the seismic hazard in Malaysia is undeniable, with seismic hazard originating from neighbouring countries such as Indonesia and Philippines. There are two active seismic sources of far-field earthquake for the region, which are Sumatran subduction zone and 1650 km long Sumatran Fault as indicated in Figure 2.1.

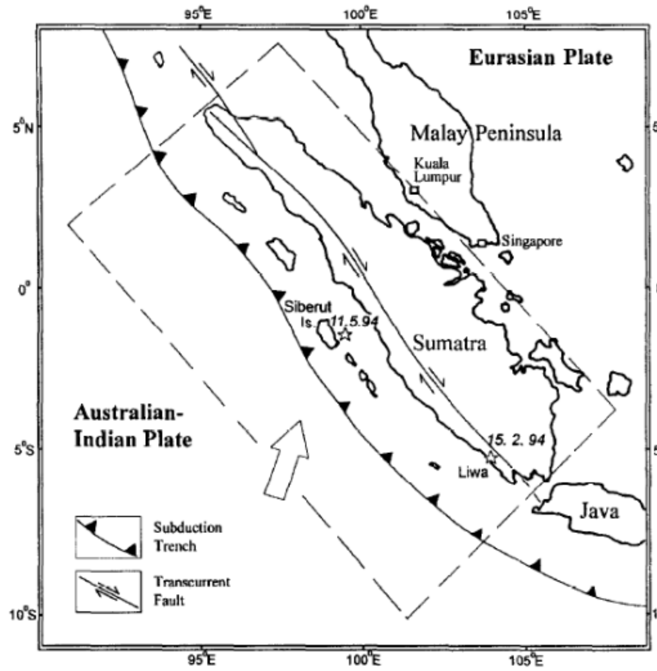

Figure 2.1: Sumatran Subduction Zone and Sumatran Fault (Sun and Pan, 1995)

Sumatran Subduction Zone is formed when the India-Australian plate subducts beneath the Eurasian plate at a rate of about 67mm per year (Hamilton, 1979). In the study done by Sun and Pan (1995), they stressed that strong earthquakes could occur in this zone due to the strongly coupling of overriding and the subducting plates as the subducted slab moves at shallow angle. One of the most devastating earthquake happened in the Sumatran Subduction Zone is Aceh earthquake in December 2004, with its moment magnitude (M_w) of 9.3 generated a huge tsunami that caused 68 human casualties in Malaysia and thousand others in Indonesia, Sri Lanka and Thailand. The second feature is the Sumatran Fault with length of 1650 km, running through the whole Sumatra Island. This dextral strike slip fault is another source of numerous earthquakes. As there is only a limited amount of energy that can be stored by the shear interlock, the energy released by this fault is at a relatively lower stress level, comparing with Sumatran Subduction Zone. Hence, the maximum magnitude of this fault may not exceed a moment magnitude of 7.8 (Balendra et al., 2002).

According to information obtained from Malaysian Meteorological Department (MMD), within a duration of more than a century, starting from 1909, Peninsular Malaysia has experienced tremors with maximum intensity of V, on the Modified Mercalli Intensity (MMI) scale. Table 2.1 shows the earthquake events that caused tremors felt in Peninsular Malaysia. In general, except 2004 Aceh earthquake that killed lives, the effects of these distant earthquakes are weak, including panick-attack among inhabitants of tall building and felt ground motion in high rise residential apartments and office buildings.

In addition, there are weak local originated earthquakes within Peninsular Malaysia. Table 2.2 shows the local earthquake occurrences in Peninsular Malaysia. Shuib (2009) suggested that the earthquakes in Bukit Tinggi Area were the results of ancient inactive fault reactivation due to the intraplate stress buildup after 2004 megaquake. The main active seismic fault that lay within Peninsular Malaysia is Bentong Fault Zone which comprises Bukit Tinggi Fault and Kuala Lumpur Fault. As Bukit Tinggi area is about 50 km from Kuala Lumpur Federal Territory, Jeffrey (2008) stated that the local earthquakes should be given a considerable attention. Thus, the studies on focal mechanisms of Bukit Tinggi earthquakes are vital to understand the seismic pattern and fault behaviour.

Table 2.1: Earthquake events that caused tremors felt in Peninsular Malaysia (Chiew, 2016)

Date	Depth (km)	Epicentre	Maximum MMI
2017.01.16	6.0	Kabanjahe, Sumatra	II
2016.03.02	24.0	Southwest of Sumatra	II
2015.11.08	69.0	Padang Sidempuan	V
2013.07.11	9.7	Sibolga, Sumatra	II
2012.06.23	104.0	Northern Sumatra	III
2012.04.11	10.0	Off West Coast of Northern Sumatra	III
2011.09.05	87.2	Northern Sumatra	III
2011.06.18	74.7	Northern Sumatra	III
2011.06.14	10.0	Northern Sumatra	III
2010.12.01	144.6	Northern Sumatra	IV
2010.07.24	55.2	Northern Sumatra	IV

Table 2.2: Local earthquake occurrences in Peninsular Malaysia (Marto et al., 2013)

Date	Case	Location	Maximum Magnitude
2007-2009	37	Bukit Tinggi, Pahang	3.5
2009	5	Kuala Pilah, Perak	3.3
2009	1	Jerantut, Pahang	2.6
2009	1	Manjung, Perak	3.2
2010	2	Kenyir Dam, Terengganu	2.6
2012	1	Mersing, Johor	3.2
2013	1	Baling, Kedah	3.8
2016	1	Kenyir Dam, Terengganu	2.7

While Peninsular Malaysia has only experienced weak local earthquakes and been jolted by distant earthquakes from Sumatra, Sabah has recorded moderate scale tremors of maximum intensity of VII, on MMI scale. It is noted that an earthquake of scale VII can cause human injuries and property damages. A study conducted by JMG confirmed the presence of the Mensaban and Lobou-Lobou active fault in Ranau-Kundasang area. According to U. S. Geological Survey (USGS, 2016), from year 1923 to 2016, there were in total 58 earthquake events with magnitude more than 3.5 were recorded in Sabah area, as shown in Figure 2.2. The most recent earthquake occurred was a 5.2 magnitude Ranau earthquake on 8th March 2018, which could be felt at locations such as Kota Kinabalu, Kundasang, Penampang, Tuaran, Kudat and Kota Marudu. According to USGS, the epicentre of earthquake was just 10 km deep and 12 km northwest to Ranau town, causing minor no-structural damages to public buildings. Hence, Sabah has its moderate seismicity condition as it shows clear rate of crustal deformation.

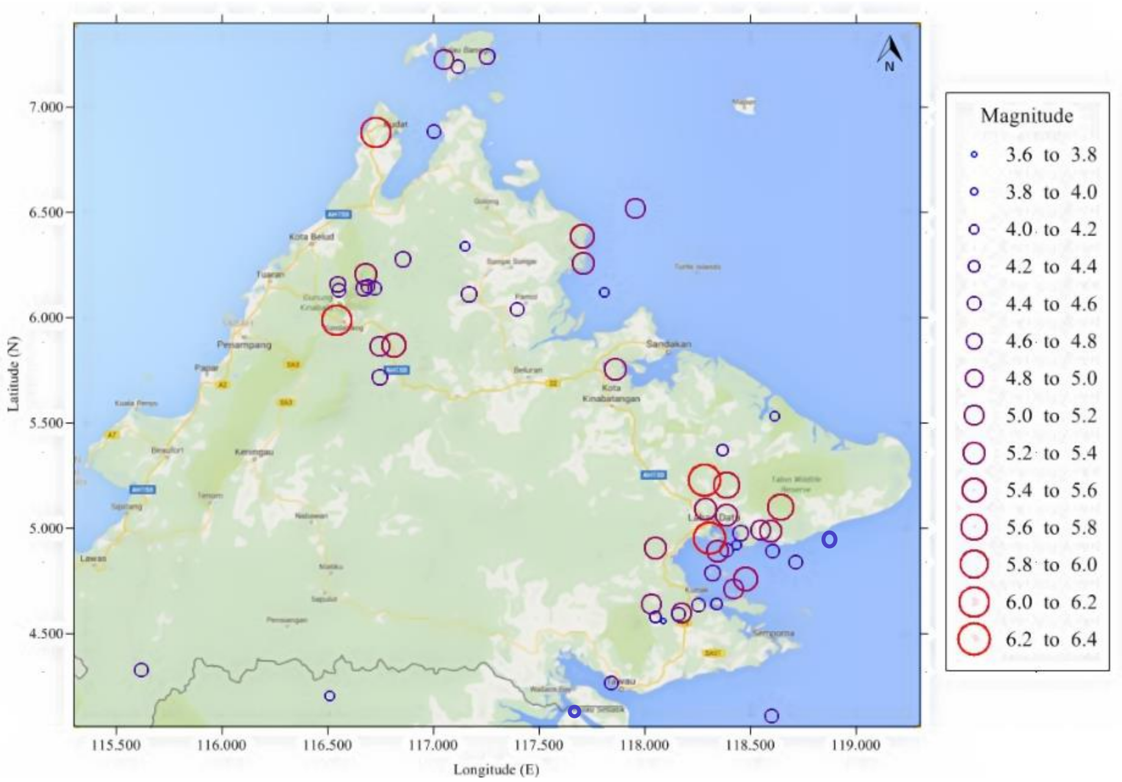

Figure 2.2: Past earthquake events in Sabah up to 2016 (Chang, 2016)

2.3 Near-Field and Far-Field Earthquakes

An earthquake induces the spreading of seismic motion from the seismic source (fault) and its characteristics at the field surface vary depending on several different factors, which are source mechanism, distance from the source, radiation pattern and site effects (Grimaz and Malisan, 2014). In an area around the epicentre, the seismic ground motion could be substantially different from the ground motion in the far field. It is known that Malaysia has experienced both near-field and far-field earthquakes. Near-field and far-field zones are illustrated in Figure 2.3. Despite local origin from Bukit Tinggi area in Kuala Lumpur and Ranau-Kundasang area in Sabah, distant earthquake epicentres from Sumatra Fault and Sumatra Subduction Zones cause tremors to be felt in Peninsular Malaysia. The structural response of buildings in this country should be taken into consideration on the effect of both near-field and far-field earthquakes. As there are important differences between near-field and far-field earthquakes, detailed study on their characteristics is essential for better structural safety evaluation (Foti, 2015; Heydari and Mousavi, 2015; Milad, 2015).

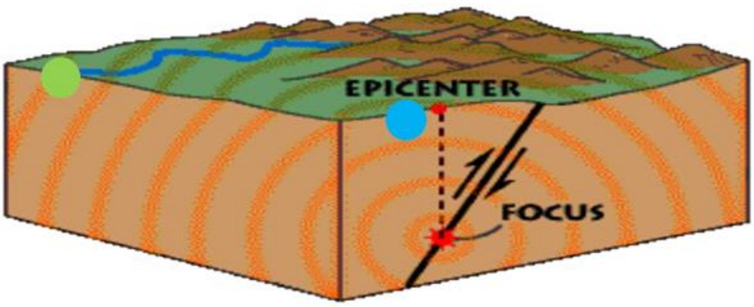

Figure 2.3: Near-field (blue dot) and far-field zones (green dot) (Milad, 2015)

Foti (2015) summarized the differences between near-field and far-field earthquakes in the study to investigate the local ground effects in near-field and far-field areas on seismically protected buildings. Firstly, the direction of propagation of the fault has a major influence in a near-field area while the stratification of the soil having minor effects. However, in case of far-field zone, the stratification of the soil and site conditions are of primary importance for the horizontal components of the seismic waves. Besides, near-field ground motion time-history acceleration plot indicates a pulse in the low frequencies range and a pronounced pulse in the velocity and displacement time-histories. The motion is of short duration in this case. On the contrary, in far-field areas, the acceleration, velocity and displacement recordings have the characteristic of a cyclical movement, with a long-lasting action. Moreover, there are very high velocities in near-field areas as the velocity appears to be the most significant parameter in the design, whereas the acceleration represents the most significant parameter in the design in far-field areas. On top of that, in near-field areas, vertical components may be higher than the horizontal ones. This condition is contrary with far-field ground motion.

Distance of a site to the epicentre decides the types of ground motion experienced at the site. Different epicentre distances have been suggested by the researchers. The near-field zone is typically considered to have epicentre distance of less than 50 km, whereas the far-field area located more than 50 km from the ruptured fault (Mohraz, 1994). Moreover, Davoodi and Sadjadi (2015) mentioned that, the ground motions in the near-field zone may be distinguished by short-duration impulsive motions, permanent ground displacement and high-frequency content, which have attracted much attention as the critical factors in the design of structure in the near-field zone. On the other hand, the far-field ground motions pose criteria of low-frequency and long-period content (Figure 2.4).

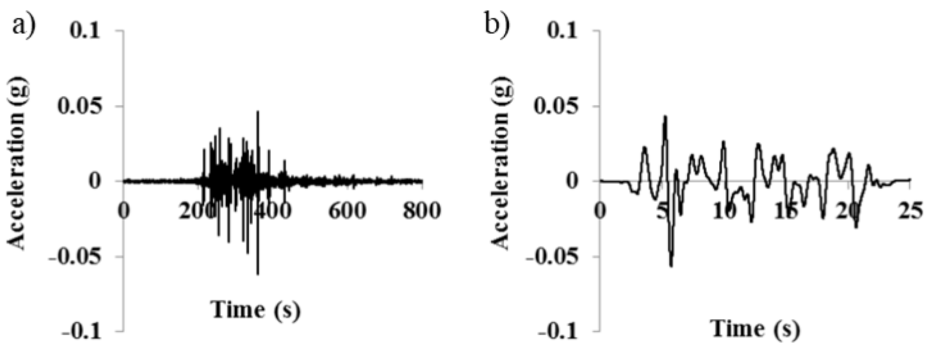

Figure 2.4: (a) Short-period (near-field) and (b) long-period (far-field) ground motions (Zhang and Goh, 2015)

In the study done by Mohraz (1994), the influences of soil condition, duration of strong motion, source to site distance and orientation of motion on ground motion were evaluated. The results shown in Figure 2.5 clearly indicate that for greater periods, both the soil and rock site show higher amplification at far-field zone, whereas the amplification at near-field area is higher for smaller periods. The cross-over period stated is 0.5 s.

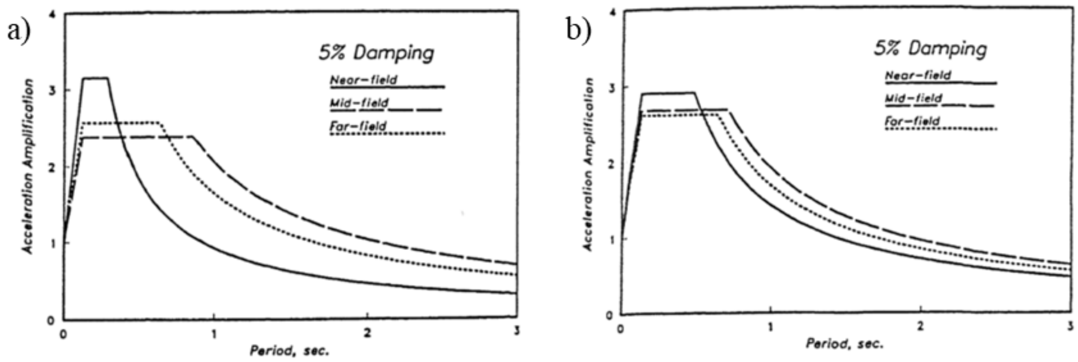

Figure 2.5: Acceleration amplification for (a) rock and (b) soil for different source to site distances for Loma Prieta earthquake (Mohraz, 1994)

2.4 Factors Affecting Soil Amplification

As the seismic waves propagate through overlying soil and reach the ground surface, the ground motion parameters such as amplitude of motion, frequency content and the duration of ground motion change during the process. The phenomenon, in which the local soil acts as a filter, modify the ground motion characteristics is known as soil amplification (Govindaraju et al., 2004).

Soil amplification plays an important role in creating extra risk to the buildings during a major earthquake. Its magnitude depends mainly on the soil condition, depth to firm ground and the input earthquake motion (Uthayakumar and Naesgaard, 2004). This amplification process begins when a fault ruptures below the earth's surface, body waves travel away from the source in all direction. As they reach boundaries between different geologic materials, they are reflected and refracted. Since the wave propagation velocities of shallower materials are generally lower than the materials beneath them, inclined rays that strike horizontal layer boundaries are usually reflected to a more vertical direction. By the time the rays reach the ground surface, multiple refractions have often bent them to a nearly vertical direction, as shown in Figure 2.6.

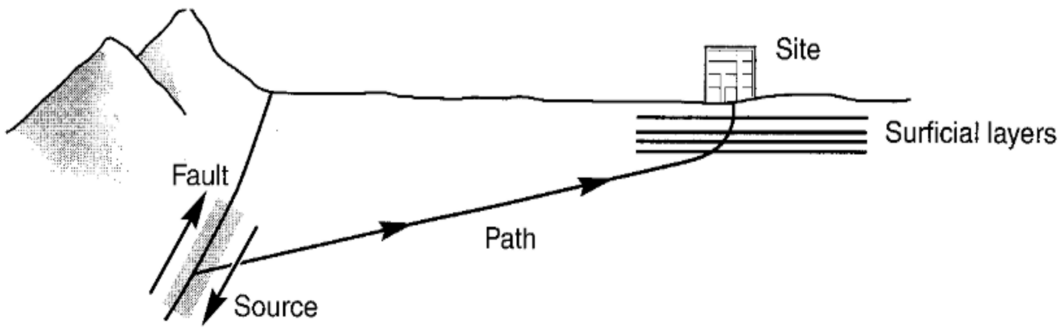

Figure 2.6: Refraction process that produces nearly vertical wave propagation near the ground surface (Kramer, 1996)

According to a study done by Southern California Earthquake Center (SCEC, 2000), the important geologic factors of a site, which are the softness of the rock or soil near the surface and the thickness of the sediments above hard bedrock, are contributed to the soil amplification. The shaking of an earthquake is amplified in softer rock. Besides, when the sediment depth increases, so thus the amplification of bedrock motion.

2.4.1 Effect of Soil Types

Studies done by Seed et al. (1976) and Mohraz (1976) found out the soil condition influences spectral shapes and amplification of ground motion significantly. The statistical study done by Seed et al. (1976) using different soil types ranging from soft to hard soil that subjected to 147 records from the western USA, as shown in Figure 2.7. The results show higher amplification on a rock site than on soil site in the shorter period range.

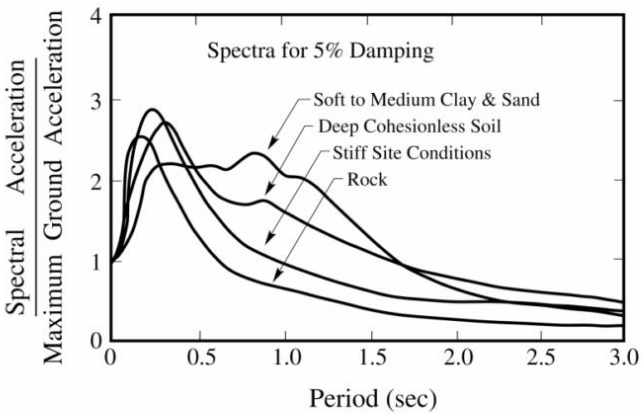

Figure 2.7: Average acceleration spectra for different site conditions (Seed et al., 1076)

In the study conducted by Mohraz (1994), computed spectral shapes and amplification from Loma Prieta earthquake were compared with those from previous earthquake. The result indicated that while the ground motion and spectral shapes for alluvium from the Loma Prieta were in agreement with those from previous earthquakes, the ground motion and spectral shapes for rock from Loma Prieta were substantially larger than their counterpart from previous earthquakes and were, indeed, close to those for alluvium. Figure 2.8 illustrates the amplification for alluvium for previous earthquakes was greater than that for rock, especially for long period range.

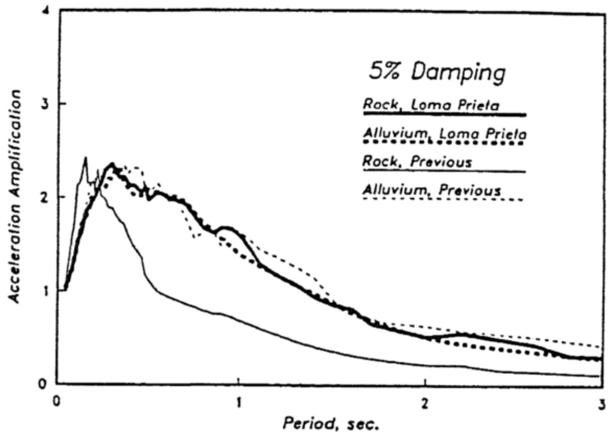

Figure 2.8: Comparison of average acceleration amplification (Mohraz, 1994)

The result of study conducted by Cubrinovski and McCahon (2011) is illustrated in Figure 2.9. The results showed that the acceleration response spectra of the ground motions recorded at LPCC and LPOC seismic stations in the Lyttelton Port during Christchurch earthquake on 22 February 2011. These stations are approximately 1 km apart where LPCC is located effectively on the volcanic rock, while LPOC is on top of approximately 30 m layer of silty and clayey soils. Typical effects of soft deposits on the response spectrum are shown in which the ground motion recorded at LPOC shows significant reduction of the low periods (high frequency) components, and conversely an amplification of the motion in the range of long periods. Meanwhile, the ground motion at LPCC shows the opposite condition of that at LPOC.

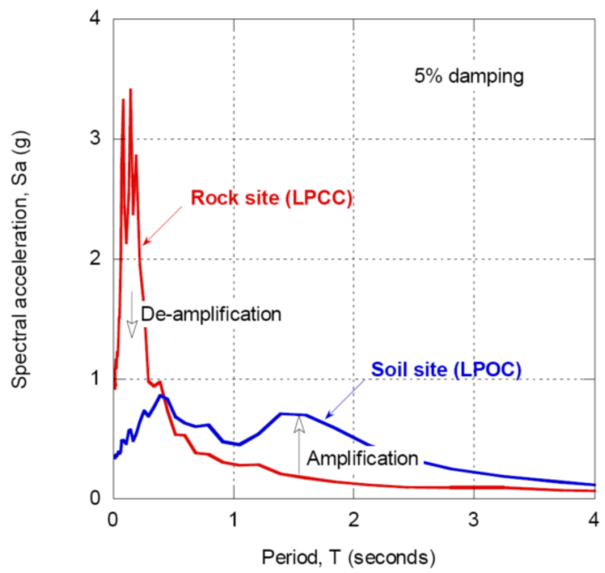

Figure 2.9: Acceleration response spectra during the 22 February 2011 Christchurch earthquake (Cubrinovski and McCahon, 2011)

In the study carried out by Loye et al. (2013), the effect of soil characteristic on structural seismic demand was evaluated. Based on New Zealand Standard (NZS1170.5) provisions, which specifies seismic design spectra corresponding to five different soil types, for all natural periods, the building demand for soft soil is either equal to or greater than that for hard soil. This is against the basis structural dynamic theory which suggests that when the stiffness of a system increased, the acceleration response increased. From the analysis done, it was found that in the same period range, stiffer soil sediments amplify the spectral acceleration response significantly more than the soft soils do. Moreover, the spectral shape curves form a soil class hierarchy of increased amplification as the stiffness of the soil decreases. This is only applicable for softer soil in the long-period range. Thus, it can be said that the soft soils amplify the long period response more than the hard soils. Meanwhile, it also showed that hard rocky deposits (soil class A & B) produce large short-period amplifications that are greater than the short-period response of soft soils.

Raheem et al. (2015) investigated the influence of soil type on the dynamic response of moment resisting frame multi-story buildings. The analysis results showed that the soil structure interaction significantly affected the base forces and roof displacement of building when compared to typical assumption in which interaction would be neglected. During the earthquake, the dynamic response of the structure will not be affected significantly by the soil properties when the ground is stiff enough. However, when the structure is resting on a flexible medium, the dynamic response of the structure will be different, owing to the interaction between the soil and the structure.

Furthermore, the finding conducted by Hoult et al. (2017) evaluated the potential revisions of the spectral shape factors used in Australian Standards for Earthquake Actions AS 1170.4:2007 in regions of low-to-moderate seismicity. Different soil site classes, from strong rock (A_e) to soft soil (E_e) were applied for this study. The results showed that the dependency of site amplification on seismic intensity was only observed for soil classes C_e, D_e and E_e. Besides, the rock site of class B_e had considerably higher response in the short period range in comparison to class E_e. From the analysis, the deep sand soil sites had a large amplification of the low period spectral acceleration. This means that low-rise buildings on sandy sites may experience much low levels of seismic loading. These results indicate that a low-to-moderate intensity earthquake event can cause a large amplification of the structural acceleration response on rock sites and cause damaging effects on stiff structures.

2.4.2 Effect of Depth of Soil

Soil depth is one of the main parameters to be considered for soil amplification. In the study done by Govindaraju et al. (2004), a time history acceleration ground motion of N 78 E horizontal component recorded at the ground floor of the Passport Office building in Ahmedabad, India during 2001 Bhuj earthquake was used as input motion. For each longitudinal, transverse and vertical component, the peak ground accelerations (PGAs) were observed to be 0.106 g, 0.08 g and 0.07 g, respectively. Through analysis, a considerable modification was obtained in the acceleration values from 0.064 g to 0.106 g between 15 m depth and ground surface respectively, resulting in PGA amplification factor of 1.66. Moreover, the value of natural frequency corresponding to the maximum amplification between the surface motion and the motion at the base is 3.51 Hz for 15 m deep soil. This clearly indicates that large amplification of shear waves by the thick sandy soil deposit result in high degree of damage to buildings above four-storey and up to ten-storey. Figure 2.10 suggests that when the depth of soil increases, the acceleration of motions decrease while resulting in a higher amplification.

Besides, ground response analysis of four sites with firm ground depth of 30 m, 50 m, 150 m and 300 m had been studied by Uthayakumar and Naesgaard (2004). With the decrease in firm ground depth, the peak spectral acceleration at the surface increases and the corresponding period at the peak spectral acceleration decreases. Furthermore, the input earthquake motion at all four sites is attenuated in small period range and then significantly amplified in large period range. The range of period over significant amplification is higher for the sites with deeper deposits than those with shallow deposits.

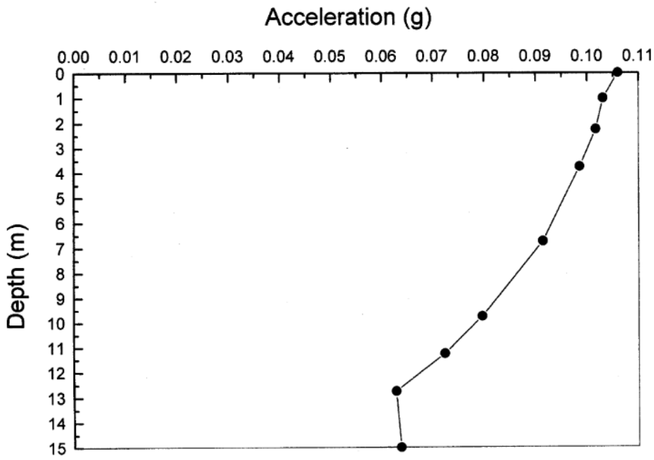

Figure 2.10: Variation peak ground acceleration (PGA) with depth
(Govindaraju et al., 2004)

Adhikary and Singh (2012) investigated the effect of variation in soil depth for the same site class on the shape of response spectra and amplification factors. Soil depth affects the shape of response spectra significantly, affecting the long-period corner period which is governed by the predominant site period. The result showed that as the amplification factor gradually reduces with depth, shallow soft layers have more amplification potential for ground acceleration than very deep soil layers. However, the effect of depth of soil deposits on displacement spectrum is different due to change in corner period. The peak displacement for deep soils is much larger, having significant influences in the context of displacement-based design.

On top of that, the detailed study conducted by Adhikary et al. (2014) on the effect of soil depth clearly brought out the significant effect of soil depth on elastic and inelastic seismic response of structures. From the analysis, it can be observed that increasing depth of soil stratum results in the decrease of peak spectral acceleration whereas, increases the peak spectral displacement. Besides, the site amplification factor decreases in the short period range and increase in long period range, with depth of soil stratum.

In addition, the effect of soil depth on seismic site amplification by considering small near-field earthquake events and large distant ones was done by Soghrat and Ziyaeifar (2015). Three different soil depths which were 30 m, 60 m and 200 m, three records of small near-field earthquake events and another three records of large distant ones that were normalized to PGA of 0.1 g, were applied to explain the effect of soil depth. This study suggested that the fundamental period as a function of thickness of soil profile is changed with different soil depths, as shown in Figure 2.11. Thicker soil profiles have longer fundamental period. Hence, it can be said that large distant earthquakes which are rich in low frequency component can amplify the response on deep soil profile.

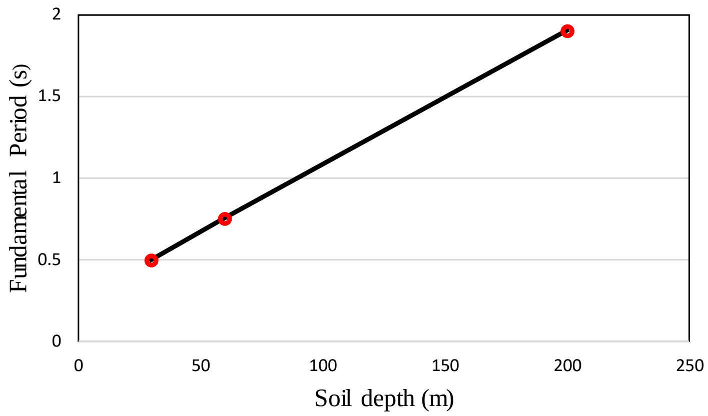

Figure 2.11: The variation of fundamental period and soil depth (Soghrat and Ziyaeifar, 2015)

2.5 Ground Response Analysis

The evaluation of ground response is one of the most important encountered problems in geotechnical earthquake engineering. Ground response analyses are used to predict ground surface motions for the development of design response spectra, to evaluate dynamic stresses and strains for evaluation of liquefaction hazards, and to determine the earthquake-induced forces that can lead to instability of earth and earth-retaining structures (Kramer, 1996). Under ideal condition, a complete ground response analysis should include factors which are the rupture mechanism at source of an earthquake, the propagation of stress waves through the crust to the top of bedrock beneath the site of interest and the influence of the soils that lie above the bedrock to ground surface motion (Govindaraju et al., 2004).

Rigidity of bedrock is considered in ground response analysis. If a bedrock is rigid, its motion will not be affected by the motion, even in the presence of overlying soil. Acting as a fixed end boundary, the rigid layer will completely reflect any travelling-downward wave back toward the ground surface, consequently trap the elastic wave energy within the soil layer. When a bedrock is elastic, the downward-travelling stress waves that reach the soil-rock boundaries will be partially reflected, causing the transmission of part of their energy through the boundary to continue travelling downward through the rock. If the rock extends to greater depth, the elastic energy of these waves will be removed from the soil layer due to a form of radiation damping, making smaller free surface motion amplitudes than those for the case of rigid bedrock.

Real ground response problem involves soil deposits with different stiffness and damping characteristics with boundaries at which elastic wave energy will be reflected or transmitted. Kramer (1996) considered a soil deposits with N horizontal layers where Nth layer is elastic bedrock as shown in Figure 2.12.

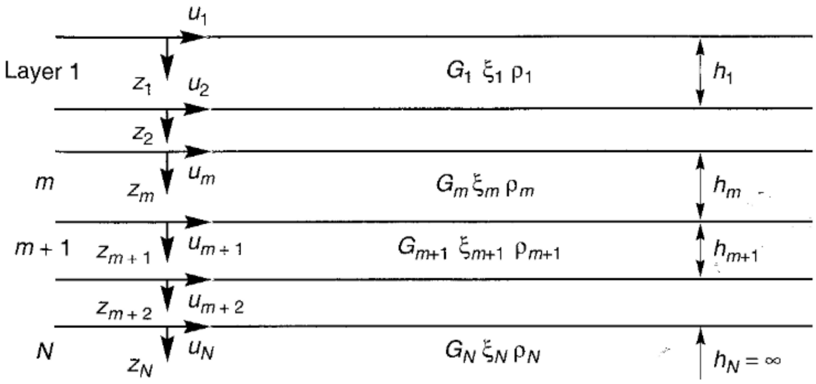

Figure 2.12: Nomenclature of layered soil deposit on elastic bedrock (Kramer, 1996)

According to Bardet et al. (2000), the one-dimensional equation of motion for vertically propagating shear waves is:

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial t}{\partial z} \tag{2.1}$$

where ρ is the unit ass in any layer. Assuming that the soil in all layers behave as a Kelvin-Voigt solid, Equation (2.1) becomes:

$$\rho \frac{\partial^2 u}{\partial t^2} = G \frac{\partial^2 u}{\partial z^2} + \eta \frac{\partial^3 u}{\partial z^2 \partial t} \tag{2.2}$$

For harmonic waves, the displacement can be written as:

$$u(z, t) = U(z) e^{i\omega t} \tag{2.3}$$

Using Equation (2.3), Equation (2.2) becomes:

$$(G + i\omega\eta) \frac{d^2 U}{dz^2} = \rho\omega^2 U \tag{2.4}$$

And admits the following general solution:

$$U(x) = E e^{ik^* z} + F e^{-ik^* z} \tag{2.5}$$

where $k^{*2} = \frac{\rho\omega^2}{G+i\omega\eta} = \frac{\rho\omega^2}{G^*}$ is the complex wave number. After introducing the critical damping ratio ξ so that $\xi = \omega\eta/2G$, the complex shear modulus G^* becomes:

$$G^* = G+i\omega\eta = G(1+2i\xi) \tag{2.6}$$

The solution of Equation (2.4) is:

$$u(z,t) = (Ee^{ik^*z} + Fe^{-ik^*z})e^{i\omega t} \tag{2.7}$$

and the corresponding stress is:

$$\tau(z,t) = ik^*G^*(Ee^{ik^*z} + Fe^{-ik^*z})e^{i\omega t} \tag{2.8}$$

The displacements at the top (z = 0) and bottom ($z = h_m$) of layer m of thickness h_m *are:*

$$u_m(0,t) = u_m = (E_m+F_m)e^{i\omega t}$$
$$\text{and } u_m(h_m,t) = (E_m e^{ik_m^*h_m} + F_m e^{-ik_m^*h_m})e^{i\omega t} \tag{2.9}$$

The shear stresses at the top and bottom of layer m are:

$$\tau_m(0,t) = ik_m^*G_m^*(E_m+F_m)e^{i\omega t}$$
$$\text{and } \tau_m(h_m,t) = ik_m^*G_m^*(E_m e^{ik_m^*h_m} + F_m e^{-ik_m^*h_m})e^{i\omega t} \tag{2.10}$$

At the interface between layers m and $m+1$, displacements and shear stress must be continuous, which implies that:

$$u_m(h_m,t) = u_{m+1}(0,t) \text{ and } \tau_m(h_m,t) = \tau_{m+1}(0,t) \tag{2.11}$$

Using Equation (2.9) and (2.10), the coefficients E_m and F_m are related through:

$$E_{m+1}+F_{m+1} = E_m e^{ik_m^*h_m} + F_m e^{-ik_m^*h_m} \tag{2.12}$$

$$E_{m+1}-F_{m+1} = \frac{k_m^*G_m^*}{k_{m+1}^*G_{m+1}^*}(E_m e^{ik_m^*h_m} + F_m e^{-ik_m^*h_m}) \tag{2.13}$$