DAMAGE AND DRIFT ANALYSES FOR 18-STOREY REINFORCED CONCRETE BUILDINGS IN PENANG DUE TO SEISMIC FORCE

by

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LIST OF ABBREVIATIONS

ABS	Absolute Sum
ACECOM	Asian Center for Engineering Computations
AIT	Asian Institute of Technology
CAM	Component Attenuation Model
COSMOS	Consortium of Organizations for Strong-Motion Observation System
CQC	Complete Quadratic Combination
DSHA	Deterministic Seismic Hazard Analysis
EQUAKEX	Equivalent static load case in X-direction
EQUAKEY	Equivalent static load case in Y-direction
ETABS	Extended 3D Analysis of Building System
IDARC2D	Inelastic Damage Analysis for Reinforced Concrete
IRIS	Incorporated Research Institutions for Seismology
ISC	International Seismological Centre
MDOF	Multiple Degree of Freedom
NEHRP 2000	National Earthquake Hazard Reduction Program
NERA	Nonlinear Earthquake Site Response Analyses
PBA	Perbadanan Bekalan Air Pulau Pinang Sdn Bhd
PEER	Pacific Earthquake Engineering Research
PGA	Peak Ground Acceleration
PGTYPEC	Response Spectrum Function for soil type S_C
PSHA	Probabilistic Seismic Hazard Analysis
SDOF	Single Degree of Freedom

SFZ	Sumatran Fault Zone
SIMQKE	Simulation of Earthquake Ground Motions
SPECX	Response spectrum analysis load case in X-direction
SPECY	Response spectrum analysis load case in Y-direction
SRSS	Square Root of the Sum of the Squares
SSZ	Sumatran Subduction Zone
TNB	Tenaga National Berhad
UBC97	Uniform Building Code 1997
USGS	United States Geological Survey
USGS-NEIC	United States Geological Survey-National Earthquake Information Center

LIST OF SYMBOLS

u	linear displacement
$\dot{u}$	velocity component
$\ddot{u}$	acceleration component
r_{io}	peak response for mode i
ξ	damping ratio
δ_m	maximum deformation of the element
δ_u	ultimate deformation
β	model constant parameter
ρ	design wind pressure in units of Pascals (MS1553)
ρ_{air}	density of air (MS1553)
ρ_{ext}	external design wind pressure (MS1553)
ρ_{int}	internal design wind pressure (MS1553)
ρ_{in}	cross-modal coefficient
Δs	altitude of the site in meter above sea level (BS6399)
ω_i	angular frequency for mode i
ω_n	angular frequency for mode n
$\int dE_h$	hysteretic energy absorbed by the element
$\sum_{i=1}^{m_j} E_{ij}$	hysteretic energy of j^{th} storey and m_j is the number of elements on j^{th} storey.
$\sum_{s=1}^{N} E_s$	overall hysteretic energy and N is the number of stories
C	viscous damping coefficient

C_a	seismic coefficient as set forth in Table 16-Q in UBC97
C_a	size effect factor (BS6399)
C_{dyn}	dynamic response factor (MS1553)
C_{fig}	aerodynamic shape factor (MS1553)
$C_{p,e}$	external pressure coefficient (MS1553)
$C_{p,\mathrm{i}}$	internal pressure coefficient (MS1553)
C_r	dynamic augmentation factor (BS6399)
C_t	Numerical coefficient given in Section 1630.2.2 in UBC97
C_v	seismic coefficient as set forth in Table 16-R in UBC97
DI	damage index
DI_{kj}	damage index of the k^{th} element on j^{th} storey
E_i	hysteretic energy for i^{th} storey
E_{kj}	hysteretic energy of the k^{th} element on j^{th} storey
F	external lateral static force
$F(t)$	applied dynamic load
F_t	lateral force acting at the topmost floor
F_i	lateral force acting at level i
F_x	force applied at level x
H	overall height of building
h	floor to floor height of building
h_i	height in feet at level i
h_n	height in feet above the base to Level n
h_x	height in feet at level x
H_e	effective height of building (BS6399)

H_{focal}	focal depth of earthquake
I	importance factor
K	lateral stiffness
K_a	area reduction factor (MS1553)
K_c	combination factor (MS1553)
K_l	local pressure factor (MS1553)
K_p	porous cladding reduction factor (MS1553)
M	mass of structure
M_d	wind directional multiplier (MS1553)
M_h	hill shape multiplier (MS1553)
M_s	shielding multiplier (MS1553)
M_w	moment magnitude of earthquake
$M_{z,cat}$	terrain/height multiplier (MS1553)
n	mode n
N	total number of responses
ODI	overall damage index
P_y	yield strength of the element
r_{io}	peak response for mode i
r_{no}	peak response for mode n
r_o	peak response
R	response modification (over-strength) factor
R_{hypo}	hypocentral distance
RSA	response spectrum analysis
S_A, SA	soil profile for hard rock

S_a	altitude factor (BS6399)
Sa	spectral response acceleration
S_B, SB	soil profile for rock
S_b	terrain and building factor (BS6399)
S_C, SC	soil profile for very dense soil or soft rock
S_D, SD	soil profile for stiff soil
S_d	directional factor (BS6399)
SDI_j	damage index for j^{th} storey
S_E, SE	soil profile for soft soil
S_p	probability factor (BS6399)
S_s	seasonal factor (BS6399)
t	time
T	fundamental period of vibration
V	total base shear
V_b	basic wind speed (BS6399)
V_{des}	design wind speed (MS1553)
V_e	effective wind speed (BS6399)
V_s	basic wind speed as read off from Figure 3.1 in MS1553 (MS1553)
V_s	site wind speed (BS6399)
V_{sit}	site wind speed (MS1553)
VX	base shear in X-direction
VY	base shear in Y-direction
w_i	seismic dead loads assigned to Level i
w_x	seismic dead loads assigned to Level x

W	total seismic dead load
Z	seismic zone factor

ANALISA KEROSAKAN DAN HANYUTAN KE ATAS BANGUNAN KONKRIT BERTETULANG 18 TINGKAT DI PULAU PINANG TERHADAP BEBAN SEISMIK

ABSTRAK

Bangunan tinggi di Pulau Pinang tidak perlu direkabentuk untuk mematuhi kod amalan yang mempunyai klause gempa bumi. Sejak kebelakangan ini, kesan gegaran akibat daripada gempa bumi di Indonesia dapat dirasai dengan nyata oleh penghuni di dalam bangunan tersebut. Oleh itu, kesepaduan struktur bangunan tersebut telah menjadi satu kebimbangan yang besar. Untuk mengatasi kebimbangan yang tersebut, pengajian analisa kerosakan dan hanyutan telah dilaksanakan untuk menyelidiki kesepaduan struktur bagi tiga buah cadangan bangunan pangsapuri 18-tingkat. Setiap bangunan tersebut mempunyai pelan susunan yang berlainan seperti berbentuk L, segiempat sama dan segiempat tepat. Spektrum sambutan rekabentuk yang dihasilkan untuk Pulau Pinang baru-baru ini telah di tambah baik didalam pengajian ini. Analisa kerosakan, secara analisa dinamik tak berelastic, telah dilaksanakan keatas kerangka yang terpilih dari ketiga-tiga bangunan itu and hasil kajian menunjukkan bahawa rekabentuk-rekabentuk itu menanggung kerosakan ringan yang boleh diperbaiki. Analisa hanyutan telah dilaksanakan melalui segi tak berseismik and segi berseismik. Dari segi tak berseismik, hanyutan bangunan yang diakibatkan oleh beban angin dan beban mendatar nosional adalah di dalam batasan yang ditetapkan didalam Standard Malaysia MS1553. Bagi analisa statik, analisa beban statik senilai menunjukkan bahawa hanyutan bangunan tersebut adalah melebihi kriteria hanyutan yang ditetapkan didalam Kod Bangunan Keseragaman

1997 (UBC97). Bagi analisa dinamik, spektrum sambutan rekabentuk menghasilkan hanyutan yang lebih kecil tetapi dua daripada tiga bangunan tersebut masih gagal mematuhi kriteria hanyutan tersebut. Kajian ini menunjukkan bahawa walaupun ketiga-tiga bangunan tersebut telah direkabentuk dengan mematuhi keperluan beban angin dan beban mendatar khayalan, tetapi ia masih terdedah kepada kerosakan yang disebabkan oleh beban seismik akibat hanyutan ufuk yang berlebihan.

ABSTRACT

High rise buildings in Penang are not required to be designed and comply with any building code for earthquake provision. In the recent years, tremors resulting from earthquakes in Indonesia were very clearly felt by occupants in some of these buildings. As such, the structural integrity of these buildings has become a major concern. To address this concern, damage and drift analyses studies were carried out to investigate the structural integrity of three proposed 18-storey apartment buildings. Each building has a different plan layout and they are L-shaped, square and rectangular. The recently developed design response spectrum for Penang was adopted and improved in this study. Damage analysis was carried out on selected frames from the three buildings and the results showed that the structures sustained slight and repairable damages when they were analysed using inelastic dynamic analysis. Drift analysis was carried out using both non-seismic and seismic related approaches. In the former, building drifts caused by wind and notional horizontal loads were found to be within the acceptable limits stipulated in the Malaysian Standard MS1553. In the latter, both static and dynamic analyses were carried out. For static analysis, equivalent static load method revealed that building drifts exceeded the drift criterion set forth in the Uniform Building Code 1997 (UBC97). For dynamic analysis, response spectrum analysis method gave results with smaller drifts but two of the three buildings still failed to comply with the drift criterion. This study concludes that while the three buildings were designed to comply with requirements for wind load and notional horizontal load, they can be vulnerable to damages caused by seismic load due to excessive lateral drifts.

CHAPTER 1
INTRODUCTION

1.1 General

The study of seismic or earthquake engineering has long been an area of great interest in the field of structural engineering. It is also a major concern in the civil engineering profession in countries where earthquakes are known to frequently occur. Malaysia is fortunate that it is not geographically located in any of the so called designated zone with high seismic activity. As a matter of fact, Malaysia is situated on the Sunda Shelf which is known to be a stable extension of the continental shelf of Southeast Asia. The Penang Island is located on the north-west coast of Peninsular Malaysia and the nearest active seismic zone is the Sumatran Fault, which is about 350km away. A further 150km to the west lies the subduction zone called the Sumatran Trench. Some of the earthquakes as reported in the United States Geological Survey's (USGS) website for these two seismic zones in the last five years are in the magnitude of 6.0 to 9.1 on the Richter scale. The complete list of these earthquake events can be found on their website.

An earthquake event which triggered a wake-up call to people living in Penang Island took place on December 2004. An undersea earthquake that occurred in this subduction zone resulted in a long rupture stretching a distance of 1600km to the north along the Sumatran Trench. It created one of the most devastating natural disaster ever recorded in the region, i.e. a massive tsunami which took thousands of lives. Tremors resulted from earthquakes in that region from 2005 to as recent as February 2008 were also felt in many areas along the western part of the peninsula.

High-rise buildings were especially affected due to the nature of their slenderness in height and to the geometry of their layout.

1.2 Problem Statement

The Sumatra-Andaman earthquake in December 2004 and those which occurred from 2005 to early 2008 have certainly caused a lot of concern to people living in high-rise buildings. Their fears are not unfounded since there are currently no mandatory requirements for structural engineers to design high-rise buildings to conform to any seismic code of practice. The accepted local practice is such that structural engineers are only required to design for wind load conforming to either the British Standard, BS6399 or the Malaysian Standard, MS1553 and to a horizontal notional load of 1.5% of the dead load as stipulated in British Standard, BS8110. Therefore, it is important to know if the three selected high-rise apartment buildings for this study would suffer any form of structural damages when subjected to tremors induced by far field earthquakes. Past reports of structural cracks caused by these tremors as reported in the media are shown in Appendix A.

1.3 Objectives

This research work studies the effect of ground tremors on local high-rise buildings subjected to far field earthquakes such as the Sumatra-Andaman earthquakes. Three 18-storey apartment buildings with distinctively different geometrical layouts are considered here. The three geometrical layouts are L-shaped square and rectangular. They are chosen to illustrate the different responses generated by horizontal ground motion when the buildings are constructed in three types of soil that have been categorised as generally found in Penang Island (Fadzli, 2007). The three types of soil are designated in the Uniform Building Code 1997 (UBC 97) as soil profile types S_C (very dense soil or soft rock), S_D (stiff soil) and S_E (soft soil) (Table 16-J, UBC97). The main objectives of this study are as follows:

i. To study the lateral floor displacements and inter-storey drifts of the buildings due to lateral wind loads and horizontal notional loads as per local design requirement.

ii. To modify and improve the design response spectrum developed for Penang.

iii. To determine the damage indices of selected frames from each of the three buildings due to the modified UBC97 code based design response spectra;

iv. To study and compare the lateral floor displacements and inter-storey drifts of the buildings due to the modified and original UBC97 code based design response spectra due to equivalent static loads method and response spectrum analysis method.

1.4 Scope of Works

This following scope of works is carried out in this research.

i. Choose three buildings with distinctively different horizontal layouts, i.e. L-shaped, square and rectangular, which are common horizontal layouts for apartment buildings in Penang. Irregular shaped structures are not in the scope of this study.

ii. Carry out non-seismic related reinforced concrete design using a computer program called EsteemPlus for the three buildings. The main purpose for using EsteemPlus is to determine the structural member sizes for the buildings. Effects of wind load and horizontal notional load are taken into consideration.

iii. Modify and improve design response spectra for soil type S_C (soft rock/dense soil), S_D (stiff soil) and S_E (soft soil) from soil data taken from Fadzli (2007). The original design response spectra from Fadzli (2007) were developed without taking into account the effect of outliers in the raw soil database on the final results.

iv. Carry out damage analyses using a computer program called IDARC2D to compute the damage indices of selected frames taken from each building for the modified UBC97 code based design response spectra. This program can determine the sequence of structural damages that occurs within a 2-D frame in terms of cracking of concrete, yielding of steel reinforcement and the formation of plastic hinges.

v. Carry out static and dynamic linear elastic analyses using a computer program called ETABS for the three buildings while subjecting them to the modified and original UBC97 code based design response spectra. The computer program EsteemPlus mentioned above is only capable of running static analysis. To perform dynamic analysis such seismic analysis, a program such as ETABS is used.

1.5 Research Methodology

This study is carried out in six phases with the aid of three different computer programs for different tasks as shown in Figure 1.1.

1.5.1 Phase 1: Select three 18-storey buildings with different horizontal layouts

Three proposed 18-storey apartment buildings in Penang are chosen as models in this study. All three buildings have distinctively different horizontal layouts and they are hereinafter referred to as Block A (L-shaped), Block B (square) and Block C (rectangular).

1.5.2 Phase 2: Compute sizes of structural members and building drifts due to wind and horizontal notional loads using EsteemPlus

The three buildings were first modelled and designed using EsteemPlus. It is one of the commonly used computer tools for design purposes among consulting engineers in Penang. Its output files include detailed and summarised structural computations, graphical detailing of all structural members drawn in DXF file format and detailed material quantity take-offs. The buildings were modelled with provision for statutory design loads (British Standard Code of Practice CP3, Chapter 5) specified for residential occupancy. The capacity of the storage water tank located on the roof level was also sized in accordance to requirements stipulated in the local by-laws. Lateral wind loads were calculated based on the Malaysian Standard MS1553 and applied to the side of the building. The points of the wind load application were at the intersecting nodes between columns and beams at every floor level. Calculation for the magnitudes of these loads was based on tributary area for each node on the windward surface.

1.5.3 Phase 3: Modify and improve the UBC97 code based design response spectra developed for Penang by Fadzli (2007) for three types of soil

The established design response spectra as per UBC97 code by Fadzli (2007) for soil type S_C (soft rock/very stiff soil), soil type S_D (stiff soil) and S_E (soft soil) were modified before they were used in the analyses. Fadzli (2207) developed his design response spectra using strong motion data from both the Imperial Valley, El

Centro (1979) and Victoria, Mexico (1980) earthquakes. For each soil type, the earthquake which gave the larger value for response spectra acceleration was chosen. Adopting the worst case scenario approach is on the conservative side since only one reference earthquake is required to be chosen in accordance to the code. When the spectral response accelerations were plotted against time period, the resulting profiles for the soil types relative to one another were found to differ from those of the original UBC97 code. This is especially true for soil types S_D and S_E in Fadzli (2007) where the former was found to give larger magnitudes than the latter. This is shown in Appendix A.

For this study, only the Mexico earthquake based design response spectra were used. The modification process involves discarding some boreholes which generated design spectra acceleration values that were greater than three times the statistical standard deviation (Z-scores method) calculated for each time stage. New C_a and C_v values were then recalculated and the modified design response spectra curves re-plotted.

1.5.4 Phase 4: Compute damage indices of selected frames from each building by IDARC2D using the modified UBC97 design response spectra

A Fortran based program developed by the University of Buffalo called IDARC2D was then used to carry out two dimensional analyses on selected frames from each building. This program is able to compute what is known as 'structural damage index' which can be defined as a way of quantifying numerically the seismic damage suffered by buildings. Details of structural members such sizes of columns and beams, their steel reinforcements and the cumulative column axial loads are taken from the results computed by EsteemPlus in Phase 2 and entered as input data in IDARC2D. Nodal weights were calculated and were based on tributary areas to the node and frame in question. The models were analysed using the modified design response spectra. The computed damage indices were tabulated for easy reference and comparison.

1.5.5 Phase 5: Compute building drifts by static and dynamic analyses for selected buildings using ETABS

The three buildings were remodelled using ETABS as an analytical tool. ETABS is chosen mainly because of its analytical features in seismic engineering and its reputation as a computer tool geared especially for the design of high rise buildings. In order to have as close a comparison study as possible, structural details such as slabs thicknesses together with beams and columns sizes were adopted from the structural output calculated by EsteemPlus in Phase 2. Steel reinforcement computed in EsteemPlus, however, could not be emulated here as this feature is not implemented in ETABS in the beams input section. The module for slab design was also not available at the time and so slabs were only modelled as shell components to provide lateral rigidity to the buildings. Their own structural analyses were, however, not carried out. In the response spectrum analysis section, modified and original UBC97 values for C_a and C_v corresponding to the three types of soil in Penang were used to generate the response spectrum functions. Since there is no provision for earthquake analysis in the British Standard BS8110 code, it was only used as the default code for analysing the reinforced concrete frame work. Calculations for lateral displacements and drifts, both statically and dynamically induced, were based on the Uniform Building Code 1997 (UBC97 Chapter 16) code.

1.5.6 Phase 6: Comparison study and discussion of results

Lateral floor displacements and inter-storey drifts for each of the three buildings constructed on the different soil types S_C (very dense soil or soft rock), S_D (stiff soil) and S_E (soft soil)) were tabulated in table form and plotted on a same scale for comparison study and discussion. This was done for both the modified and original UBC97 design response spectra cases.

1.6 Organisation of thesis

This thesis consists of five chapters. General background, objectives, scope of work and research methodology for this study are presented in Chapter 1.

Chapter 2 reviews the recent seismic hazard analysis (Fadzli, 2007) carried out for Penang and the current design requirements for high-rise buildings in this region. The type of static and dynamic seismic analyses carried out in this study, the damaging effects of building drifts have on structural and non-structural members and the use of damage indices to quantify the damage state in structures are also reviewed in this chapter.

In Chapter 3, the research methodology for this study is discussed in detail and this includes the modification/improvement of the recently developed design response spectrum for Penang. Other topics discussed in this chapter are the selection of the three buildings, the computations for sizes of structural members, damage indices and building drifts contributed by seismic load.

Chapter 4 presents and compares the results obtained from the various analyses carried out in this study. The conclusions drawn from this study are presented in Chapter 5, which also includes some recommendations for future research works to be carried out.

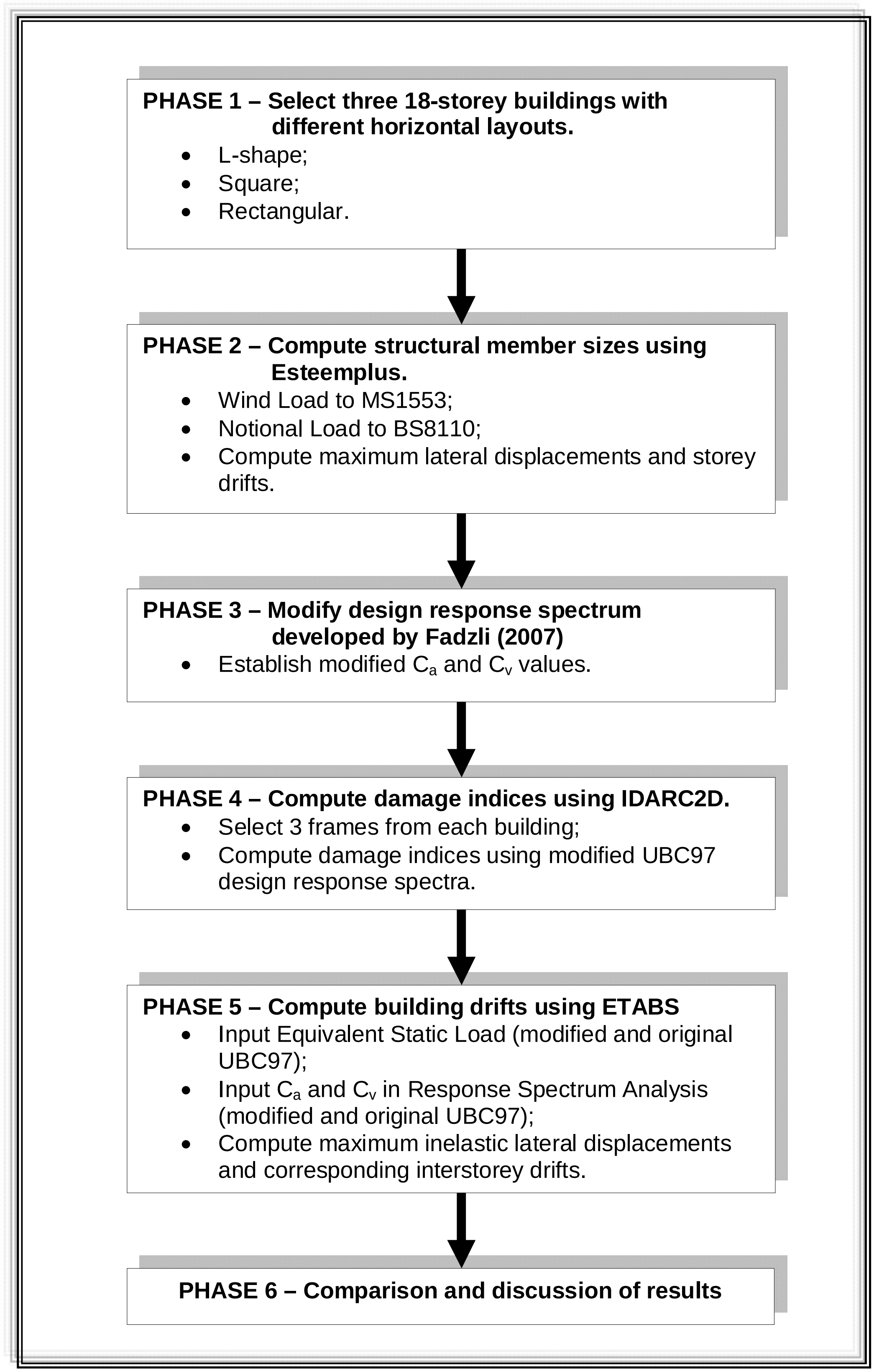

Figure 1.1: Flow chart for research methodology

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This literature review consists of two parts. The first part looks into development of the design response spectra via seismic hazard analysis. Although this is not the main focus of this research, it is nevertheless an integral part of seismic analysis for any structure. When defining the response spectrum functions in the ETABS program, the data input are taken from the design response spectra. The second part of this review looks into the present design requirement for high rise buildings in Malaysia and briefly describes the various aspects of structural analysis in seismic engineering with special attention given to two types of structural analysis, i.e. equivalent static load analysis and response spectrum analysis.

2.2 Seismic Hazard Analysis

The first part of this review will discuss three topics pertaining to seismic hazard analysis. They are listed down as follows:

i) Peak ground acceleration

ii) Attenuation relationships for

   a) Subduction zone

   b) Fault zone

iii) Design response spectra

2.2.1 Peak Ground Acceleration

Peak ground acceleration (PGA) is often described as a measure of earthquake acceleration. It is not the same as the Richter Magnitude Scale which is the measure of the overall magnitude or size of an earthquake. It is also unlike the Mercalli Intensity Scale, which is a means of describing the intensity of an earthquake that is based on personal reports from firsthand observers following an earthquake event. During an earthquake, the intense built-up energy that is stored in the Earth's crust is suddenly released giving off seismic waves. The resulting seismic waves travel over long distances in all directions. The waves attenuate to little tremors and eventually die off.

This attenuation process is one where the released energy dissipates into the ground as the waves travel through many different soil strata in its path. A ground particle lying in the path of these seismic waves will tend to move back and forth in a random irregular manner. This movement can be described by one of three changing variables as a function of time. The variables are the position of the particle, the velocity of its movement and the acceleration of its movement (USGS, 2007). Depending on whichever is more convenient, any one of the three variables can be used to design a building to withstand seismic excitation as they are inter-related. Since most seismic codes require buildings to be designed to withstand a certain amount of horizontal forces during an earthquake, acceleration is chosen because the horizontal force is related to the ground acceleration.

For any given geographical area, the intensity of how violently or hard the ground shakes as a result of those seismic waves is termed as peak ground acceleration (PGA) for that area. It is an instrumented measurement and the numerical value of any peak ground acceleration (PGA) is usually denoted as a function of "g", the acceleration due to gravity which is equalled to 9.81 m/s^2.

2.2.2 Attenuation

In order to estimate the expected peak ground acceleration (PGA) for a particular geographical region, it is essential to first establish an attenuation relationship that is unique for that region. Attenuation relationships or ground motion relationships, as they are also commonly called, are simple mathematical models. They are used to establish certain relationships between the source of the earthquake and the site in question. Examples of such relationships are ground motion parameters to earthquake magnitude, distance between source to site, style of faulting and local site conditions (Campbell, 2002).

Two different regions sitting on the same geographical tectonic plate can have totally different attenuation relationships (Faisal, 2003). This may be attributed to the fact that the two regions may have different soil conditions and they may not share the same geographical proximity to any one particular earthquake source. Various ways and methods have been developed to predict these attenuation relationships. One such method is using Component Attenuation Model (CAM) to predict earthquake wave attenuations for different type of soil condition that are applicable to both near field and far field earthquakes (Lam et al., 2002 and Chandler et al., 2002). A comprehensive summary of previous researches pertaining to the development of attenuations models can be found in Douglas (2001 and 2002).

Active earthquake zones within a 500 km distance to Malaysia can be found in the neighbouring country of Indonesia. They are the Sumatran subduction zone and the Sumatran fault zone. Table 2.1 show some of the recorded earthquakes in these zones between years 2000 to 2008.

Table 2.1: Earthquakes in Sumatran Subduction and Fault Zones (2002 to 2008) (USGS, 2008)

Date	Location	Richter Magnitude Scale
October 10, 2002	Irian Jaya, Indonesia	7.6
November 2, 2002	Northwest Sumatra, Indonesia	7.4
February, 2004	Papua, Indonesia	7.0
July 25, 2004	Southern Sumatra, Indonesia	7.3
November 11, 2004	Alor, Indonesia	7.5
November 26, 2004	Papua, Indonesia	7.1
December 26, 2004	Sumatra-Andaman Islands	9.1
March 2, 2005	Banda Sea	7.1
March 28, 2005	Northern Sumatra, Indonesia	8.7
January 27, 2006	Banda Sea	7.6
May 26, 2006	Java, Indonesia	6.3
July 14, 2006	Java, Indonesia	7.7
March 6, 2007	Southern Sumatra, Indonesia	6.4 & 6.3
January 21, 2007	Molucca Sea	7.5
August 8, 2007	Java, Indonesia	7.5
September 12, 2007	Southern Sumatra, Indonesia	8.4
September 24, 2007	Kepulauan Mentawi region, Indonesia	6.7
February 20, 2008	Simeulue, Indonesia	7.4
February 25, 2008	Offshore Padang, Sumatra, Indonesia	7.0

Figure 2.1 and figure 2.2 show the locations of the Sumatran subduction zone and Sumatran fault zones respectively.

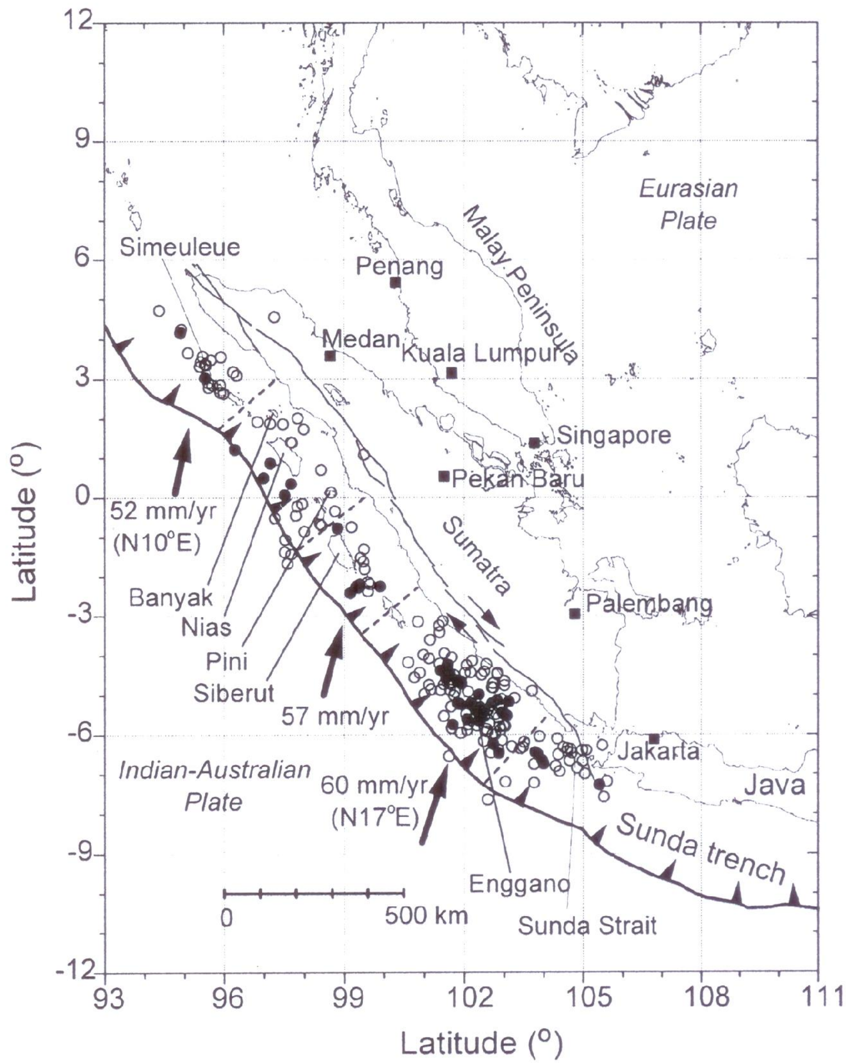

Figure 2.1: Sumatra subduction zone (Megawati *et al.,* 2005)

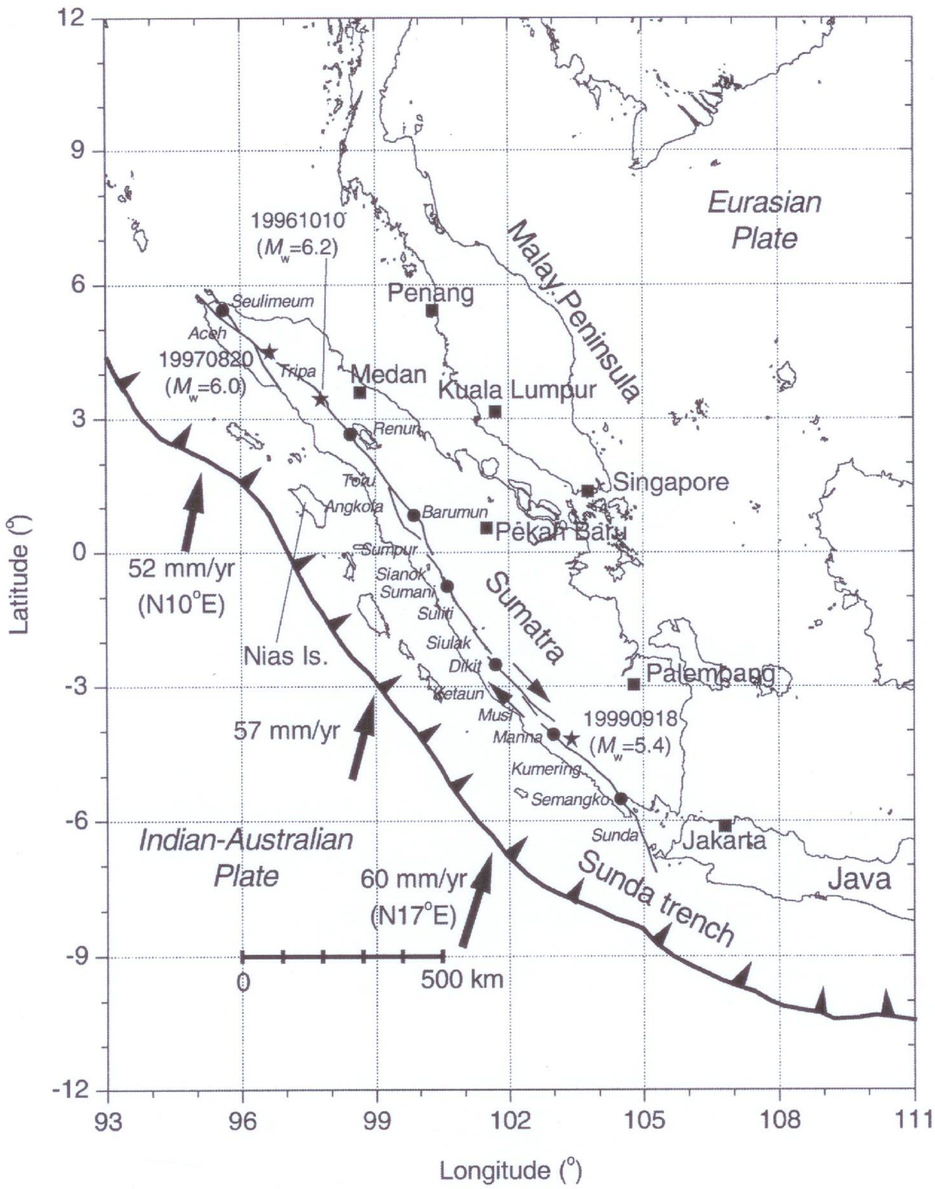

Figure 2.2: Sumatra fault (Megawati *et al.,* 2003)

2.2.3 Attenuation relationship for subduction zone

For the subduction zone, the ground motion relationship developed by Youngs et al. (1997) using regression analysis has been commonly used in seismic related engineering studies. In fact, it was used in the development of current seismic hazard maps for building code applications (Atkinson and Boore, 2003). In Malaysia, these ground motion relationships were developed by Adnan et al. (2005)

in order to develop the appropriate attenuation functions after factoring in local seismology and geology conditions. The three independent variables used in the regression analysis are moment magnitude, M_w, hypocentral distance, R_{hypo}, and focal depth, H_{focal}.

2.2.4 Attenuation relationship for fault zone

For the fault zone, most of the ground motion relationships developed earlier are mainly applicable to cases where the distance between the earthquake source and the site under consideration is less than 300km. These ground motion relationships are either developed empirically or theoretically. The empirical method would be valid if strong motion recordings are abundantly and readily available. However, when the availability of such recordings is scarce and limited, theoretical method is the more appropriate path to choose. It is a known fact that there is a large degree of uncertainties in calculating absolute values of ground motion. Campbell (2002) proposed a hybrid empirical method to resolve the problem. Using regression analysis, this hybrid method extended the range of validity between source and site to 1000 km.

2.2.5 Design response spectra

Once the peak ground acceleration (PGA) value has been established, a set of design response spectra can then be developed. The development of design response spectra requires the availability of soil data from soil investigation reports. A set of strong motion data is adopted to simulate the ground motion of an earthquake event. According to Bommer and Acevedo (2004), there are three ways in obtaining this ground motion data. The first one is by means of using a computer program called

SIMQKE to generate an artificial spectrum-compatible accelerograms. The second one is to generate synthetic accelerograms from seismological source model while accounting for path and site effects. The third one is to use real accelerograms recorded during a real earthquake event. Real accelerograms can be downloaded from the Internet websites such as those maintained by the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) and the Pacific Earthquake Engineering Research (PEER). A guideline on how to choose the appropriate type of accelerogram to use for analysis purposes is reported in Bommer and Acevedo (2004). A computer program such as Nonlinear Earthquake site Response Analyses (NERA) can be used to calculate the response spectrum acceleration values. Other factors required in the final development of the design response spectra are site classification, response spectrum of acceleration and amplification factor (Fadzli et al., 2007). Various codes of practice such as the Uniform Building Code of 1997 (UBC 97), the National Earthquake Hazards Reduction Program 2000 (NEHRP 2000) and the Eurocode 1998 (EN 1998) can be used as references to construct the response spectra curves.

2.3 Structural analysis requirements for high rise buildings in Malaysia

Since Malaysia is not located in a region of high seismic risk, there is presently no specific code requirement for dynamic lateral loading to seismic activity when designing high rise buildings. As far as resistance to lateral loading is concerned, engineers are only required to cater for two requirements. The first requirement is to consider wind loading designed in accordance to either Malaysian Standard MS1553 or British Standard BS6399. The choice of code to use depends on the preference of design engineer and on the type of computer software used. The second requirement is to consider a notional horizontal load equivalent to 1.5% of the structure's dead load. This load is applied to cater for accidental eccentricity and is in accordance to British Standard BS8110. A study based on nine selected time history analyses on a 280 meter tall building in Singapore by Pan et al (2004) found that the maximum value for base shear force was about 0.15% of the total characteristic dead weight of the building, which is very much less than the above mentioned notional horizontal load requirement.

Buildings in Singapore are also not required to be designed for seismic provision like those in Malaysia. The belief that the provision for notional horizontal load (NHL) was enough to cater for the seismic actions in this region was further investigated by Brownjohn, (2005) on the 280 meter tall building mentioned above. It was found that while the base shears generated by NHL and seismic response of the building in the first mode may be similar, the latter would generate a much larger overturning moment at the base. As such, it was recommended that more attention should be paid to the currently adopted local code provision.

As a matter of fact, the study of dynamic responses of tall buildings due to long distance earthquakes in Singapore has been an ongoing endeavour by researchers, as can be seen in early studies such as Brownjohn and Ang (1998), Brownjohn et al (1998) and Brownjohn and Pan (2001). The latest of such a study can be found in Brownjohn and Pan (2008). Findings from these studies would make good reference materials if studies of similar nature were to be carried out in Malaysia.

2.4 Basic types of structural analysis

There are basically eight types of analysis in the field of structural analysis and they are shown in Table 2.2.

Table 2.2: Basic types of structural analysis (Anwar and Sharma, 2005)

Excitation	**Structure**	**Response**	**Analysis Type**
Static	Elastic	Linear	Linear-Elastic-Static
Static	Elastic	Nonlinear	Nonlinear-Elastic-Static
Static	Inelastic	Linear	Linear-Inelastic-Static
Static	Inelastic	Nonlinear	Nonlinear-Inelastic-Static
Dynamic	Elastic	Linear	Linear-Elastic-Dynamic
Dynamic	Elastic	Nonlinear	Nonlinear-Elastic-Dynamic
Dynamic	Inelastic	Linear	Linear-Inelastic-Dynamic
Dynamic	Inelastic	Nonlinear	Nonlinear-Inelastic-Dynamic

2.4.1 Linear-Elastic-Static analysis

The basic equilibrium equation for linear-elastic-static analysis is given by:

$$Ku = F \qquad (2.1)$$

where K is the lateral stiffness of the system; u is the linear displacement and F is the external lateral static force. This linear relationship implies that F is a single-value function of u and is assumed to be applied very slowly to the system. The deformation is also assumed to be small. Both F and u are not functions of time. When F is plotted against u in a force-displacement graph, the loading and unloading curves would be identical.

2.4.2 Linear-Elastic-Dynamic analysis

Static analysis is appropriate when only the fundamental mode of the structure is considered. When higher modes are significant such as those found in three dimensional high rise buildings, dynamic analysis is required and the structure is usually modelled with multiple degrees of freedom (MDOF). The basic equilibrium equation of motion for this type of analysis is given by:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F(t) \qquad (2.2)$$

where M is the mass of the structure; $\ddot{u}$ is the acceleration component; C is the viscous damping coefficient and $\dot{u}$ is the velocity component. K and u are as defined in Equation (2.1) while F(t) is the applied dynamic load. All parameters are functions of the time, t.

2.4.3 Structural analyses used in this study

In this study, linear-elastic-static analysis was carried out using EsteemPlus to compute the sizes of structural elements and building drifts due to wind load and notional horizontal load. It is also carried out by ETABS in its equivalent static load method to compute building drifts. Linear-elastic-dynamic analysis was carried out by ETABS via response spectrum analysis to compute building drifts as well. Nonlinear-inelastic-dynamic analysis was carried out using IDARC2D to compute damage indices in selected frames from the three buildings.

2.5 Structural analysis in seismic engineering

Section 1626.1 of the Uniform Building Code 1997 (UBC97) states that the purpose of the earthquake provisions is to safeguard against major structural failures and loss of life and not to limit damage to the structure or to maintain function of the structure. Weller (2005) stated that the aim of code provisions in earthquake engineering is to avoid collapse of the structure. To do so, the structure must be able to deform with the earthquake while absorbing energy without its vertical supports such columns giving way.

Even way back in the early days, seismic engineering experts such as Newmark and Rosenblueth (1971) recognized that the effects of earthquakes have on structures would systematically bring out the mistakes made in design and construction because of their unpredictability. Appreciable probabilities that failure will occur in the future should be an integral part of a design engineer's line of thought when dealing with earthquakes. The fact that earthquake is a phenomena whose characteristics are unpredictable means a large scale of uncertainties is involved in the task of designing earthquake resistant engineering systems.

Earthquake engineering is an area of structural engineering where assumptions have to be made in order to develop critical design parameters. Some of these assumptions may be based on probabilistic analytical procedures such as the development of attenuation relationships. This is especially true for regions where ground motion data are scarce or not available. Some are based on engineering judgments such as the correct interpretation of soil data in the process of establishing the design response spectra for a region. Even when it comes to the design of the superstructure itself, engineering assumptions are often made in order to facilitate or simplified the analytical process.

For example, in a numerical simulation of buildings, the floor slabs are often assumed as a rigid horizontal diaphragm and thus modeled as such to reduce computation time. However, this simplification tends to cause errors in the analysis especially when the building's shape is somewhat special such as having long, narrow rectangular floor plans with large length/width aspect ratio (Pan et al., 2006). Disregarding the flexural stiffness of the floor slabs in the dynamic analysis of the analytical model by replacing them with rigid floor diaphragms would induce substantial analytical errors (Lee et al., 2005).

While preventing fatal structural failures is the fundamental role of any building code, the task of preventing hefty economic loss due to serious damages in non-structural components is just as important. Non-structural components such as brickworks, claddings, glass window panels, etc, are especially susceptible to damage as a result of excessive building drifts. The fundamental philosophy of earthquake engineering can be summed up and quoted from Bertero (1997):

i) To prevent non-structural damage in frequent minor ground shaking.
ii) To prevent structural damage and minimize non-structural damage in occasional moderate ground shaking.
iii) To avoid collapse or serious damage in rare major ground shaking.

It is not easy to quantify the extent of the damages incurred to a building following an earthquake event. It is even more difficult to quantify what constitutes frequent minor, occasional moderate and rare major ground shaking (Bertero, 1997). It is also common knowledge that all structural analysis involves approximations by means of idealizations. At present, three common types of structural analysis are used to analyze high rise buildings subjected to earthquakes (Wilkinson and Hiley, 2006) and they are equivalent static load analysis, response spectrum analysis and time history analysis.

In this study, only the first two methods of analysis are carried out. Although time history analysis is often regarded by the academic community to be the most reliable tool for dynamic analysis, it is not routinely adopted in the design office partly because of inadequate design guidelines and mainly because it is an extremely computation time consuming and labour intensive procedure.

2.6 Equivalent static analysis – linear static

The equivalent static analysis method is the least complicated method to analyse a structure that is subjected to seismic excitation. It is a simplified linear static method applicable to a single degree of freedom (SDOF) model. The basic notion is to convert the seismic excitation into an equivalent lateral force which is applied at the base of the building. This lateral force is called the base shear. (Anwar and Sharma, 2005). Once the base shear has been computed, it is then numerically distributed over the entire height of the building via an inverted triangular distribution with zero force at the base and maximum force at the top. There are, however, limitations in which this method can be used. O'Hara and Ballast (2005) states that under the Uniform Building Code 1997 (UBC97), the following types of structure are allowed to be designed using the equivalent lateral force method.