DYNAMIC CHARACTERISTICS AND SEISMIC PERFORMANCE OF REINFORCED CONCRETE BUILDINGS EXPERIENCING 5 JUNE 2015 AND 8 MARCH 2018 SABAH EARTHQUAKES

HO KAR MENG

SCHOOL OF CIVIL ENGINEERING
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HO KAR MENG

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Name of Student: HO KAR MENG

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

Signature:

HO KAR MENG

Date :

Approved by:

(Signature of Supervisor)

Name of Supervisor : ASSOC. PROF. DR. LAU TZE LIANG

Date :

Approved by:

(Signature of Examiner)

Name of Examiner : IR. DR. SHAHARUDIN SHAH ZAINI

Date :

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ABSTRAK

Kuarters staf S.M.K. Ranau dan kuarters pengawai Hospital Ranau telah mengalami kerosakan selepas gempa bumi Sabah berskala 6.0 pada 5 Jun 2015 dan telah dibaiki pada 2016. Akan tetapi, satu gempa bumi berskala 5.2 telah melanda Ranau, Sabah pada 8 Mac 2018 dan keadaan semasa kedua-dua bangunan ini masih tidak diketahui. Disertasi ini membentangkan hasil mengenai ciri dinamik kedua-dua bangunan ini yang mengalami peristiwa gempa bumi Sabah pada 2015 dan 2018 berdasarkan pemerhatian mikrogegaran pada Januari 2016, April 2017 and November 2018. Frekuensi modal dan bentuk ragam gegaran masing-masing ditentukan dengan kaedah Nakamura dan Penguraian Domain Masa (TDD). Disebabkan tiada kajian dilakukan ke atas ciri dinamik dua bangunan berkenaan sebelum gempa bumi pada 2015, analisis berkomputer telah dilakukan menggunakan ETABS berpandukan pelan arkitek dan pengukuran di tapak untuk mensimulasikan ciri dinamik dua bangunan berkenaan sebelum gempa bumi Sabah pada 2015. Hasil kajian menunjukkan bahawa frekuensi asas model bagi kuarters staf S.M.K. Ranau dan kuarters pegawai Hospital Ranau telah berkurang sebanyak 20 % selepas gempa bumi Sabah pada 2015. Pengurangan ini adalah ketara dan ia konsisten dengan kerosakan sederhana yang dialami oleh kedua-dua bangunan. Untuk kes selepas gempa bumi pada 2018, frekuensi asas kedua-dua bangunan telah menurun kurang daripada 2.5 %. Ini menunjukkan bahawa kedua-dua bangunan mungkin mengalami kerosakan yang sangat minor semasa gempa bumi. Prestasi seismik kuda-dua bangunan di bawah beban reka bentuk yang dinyatakan dalam *Malaysia National Annex to MS EN 1998-1:2015* telah diperolehi melalui simulasi berangka dengan menggunakan analisis spectrum sambutan modal. Di bawah pecutan reka bentuk sebanyak 0.16 g, hanyutan antara tingkat maksimum berlaku di tingkat satu disebabkan kesan tingkat lembut. Hanyutan antara tingkat maksimum untuk kuarters staf S.M.K. Ranau telah melebihi had kerosakan yang dinyatakan dalam Eurocode 8. Keputusan juga menunjukkan jaket tiang yang digunakan terhadap kuarters staf S.M.K. Ranau semasa pembaikan pada 2016 telah meningkatkan frekuensi asas dan telah menggurangkan anjakan bangunan maksimum dan hanyutan antara tingkat maksimum, tetapi jaket tiang juga telah meningkatkan daya ricih tingkat dan momen terbalikkan maksimum di tingkat bawah.

ABSTRACT

Staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau that were damaged during a Sabah earthquake with a magnitude of 6.0 on 5 June 2015 were repaired in 2016. However, an earthquake with a magnitude of 5.2 struck Ranau, Sabah again on 8 March 2018, thus it is unknown for the present condition of both buildings. This dissertation presents the results on dynamic characteristics of these buildings experiencing both Sabah earthquake events based on microtremor observations in January 2016, April 2017 and November 2018. The modal frequencies and vibration mode shapes of the buildings were determined by using the Nakamura method and Time Domain Decomposition method, respectively. Due to the absence of the study on dynamic characteristics of both buildings before 2015 Sabah earthquake, computational analyses were performed using ETABS based on the architectural plan and on-site measurement in order to simulate the building condition before the earthquake. The results show that the fundamental frequencies for staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau reduced up to 20 % after 2015 Sabah earthquake. This reduction is significant and consistent with moderate damages suffered by both buildings. For the case after 2018 Sabah earthquake, the fundamental frequencies of both buildings reduced less than 2.5 %. This implies that both buildings may suffered very minor damages during the earthquake. Seismic performances of both buildings under the design load stipulated in Malaysia National Annex to MS EN 1998-1:2015 were obtained through numerical simulation by using modal response spectrum analysis. Under the design acceleration of 0.16 g, the maximum interstorey drift occurs at the first floor due to soft storey effect. The maximum interstorey drift for the staff quarters of S.M.K. Ranau exceeded the damage limitation as specified in Eurocode 8. The results also showed that the column jacketing applied to staff quarters of S.M.K. Ranau during repair in 2016 increased the fundamental frequency and reduced the maximum storey displacement and interstorey drift, but this also increased the maximum storey shear force and overturning moment at the ground floor.

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CHAPTER 1

INTRODUCTION

1.1 Overview

A disaster is an event that causes disruption to community activities and national affairs, which is beyond the coping capacity of the community of the affected area and require extensive resource mobilization. Natural disasters such as earthquake, volcanic eruption and tsunami may cause loss of life, property damage, economic loss and environment destruction.

In term of geological condition, Malaysia is located on the relatively stable Sunda Plate as shown in Figure 1.1, which was formerly considered as a part of Eurasian Plate, but Global Positioning System (GPS) measurements have confirmed its independent movement at 10 mm per year eastward relative to Eurasia (Socquet et al., 2006). Due to the geographical location of Malaysia which is not located along the plate tectonic boundaries and away from Ring of Fire, major earthquakes and volcanic eruptions are rare in Malaysia.

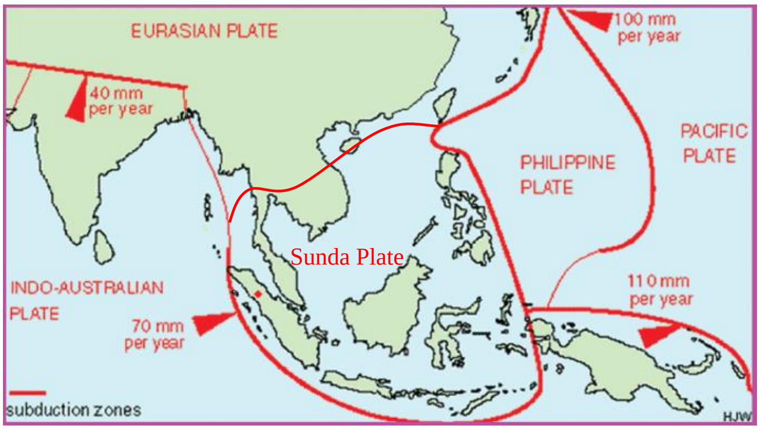

Figure 1.1: Location of Malaysia and Tectonic Plates Surrounded Malaysia (Tongkul, 2017)

However, presence of compression energy formed by the interaction of tectonic plates may cause minor quake in Malaysia especially near the regions with fault lines (Noor, 2018). Philippine Plate and Pacific Plate which are moving westward at a rate of 10 cm per year as well as southern part of the Indo-Australian Plate which is moving northwards at a rate of 7 cm per year colliding to the Eurasian Plate resulted Sabah to consistently receive compression forces. As a brittle response to stress, there were a total of 16 earthquakes with magnitude more than 4.0 in Sabah for the past 20 years from 1995 to 2015 (Tongkul, 2017).

Among all the 16 earthquakes, the Ranau earthquake with magnitude of 6.0 that happened on 5 June 2015 was the most remarkable because it was the second highest recorded magnitude of earthquake in Sabah. Based on Sabah Minerals and Geoscience Department's studies, this earthquake was caused by the presence active faults, namely Kedamaian and Lobou-Lobou faults that lie within Ranau district and crisscrossing Mount Kinabalu as shown in Figure 1.2. This earthquake had taken 18 lives and caused water shortage due to damaged pipes, rock falls as well as landslides near the summit of Mount Kinabalu and physical damage to infrastructure and public buildings (Tongkul, 2016). During this earthquake, the soft storey buildings, such as staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau suffered more severe damage than those infilled frame reinforced concrete buildings because the soft storey buildings are more seismic vulnerable. Figure 1.3 shows the damages of both buildings after 2015 Sabah earthquake. A building is considered as soft storey if the soft storey level is less than 70% as stiff as the floor immediately above it, or less than 80% as stiff as average stiffness of three floors above it. For soft-storey buildings, the storey drift of open ground storey frame is very large than the upper storeys due to absence of infill wall which contributes to vast deviation of lateral stiffness between ground and upper storeys. These damaged buildings of S.M.K. Ranau and Hospital Ranau were repaired in the period from August to December 2016. On 8 March 2018, another earthquake with magnitude of 5.2 struck the north-west of Sabah again. The structural integrity of these repaired buildings may alter even though there are no visible damages is observed. Hence, dynamic characteristics of the buildings should be properly assessed so that possible measures can be done to increase the lifespan of these structures to withstand various dynamic loadings. The details of 5 June 2015 and 8 March 2018 Sabah earthquakes are shown in Table 1.1.

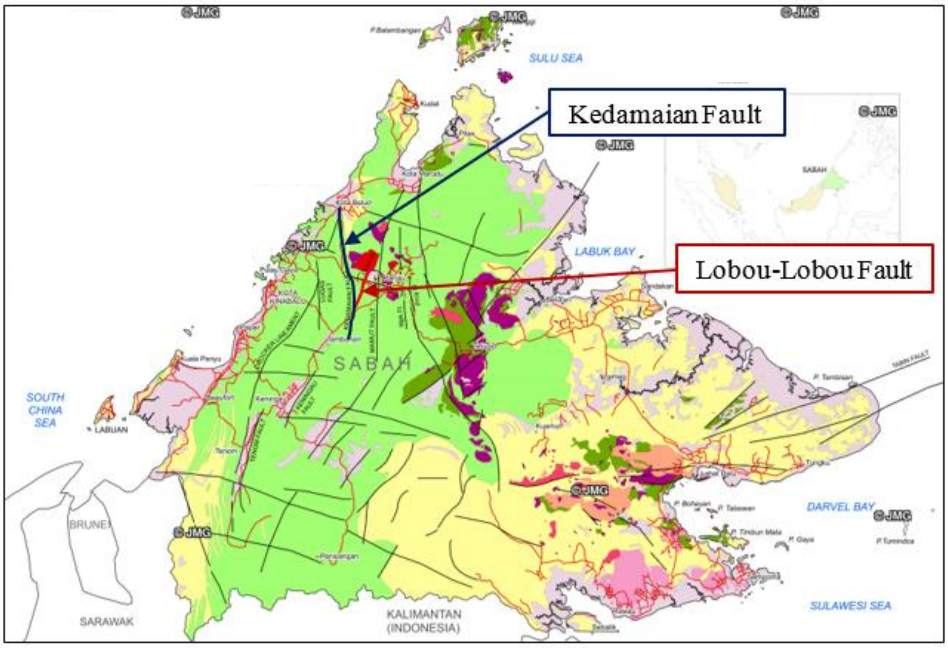

Figure 1.2: Kedamaian and Lobou-Lobou Faults Lie within Ranau District and Crisscrossing Mount Kinabalu (Mineral and Geoscience Department Malaysia, 2012)

Table 1.1: Details of 5 June 2015 and 8 March 2018 Sabah Earthquakes (United State Geological Survey, 2019)

Sabah Earthquake	5 June 2015	8 March 2018
Magnitude (USGS)	6.0	5.2
Local Time of Malaysia	07:15	21:06
Epicenter	14 km, Northwest from Ranau Town	16 km, Northwest from Ranau Town
Hypocentral depth	10 km	10 km

Cracking of the Masonry Wall Covering Column

Diagonal Shear Crack on Masonry Infill Wall

Beam-column Joint Damage

(a)

Cracking at the Bottom of Column

Beam-column Joint Damage

Diagonal Shear Crack on Masonry Infill Wall

(b)

Figure 1.3: Damages of (a) Staff Quarters of S.M.K. Ranau and (b) Officer Quarters of Hospital Ranau after 5 June 2015 Sabah Earthquake

1.2 Problem Statement

In Malaysia, dynamic characteristics of existing buildings are seldom being emphasized in which most of the buildings are designed considering only various vertical load combinations according to British Standard, BS 8110:1997. This may due to the mindset of the designers that Malaysia is not located on seismic prone area. The lacking of research works being carried out to determine the structural dynamic behaviour in Malaysia had led to the insufficient data to examine the newly established Malaysia National Annex to Eurocode 8: Design of Structures for Earthquake Resistance in 2017. In addition, the incident of earthquake tragedy with magnitude of 6.0 that hit Ranau and Kundasang areas on 5 June 2015 had triggered the response from Malaysia government to emphasize on the seismic design and concern on the dynamic behaviour of the buildings. Hence, comprehensive studies on the dynamic behaviour of buildings should be carried out promptly.

Staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau experienced critical damage after 5 June 2015 Sabah earthquake and were repaired in the period from August to December 2016. During 8 March 2018 earthquake, an earthquake with magnitude of 5.2 struck the north-west of Sabah. Therefore, it is unknown for the present condition of both buildings. Since changes in dynamic characteristics of these soft storey buildings after an earthquake is a public concern, hence they are chosen to be investigated in this research.

During a strong earthquake, the dynamic characteristics of buildings may significantly altered as proven by many researchers, such as Ohba and Fukuda (2000) and Sato et al. (2008). Lim (2016) conducted a research to compare the dynamic characteristics of buildings before and after an earthquake. Both conditions are determined via numerical simulation and microtremor observation, respectively. Since the simulated buildings are assumed to be perfectly constructed by ignoring the factors of imperfections and errors in construction, thus the simulated dynamic behaviour may not be the true response of the structures at pre-earthquake condition. Moreover, the simulated models representing pre-earthquake condition were not verified due to the absence of field measurement record. Hence, definite conclusion on significant changes in the dynamic characteristics of buildings after an earthquake event cannot be precisely defined. A properly verified model should be simulated so that the true response of the structures at pre-earthquake condition can be obtained.

1.3 Objectives

The objectives of this research are as below:

i. To evaluate the modal frequencies and vibration mode shapes estimated from microtremor observation for reinforced concrete buildings (staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau) experiencing 5 June 2015 and 8 March 2018 Sabah earthquakes.

ii. To assess the seismic performance of reinforced concrete buildings (staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau) subjected to design seismic load stipulated in Malaysia National Annex to Eurocode 8: Design of Structures for Earthquake Resistance – Part 1: General Rules, Seismic Actions and Rules for Buildings (MS EN 1998-1:2015).

iii. To investigate the effect of jacketed column at the ground floor of staff quarters of S.M.K. Ranau.

1.4 Scope of Work

The scope of work in this research focuses on the field measurement of microtremor data at two selected multi-storey reinforced concrete buildings experiencing

5 June 2015 and 8 March 2018 Sabah earthquakes. Microtremor observation are carried out at staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau. This involves data collection at the center of buildings for four and five different floor levels of staff quarters of S.M.K. Ranau and officer quarters of Hospital Ranau, respectively. Modal frequency and vibration mode shape of the buildings are computed by using the Horizontal to Vertical Spectral Ratio (HVSR) method developed by Nakamura (1989), and Time Domain Decomposition (TDD) method, respectively. Numerical models representing repaired buildings after 2015 Sabah earthquake is done based on the existing drawing and on-site measurement, and the numerical analysis results are verified with the measured microtremor data. Due to the absence of field measurement before 2015 Sabah earthquake, the pre-earthquake condition is simulated using the verified models. The dynamic characteristics of the repaired buildings after 2015 Sabah earthquake are assumed to be same as the dynamic characteristics of the buildings before 2015 Sabah earthquake for officer quarters of Hospital Ranau. For staff quarters of S.M.K. Ranau, the simulated model is replaced with non-concrete-jacketed columns in order to assume the dynamic characteristics before 2015 Sabah earthquake. The effect of adding jacket on the perimeter columns at the ground floor is investigated. Moreover, the seismic performance of the buildings based on the seismic loading recommended in Malaysia National Annex to Eurocode 8 is included at the end of the dissertation.

1.5 Justification of Research

In the dynamic response analysis of a structure, important dynamic properties are predominant frequency and vibration mode shapes. The predominant frequency is used to determine the seismic coefficient and site-structure resonance factor in the base shear formula used in the static approach of many earthquake codes, while the mode shape is used to determine the base overturning moments and vertical distribution of shear forces (Brownjohn et al., 2000). The natural frequency of the buildings must not be closed to the forcing frequency of the ground vibration in order to avoid resonance effect to the structures. Besides, identification of these dynamic properties are crucial to check for structural integrity as buildings age and are subjected to ever increasing loads, or after some specific damaging events such as earthquake. In addition, these dynamic properties identified from microtremor test can be correlated with finite element analyses to enhance the analytical model (Brownjohn, 2003). By identifying dynamic factors, early improvement works can be done to buildings prior to any potential seismic load failure. The findings of this project will contribute to the assessment of building after an earthquake event and the design of seismic resistant building for engineers.

1.6 Structure of Dissertation

This dissertation consists of five chapters. Chapter 1 includes an overview, problem statement, objectives, scope of work and justification of the research. Chapter 2 reviews literatures and discusses the findings on determination of dynamic characteristics of buildings in both the field measurement and numerical studies. Introduction to microtremor, techniques of using Horizontal to Vertical Spectral Ratio (HVSR) for obtaining dynamic characteristics of the building and implementation of equivalent diagonal struts method for the effect of non-structural elements are elaborated in this chapter. Chapter 3 discusses the methodology of research which include study location, procedure of data acquisition and analysis and numerical simulation. In Chapter 4, the results obtained from this research are presented in the form of tables, figures and graphs and are further discussed. Lastly, the conclusions of the findings in this research are stated and recommendations for future research are proposed in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

In the absence of any earthquake event, daily human activities and natural phenomenon had caused the surface of Earth always in constant motion at seismic frequencies with generally small amplitude of displacement. These constant vibrations are known as microtremors (Okada and Suto, 2003).

The important dynamic characteristics of buildings include predominant frequency and vibration mode shape. Both ambient and forced vibration tests can be used to determine the dynamic characteristics of the buildings. Microtremor observation is actually the ambient vibration test. Horizontal to Vertical Spectral Ratio (HVSR) is a method used to estimate the predominant frequency and amplification factor of ground and structure from the measured microtremor as proposed by Nakamura (1989). As compared to forced vibration test, the advantages of the ambient vibration are that only light equipment and smaller number of operator are required (Ivanovic et al., 2000). Trifunac (1972) and Oliveira and Navarro (2010) confirmed that both ambient and forced vibration surveys can give mutually consistent results. Moreover, Hans et al. (2005) assured that simple ambient measurements is sufficient to identify the structure’s dynamic behaviour.

According to Dohare and Maru (2014), buildings with and without infill masonry walls in upper storeys and ground storey, respectively are regarded as soft storey buildings. The open ground storey is mainly for the purpose of open space for parking and for community gathering area. The ground floor is weaker due to its inadequate rigidity and it is usually vulnerable to earthquake collapse (Apostolska et al., 2016).

According to Su et al. (2005), the behaviour and stiffening effect of non-structural components (NSC) under lateral loading have normally been ignored by design engineers. In fact, NSC can improve the stiffness and performance of structures. In addition, Tamboli and Karadi (2012) confirmed that the presence of NSC, such as infill wall will increase the lateral stiffness of the structure. Hence, in order to model the infill wall, equivalent diagonal strut method is used.

2.2 Microtremor

According to Okada and Suto (2003), microtremor is the constant vibration of the surface of the Earth at seismic frequencies, even without earthquake. The amplitude of the microtremor is generally very small with its displacement in the range of 10^{-4} to 10^{-2} mm, which is far below human sensing. Microtremors are caused by both daily human activities such as motor cars, people walking and movement of machinery in factories, and natural phenomena such as rain, wind and ocean waves. Since human activity and natural phenomena vary with time, hence microtremor activity varies over time as well. In other words, variation of microtremor is very complex and irregular, and not repeatable both spatially and temporally. Microtremors originating from human activity and natural phenomena have dominant period shorter than and larger than one second, respectively (frequency higher than and lower than 1 Hz, respectively). Microtremors are an assemblage of waves that travel in various direction, include horizontal (North-South, NS and East-West, EW) and vertical (Up-Down, UD) directions.

Microtremor observation can also be known as ambient vibration test. Ambient vibration test is direct and practical method of determining the dynamic characteristics of structure (Stubbs and McLamore, 1973). Even though forced vibration tests, such as resonance and free vibration decay tests can also be carried out to determine the dynamic characteristics of structure, but the advantages of the ambient vibration over the forced vibration surveys are that usually only light equipment and smaller number of operator are required (Ivanovic et al., 2000). Full scale testing of buildings using forced vibration tests are still rare (Brownjohn et al., 2000). Besides, ambient vibration survey implies minimum interference and destruction with the normal use of structure (Gentile and Saisi, 2007).

Microtremor observation are performed to derive the ground shaking characteristics, predominant period and amplification factor in order to estimate the dynamic behaviour of structure for seismic resistant design and seismic microzoning for the damage assessment due to future predicted earthquake (Enomoto et al., 2000). Figure 2.1 shows the sample of measured microtremor waveforms in the three directions. The waveforms shown were in the form of velocity time history recorded in three directions include two horizontal (North-South, NS and East-West, EW) and one vertical (Up-Down, UD) directions.

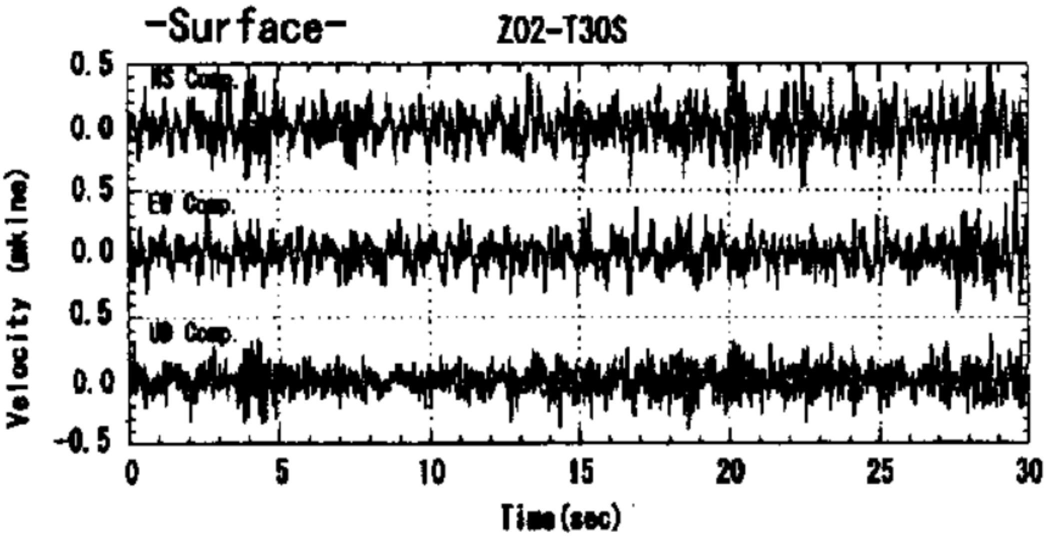

Figure 2.1: Example of Measured Microtremor Waveforms in the Three Directions (Enomoto et al., 2000)

2.3 Horizontal to Vertical Spectral Ratio (HVSR)

According to Nakamura (1989, 2000, 2008), HVSR or also known as Nakamura's method was a method used to estimate the predominant frequency and amplification factor of ground and structure from the measured microtremor. Due to its simplicity together with quick information about dynamic characteristics of ground and structures, this technique had received great attention from all over the world. Microtremors are an assemblage of waves, such as body waves, which consists of Primary (P) waves and Shear (S) waves, and surface waves such as Rayleigh waves and Love waves. Due to this reason, spectrum produced by the microtremor will have various peaks corresponding to the wave components.

The major earthquake damage is mainly caused by the body waves, while Rayleigh waves will not cause significant earthquake damage. Thus, Rayleigh wave contained by the microtremor was considered as noise and should be eliminated by using HVSR technique. HVSR shows the characteristics contaminated by the Rayleigh waves as shown in Figure 2.2 and Figure 2.3.

Rayleigh waves cannot propagate in the frequency range under predominant frequency of surface ground (F_0). Hence, first peak near F_0 consists of S-wave mainly. Around F_0, there is almost no energy of Rayleigh waves, so the dispersion curves are unstable near F_0. On the contrary, the first trough near $2F_0$ is caused by Rayleigh waves as they can transmit the energy peak around the frequency of minimum group velocity ($2F_0$, Airy phase). The weaker the Rayleigh waves, the more correct the amplification factor. The amplification characteristics by the effect of multiple reflections of the Horizontal Shear (SH) wave is mainly composed around F_0. It is verified that HVSR of microtremor observation is useful for estimation of fundamental frequency and its amplification factor by observing to the HVSR preliminary peak. It is natural that the vibration of hard ground is uniform for each frequency range and each direction, hence there is no reason to enlarge the amplitude of a particular frequency range and of a particular direction at hard and uniform ground.

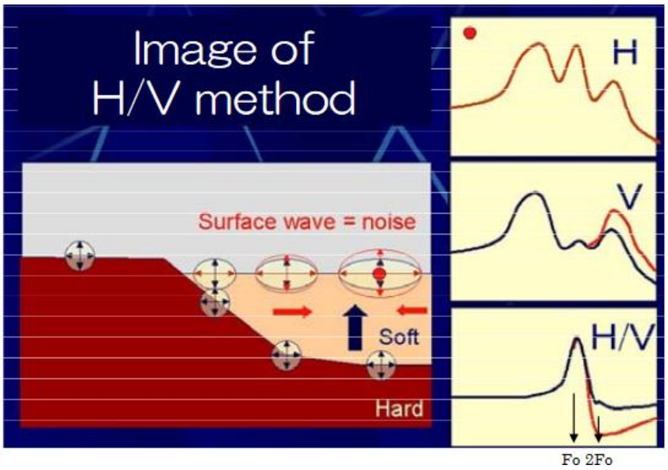

Figure 2.2: Image of HVSR method (Nakamura, 2008)

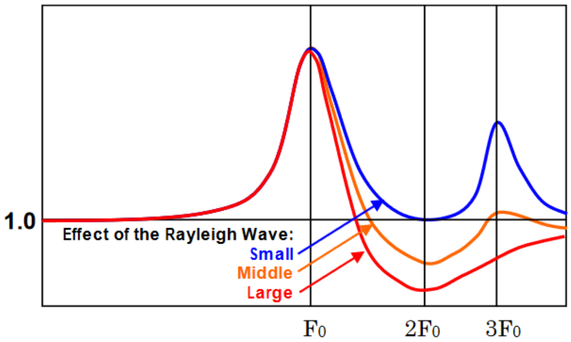

Figure 2.3: Image of the HVSR (Nakamura, 2008)

The effect of the Rayleigh wave for the surface to the basement ratio of the horizontal motion, R $(= A_{hs}/A_{hb})$ is estimated by the surface to the basement ratio of the vertical motion, E $(= A_{vs}/A_{vb})$, where A_{hs} = horizontal surface motion amplitude, A_{hb} = horizontal basement motion amplitude, A_{vs} = vertical surface motion amplitude and A_{vb} = vertical basement motion amplitude. Then, the corrected amplification characteristic, A_m is given by Equation 2.1.

$$A_m = \frac{R}{E} = \frac{A_{hs}/A_{hb}}{A_{vs}/A_{vb}} \tag{2.1}$$

By using an observational fact that the ratio A_{hb} and A_{vb} is nearly equal to 1 for wide frequency range, A_m could be expressed as Equation 2.2 and it is actually the HVSR.

$$A_m = \frac{A_{hs}}{A_{vs}} \tag{2.2}$$

2.4 Estimation of Predominant Frequency Using Microtremor Observation

Microtremor observation had been adopted by Nakamura et al. (2000) to estimate the dynamic characteristics of surface ground, such as predominant frequency and amplification factor at the damaged and surrounding area of Kobe city due to Hyogo-Ken-Nanbu earthquake. For each measurement points, an instrument named Portable Intelligent Collector (PIC) with sampling interval of 1/100 s was set on the soil. The two horizontal components of microtremor (NS and EW direction) and a vertical component were measured at the same time. The length of each record was 40.96 s. Fourier spectrum for each component were then calculated. By employing the Horizontal to Vertical Spectral Ratio (HVSR) technique as proposed by Nakamura (1989), the predominant frequency and amplification factor can be determined. According to the measurement results in the damaged zone, the amplification factor and predominant frequency ranges between 2 and 3, and 1.5 and 2 Hz, respectively which corresponds to that of strong motion. More detailed graphs of distribution of predominant frequency (*F*) and amplification factor (*A*) for each soil profile are summarized in Figure 2.4. Amplification factor has large values in the area where heavy damage occurred.

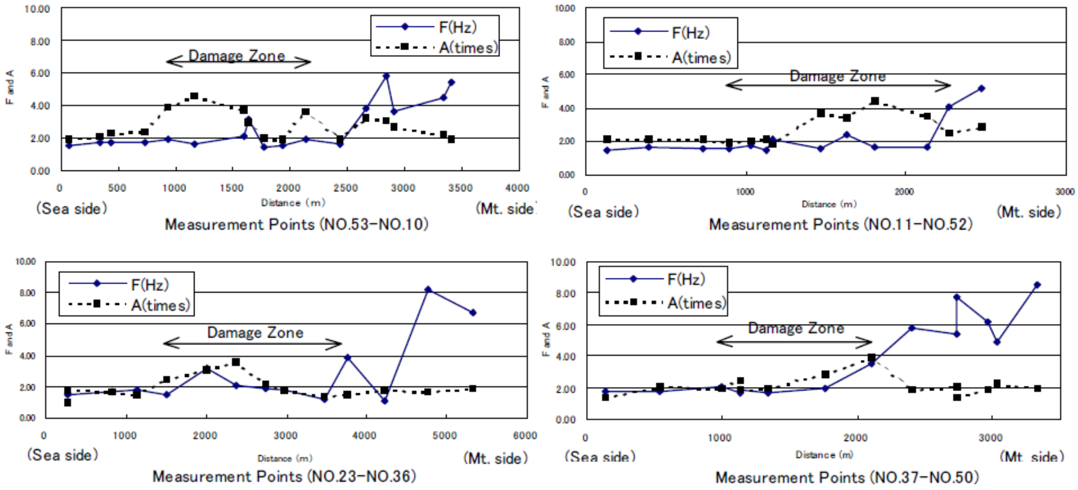

Figure 2.4: Distribution of Predominant Frequency and Amplification Factor in Each Profile (Nakamura et al., 2000)

Besides, microtremor measurement was also conducted by Parajuli et al. (2011) at a 300-year-old brick masonry buildings located in Latipur Sub-Metropolitan City. The building had always suffered earthquake damage and has been repaired many times. Ambient vibrations were measured at different parts of the building in the ground and on the first and second floors at the seven locations as shown in Figure 2.5. As in HVSR calculation, 12-minute records were segmented into six, yielding 4096 data items in each segment to make them compatible for Fast Fourier Transform (FFT) excluding external noise factors such as pedestrians and vehicles. Fourier spectra of all records together with longitudinally and transversely at different parts of the buildings were plotted and calculated, yielding natural frequencies of the buildings at different modes at the highest Fourier spectrum amplitude. Example of Fourier Spectra for ground floor locations 1, 2 and 3 are shown in Figure 2.6. The most predominant frequencies are 4.30 Hz and 6.52 Hz transversely and 6.80 Hz and 9.39 Hz longitudinally.

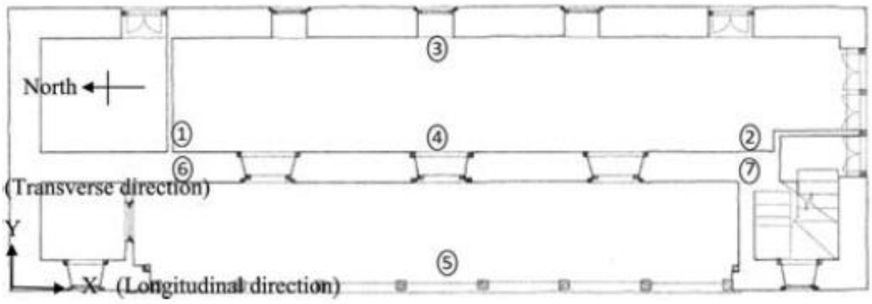

Figure 2.5: Building Plan and Microtremor Measurement Locations
(Parajuli et al., 2011)

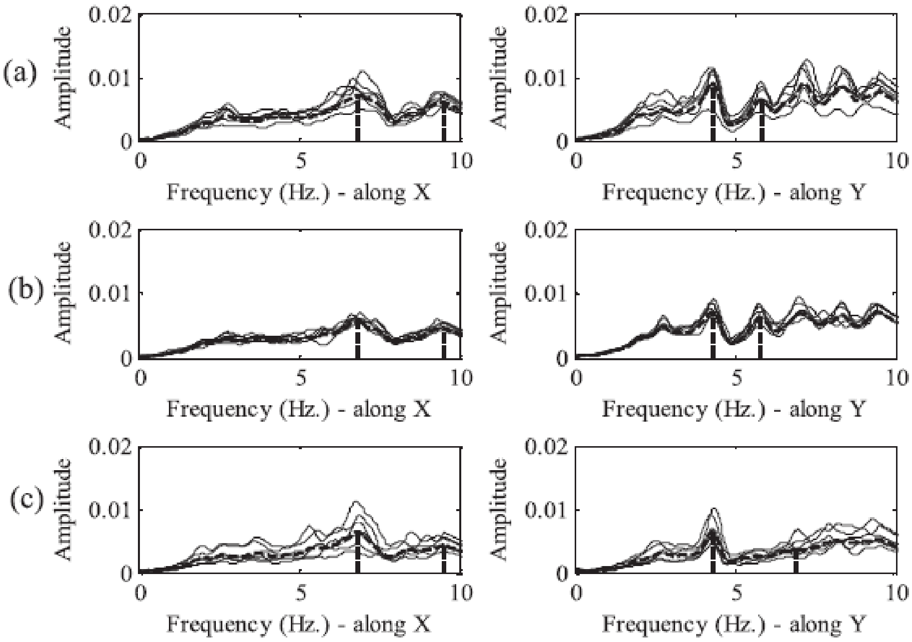

Figure 2.6: Fourier Spectra, Ground Floor Location (a) 1, (b) 2 and (c) 3
(Parajuli et al., 2011)

2.5 Reliability of Ambient Vibration Test and HVSR Method

The ambient and forced vibration techniques for testing dynamic behaviour of structures are carried out by Trifunac (1972). Both tests were carried out in a twenty-two storey steel frame building in San Diego. Ambient vibration tests were performed immediately after forced vibration tests. Since there were no major earthquakes happen during or between the two tests, thus it was assumed that the structure and its foundation characteristics remained unchanged. The predominant frequencies of the steel frame building as computed by ambient and forced vibration tests are shown in Table 2.1. Since both techniques gave mutually consistent results, thus the ambient vibration test was reliable to be carried out.

Table 2.1: Natural Frequencies for Ambient and Forced Vibration Tests of San Diego Gas and Electric Building (Trifunac, 1972)

Mode	NS Translational Frequency, Hz		EW Translational Frequency, Hz	
	Ambient	Forced	Ambient	Forced
1	2.7	2.40	2.5	2.47
2	7.5	6.91	8.2	7.55
3	12.5	12.5	15.4	14.3
4	19.0	18.9	22.2	21.4
5	25.3	25.8	29.1	28.1
6	31.7	32.1	-	33.3

According to Castro et al. (1998), HVSR technique can provide reliable estimate for fundamental frequency of a structure by using the ratio between amplitude of Fourier spectra of horizontal and vertical components. Besides, HVSR method gives the ease of data collection and is applicable in areas of low or even no seismicity (Nakamura, 2000). Hans et al. (2005) carried out in-situ measurements to determine the dynamic characteristics of existing buildings in Vaulx-en-Velin, suburbs of Lyon, France. Three types of in-situ monitoring methods, namely ambient vibrations, harmonic forcing and shock tests were used. The predominant frequency was determined through HVSR method. The comparison of modal characteristics in longitudinal direction of one of the buildings where its floor and transverse shear walls were made of reinforced concrete is shown in Table 2.2. The experimental findings assured that the structures respond systematically by following the same quasi-elastic behaviour from small amplitudes of ambient vibrations to significant larger amplitudes reached by employing shocks. Thus, the simple ambient measurements and HVSR method is sufficient to identify the structure’s dynamic behaviour.

Table 2.2: Comparison of Modal Frequencies Using Different Methods
(Hans et al., 2005)

Mode	Monitoring Method	Modal Frequency in Longitudinal Direction
1	Ambient	4.3
	Free Oscillation	4.25
	Harmonic	4.19
	Shock	4.18
2	Ambient	13.4
	Shock	12.8
3	Ambient	23
	Shock	22.5

Gallipoli et al. (2009) stated that HVSR technique on earthquake recordings is widely used for seismic amplification studies. Gallipoli et al. (2009) compared several techniques for structural dynamic identification using ambient noise and the results confirmed that HVSR method is very useful for characterizing fundamental frequency and related mode shapes. Mirtaheri and Salehi (2018) stated that ambient vibration testing has been used as an accurate experimental method available for dynamic identification of full scale structures. The office building of the K. N. Toosi University of Technology campus was tested using ambient and forced vibration testing. The results as shown in Table 2.3 are perfectly matched. Once again, this confirms the validity of the function of ambient vibration test.

Table 2.3: A Comparison Study with Natural Frequency Obtained from the Ambient and Forced Vibration Testing (Mirtaheri and Salehi, 2018)

Direction	Natural Frequency (Hz)		Difference (%)
	Ambient Vibration Testing	Forced Vibration Testing	
X	2.5	2.5	0.0
Y	2.7	2.7	0.0

2.6 Determination of Vibration Mode Shapes

According to Ward and Crawford (1966), vibration mode shapes indicate the relative magnitude of the displacement of structure. Mode shapes of buildings are important in earthquake engineering design because they determine the manner in which earthquake loads are distributed though the height of structure.

Ivanović et al. (2000) had carried out ambient vibration tests on a damaged seven-storey reinforced concrete building in California due to 1994 Northridge earthquake. The two- and three-dimensional vibration mode shape for longitudinal, transverse and vertical vibrations were calculated. Fast Fourier Transform (FFT) was carried out to compute the Fourier spectra on the recorded field data. Then, for each measuring point and component of motion in longitudinal (EW) and transverse (NS), the transfer function amplitudes were computed as shown in Figure 2.7. The longitudinal vibration mode shapes of the first four peaks of natural frequencies obtained from the transfer function amplitude corresponding to its frequency is shown in Figure 2.8.

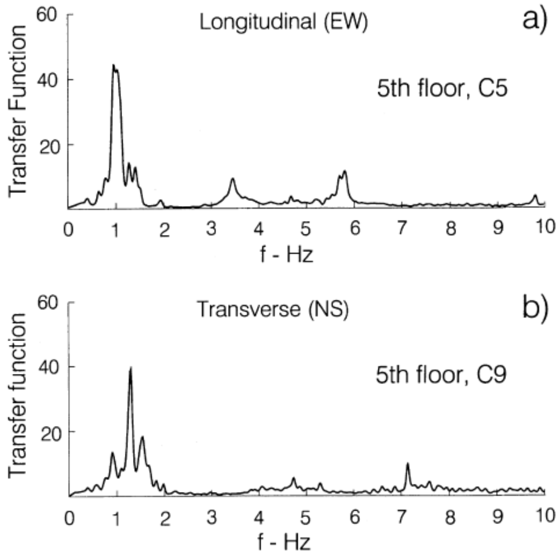

Figure 2.7: Typical Sample of Transfer Function Amplitudes for Longitudinal and Transverse Direction (Ivanović et al., 2000)

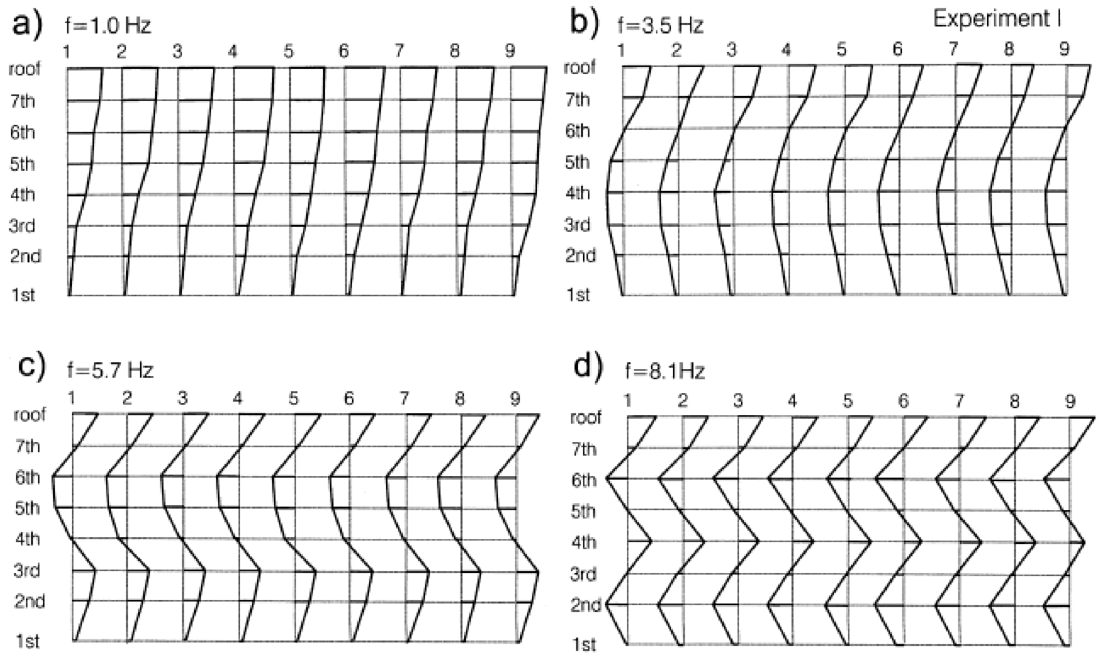

Figure 2.8: Vibration Mode Shape along Longitudinal Direction (Ivanović et al., 2000)

Ojeda (2012) introduced MATLAB implementation of Time Domain Decomposition (TDD) techniques to determine the vibration mode shape of the 11-node and 21-node simply supported beam models. An overview of the TDD implementation in MATLAB is shown in Figure 2.9. The acceleration time history data for each node in the structure was input into the MATLAB script. After specified numbers of modal frequencies were obtained, the modal frequencies were used to create a band-pass filter object. Each acceleration time history response was filtered with the band-pass object and arranged to create the response matrix for each respective mode. Lastly, through singular value decomposition, the mode shape of the structure was obtained. The various vibration mode shape obtained for the 11-node model simply supported beam are shown in Figure 2.10.

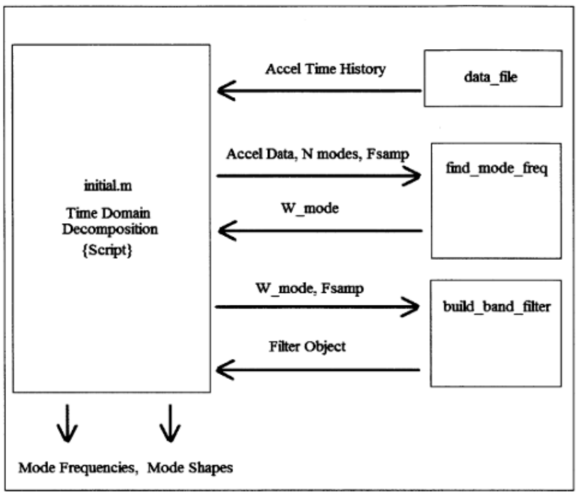

Figure 2.9: Overview of the MATLAB TDD Implementation (Ojeda, 2012)

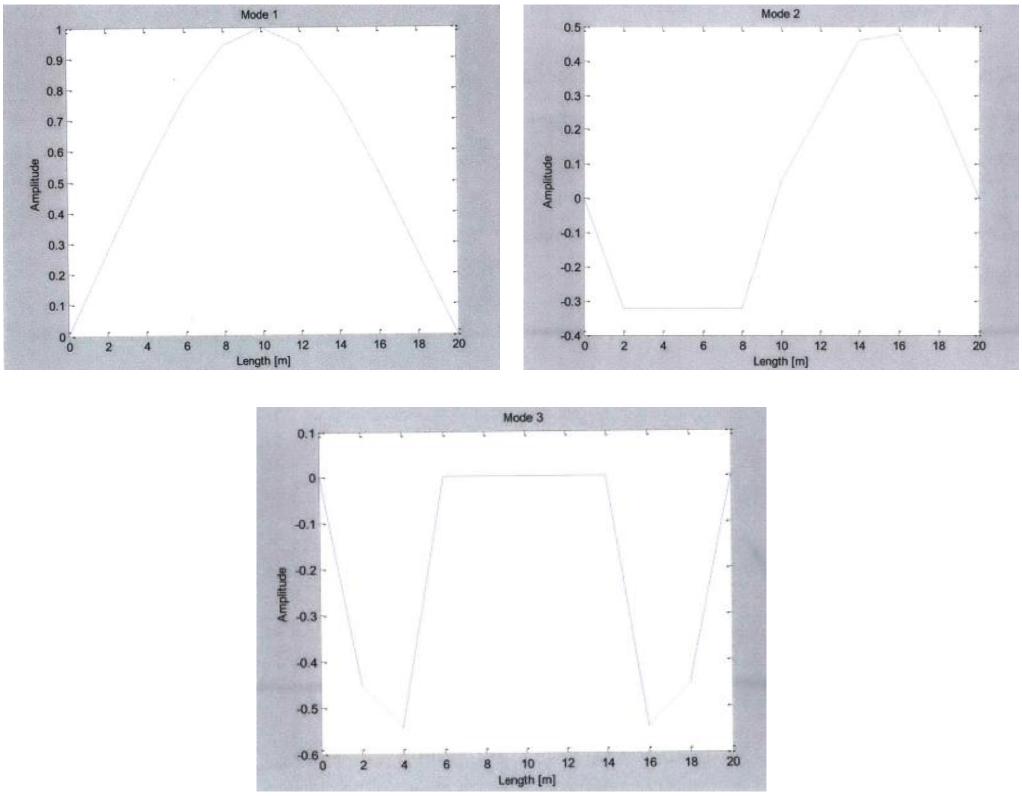

Figure 2.10: Vibration Mode Shape Obtained for 11-Node Model Simply Supported Beam (Ojeda, 2012)

Lim (2014) and Lim (2016) adopted the MATLAB implementation of TDD techniques as proposed by Ojeda (2012) to determine the vibration mode shape of the buildings from the measured microtremor data. The relative mode shape of the base of the building was taken as 0. The mode shapes of studied buildings as deduced by Lim (2014) and Lim (2016) are shown in Figure 2.11 and Figure 2.12, respectively. These mode shapes showed good agreement with the mode shapes of other buildings estimated by Ivanovic et al. (2000) as well as mode shape results from numerical simulation. Therefore, MATLAB implementation of TDD method provided reliable and consistent results in determining the vibration mode shapes of the structure.

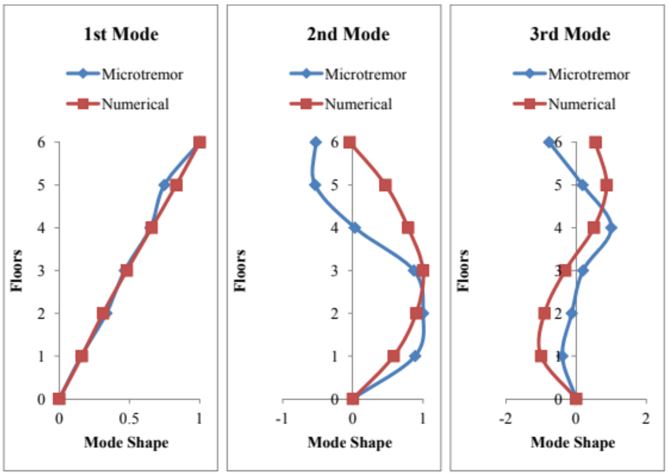

Figure 2.11: First Three Vibration Mode Shapes of Desasiswa Utama, Universiti Sains Malaysia (USM) (Lim, 2014)

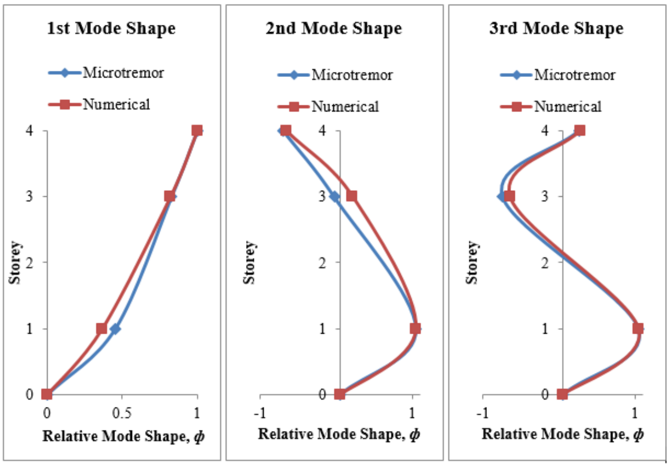

Figure 2.12: First Three Vibration Mode Shapes of Officer Quarters, Hospital Ranau (Lim, 2016)

2.7 Weakness of Open First Storey Frame

Tamboli and Karadi (2012) found that the predominant frequency of open first storey frame was lower than infilled frame as the presence of infill wall increased the strength and stiffness of structure. The comparison of predominant frequencies of the infilled and open first storey frame in transverse and longitudinal direction is shown in Table 2.4. In addition, the storey drift of first storey of open first storey frame was very large than the upper storeys due to the absence of infill walls in the ground storey. The comparison of inter-storey drift for infilled and open first storey frame is shown in Figure 2.13.

Table 2.4: Comparison of Predominant Frequencies of the Infilled and Open First Storey Frame in Transverse and Longitudinal Direction (Tamboli and Karadi, 2012)

Type of frames	Predominant Frequency, Hz	
	Transverse Direction	Longitudinal Direction
Infilled Frame	11.341	9.066
Open First Storey Frame	6.756	3.414

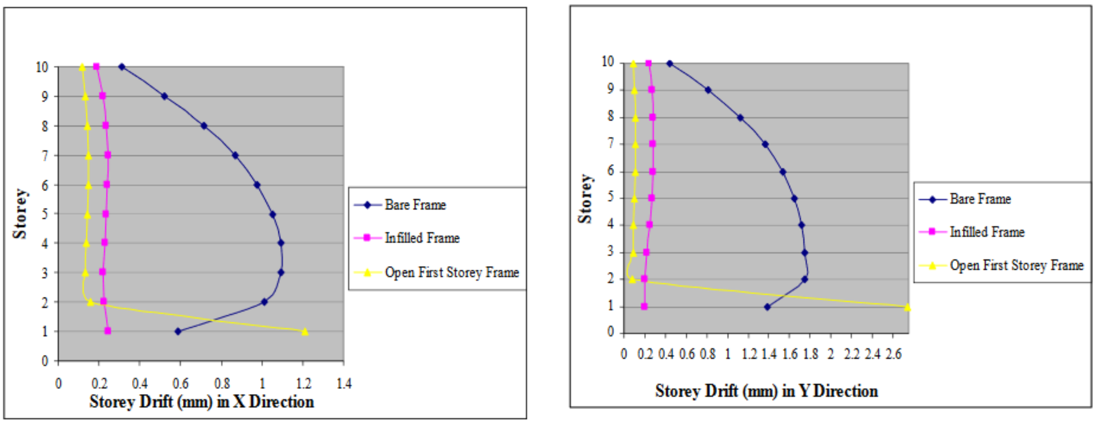

Figure 2.13: Comparison of Inter-Storey Drift for Infilled and Open First Storey Frame (Tamboli and Karadi, 2012)

According to Dohare and Maru (2014), soft storey buildings are buildings with no infill masonry walls in ground storey, but all upper storeys are infilled with masonry walls. They are vulnerable to collapse due to earthquake. When soft storey buildings are subjected to earthquake loading, this lateral force cannot be well distributed along the height of the structure as the distribution of lateral force along the height of a building is dependent to mass and stiffness of each storey. Due to flexibility and inadequate stiffness of the ground floor, the disproportion causes larger disproportional displacement focused at that storey which indirectly make the ground floor weak and more susceptible to damage (Apostolska et al., 2016). Soft storey RC buildings were among the most damaged structures during the M6.0 2015 Sabah earthquake (Alih and Vafaei, 2019).

2.8 Effect of Non-structural Elements on Performance of Building

Non-structural elements such as masonry infills can contribute significant lateral stiffness, strength, overall ductility and energy dissipation capacity as described by Murty and Jain (2000). Besides, infills can affect the lateral deformations and stiffness of the Reinforced Concrete (RC) frame. Separation of frame and infill takes place along one diagonal, while a compression strut is formed along the other diagonal. The load transfer mechanism is changed from frame action to predominant truss action as shown in Figure 2.14. The frame columns will experience increased axial forces and reduced bending moments and shear forces.

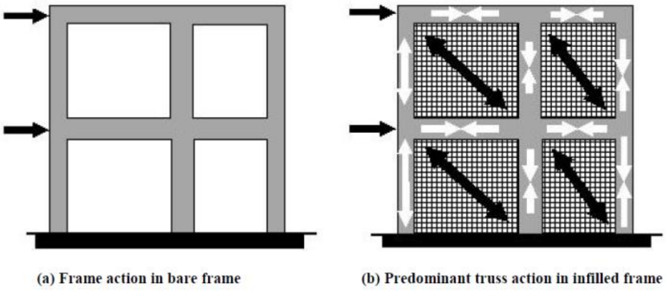
(a) Frame action in bare frame (b) Predominant truss action in infilled frame

Figure 2.14: Change in the Lateral Load Transfer Mechanism due to Inclusion of Masonry Infills Walls (Murty and Jain, 2000)